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Influence of nitrogen fertilization on lettuce yields (*Lactuca sativa L.*) using the ^{15}N isotope label

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Abstract. Nitrogen fertilization plays an important role in the growth of market gardening and the improvement of yields. Its efficiency of use is imperative for the preservation of the agricultural environment. An experiment is carried out over three consecutive years (2014/2015), (2015/2016) and (2016/2017), in a sub humid climate. The methodology adopted focuses on the variation of optimal nitrogen doses and their effects on the evolution of lettuce cultivation (*Lactuca sativa L.*), which has a socio-economic impact. The approach takes into account the isotopic marking technique, ^{15}N. The experimental device adopted is of the complete random block type, with four (04) levels: 0 (control), 60, 120 and 180 kg N ha^{-1} with four (04) repetitions. These levels are used to diagnose the effect of different doses on biomass (dry matter) and yield. It has been shown those doses between 0 and 120 kg N ha^{-1} increase significantly ($p < 0.05$), yields and dry matter with values of 18.32, 45.49 to 57.93 t ha^{-1} and 4.32, 5.52 to 9.77 t ha^{-1}, respectively. The rate of 120 kg N ha^{-1}, is shown statistically, as the efficient rate to cover the nitrogen needs of lettuce. This efficiency reaches 74.48%. Beyond that, nitrogen is not valorized by the crop. These results contribute to the realization of a technical reference system for lettuce cultivation, for an efficient use of nitrogen.

Key words: efficient rate, isotopic nitrogen ^{15}N, lettuce, nitrogen use efficiency.

INTRODUCTION

Agricultural potential in Algeria is 20% focused in the north of the country, characterized by unfertile soils. These soils, represented by a pH greater than 8, have low nutrient content, low water retention capacity and low organic matter content, according to Mazoyer (1970) and Belaid (2016), this matter does not exceed 2%. This situation contributes to low crop yields. The technical itinerary that makes it possible to correct these deficiencies is fertilization.

As several authors have shown in their work on Algerian soils. In this context, the Halilat (2004) showed that the interaction of potassium (P) and nitrogen (N) fertilization significantly affects wheat grain yield in the Saharan zone. The maximum yield is 6.780 MT ha^{-1} with the $N_{250}P_{180}$ rate. Boukhalfa–Deraoui et al. (2011) showed that the influence of phosphate fertilization on the behavior and yield of the common wheat crop grown under irrigation in arid areas increases the grain yield by 49.3% compared to the control. Haffaf et al. (2016); Saoudi et al. (2016), who conducted trials in the same semi-arid climate, respectively, on the production of durum wheat and barley seed, obtained maximum yields at similar rates. These yields reach the respective values of 33.82 and 33.25 q ha^{-1}, i.e. gains of 11.52 and 9.76 q ha^{-1}.

In Tunisia and Morocco, which have a similar climate, Marouani et al. (2013) have shown poor nitrogen use efficiency in seasonal potato cultivation. This inefficiency is linked to significant losses due to leaching. Kchaou et al. (2011) compared the nitrogen fertilizer value of sludge with that of urea, using isotope marking with ^{15}N, applied to forage sorghum. These authors found that sludge inputs caused significant increases in sorghum nitrogen yields and exports, comparable to those obtained in the presence of urea. They concluded that the actual nitrogen utilization coefficient of sludge nitrogen and urea offers values fluctuating between 25 and 32%. Ryan et al. (1997) showed that the effect of nitrogen fertilization on five durum wheat cultivars (Kyperounda, Marzak, Massa, Cocorit and Karim), conducted in rainy conditions, significantly influences biomass and yield.

According to FAO (2005), in Algeria, the use of fertilizers in agriculture is not controlled, despite the efforts made by farmers in charge of the cereal intensification program and potato farmers. Market gardening, which represents strategic crops in the country, is undergoing significant development. Their area of 320 100 ha in 2003, or 0.75% of the Utilized Agricultural Area (SAU), increased to 511 018 ha in 2015, or 1.18% of the SAU. Production increased from 49.08 million quintals to 124.69 million quintals, respectively, Ministry of Agriculture and Rural Development (MADR, 2015). Despite its importance in the country's economy, this sector suffers from a lack of a database and a scarcity of studies relating to fertilization in general and fertilizer use in particular.

According to National Institute of Soil for Irrigation and Draining (INSID, 2009), fertilizers are applied in the absence of technical standards, neglecting the initial content of the soil; and consequently, inputs are often poorly fractionated resulting in waste, which is a source of soil and water pollution. In this perspective, this study uses the 15N isotopic approach to assess nitrogen use efficiency. This new method, used by the IAEA (2001), highlights isotopic nitrogen ^{15}N, which represents the most commonly used stable isotope, in studies related to agriculture. It is the direct means of measuring nitrogen uptake by applied fattening, and the most reliable means of monitoring the flow and fate of nitrogen in the soil-plant system (Zapata, 1990; Bedard–Haughn et al., 2003).

To highlight the monitoring of this system, the plant material chosen is lettuce (*Lactuca sativa L.*), due to its short growing cycle. But also, because of the socio-economic impact that is beginning to dominate, at the national level. It is a source of wealth and income for producers. The average price of a kilo of lettuce is around € 0.49 (64 DZD), varying between a minimum price of € 0.22 (30 DZD) and a maximum price of € 0.89 (120 DZD). The objective of this study is essentially oriented towards the search for optimal nitrogen fertilizer doses in order to contribute to the production of technical standards for the efficient use of fertilizers.

MATERIALS AND METHODS

Experimental site

The experiment was carried out at the experimental station of the National Institute of Agronomic Research (INRA) of Mahdi Boualem (Fig. 1) located southwest of Algiers in the eastern part of Mitidja. The research station is located between 36°68' North of Latitude and 3°1' East of Longitude and at an altitude of 18 m.

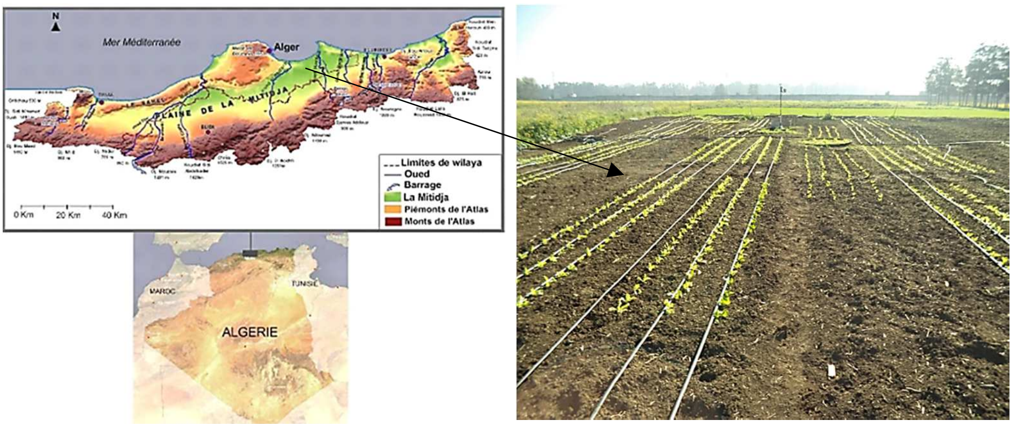

Figure 1. Location of the study area.

To give an overview of the climate that characterizes the area, the climate data used comes from the research station's automatic weather station. The measurements taken, at a daily time step, cover minimum and maximum temperatures (°C), precipitation (mm), wind speed (m s^{-1}) at 2 m above the ground, solar radiation (W m^{-2}) and relative humidity (%). These parameters were used to calculate the reference evapotranspiration using the FAO Penman–Monteith method (Allen et al., 1998).

To give the soil characteristics, a soil profile was carried out over a depth of one meter, including three horizons, the results of which are presented in Table 1.

Experimental protocol

The test is carried out in the field according to a complete randomized block experimental design, with four nitrogen levels, namely: T1 (0 kg N ha^{-1}), T2 (60 kg N ha^{-1}), T3 (120 kg N ha^{-1}) and T4 (180 kg N ha^{-1}) arranged in four blocks. Each block has four sub-plots (Fig. 2). Each micro-plot is 6 m long and 3 m wide, for a total area of 18 m^2, of which 4.5 m^2 is used for ^{15}N-labelled nitrogen. 100 kg K ha^{-1} and 150 kg P ha^{-1} of phosphate and potassium fertilizers were incorporated into the soil as bottom manure. This trial was repeated over the three years (2014/2015), (2015/2016) and (2016/2017). We used the ^{15}N isotopic technique only in the 2014/2015 test because of its high cost. The quantities of nitrogen used are distributed throughout the crop development cycle, namely: 10% at 15 days after transplanting (DAT), 30% at 40 DAT, 40% at 60 DAT and 20% at 75 DAT.

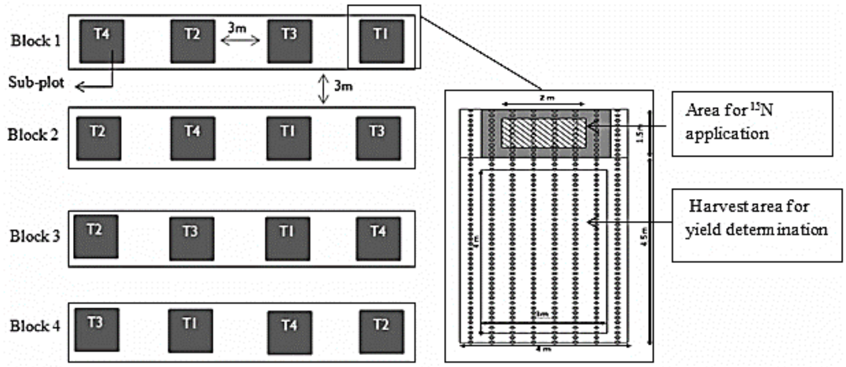

Figure 2. Experimental device.

The crop taken into consideration is variety lettuce, stubborn from Nîmes, belonging to the lettuce to be applesauce class, which is eaten young, before it goes to seed. Lettuce seeds were sown in the honeycomb plates for 19 to 25 days in the nursery before being transplanted. The young lettuce plants were transplanted at the 3 to 4 leaf stage onto well ploughed soil in the field.

Evaluation

Biomass is one of the essential parameters of research on the effectiveness of fertilizers, particularly in lettuce, where the growth of the aerial part is a determining factor in the agricultural value of this crop (Begoña et al., 2011). To evaluate this parameter, every ten days, six (6) plants per sub-plot were cut at ground level, field samples were taken back to the laboratory for drying in an oven for 48 hours at 70 °C.

To determine the isotopic composition of lettuce plants. The heads of the latter receiving ^{15}N were divided into two parts (roots and leaves). Fresh weight was evaluated for all parts of the crop. The samples were dried at 70 °C for 24 hours, weighed to determine the dry weight, ground to a fine powder using a 0.3 mm sieve, then homogenized, for the determination of total nitrogen and excess ^{15}N. Isotopic analysis of the samples from the lettuce culture was carried out at the National Center for Energy, Science and Nuclear Techniques (CNESTEN-Morocco).

The quantification of nitrogen from the fertilizer was measured using the isotopic dilution method from Ndff (nitrogen from the fertilizer), and the rate of nitrogen fertilizer applied, according to the following equations defined by the IAEA (2001):

$$\%\,Ndff = \frac{\text{atom }\%15\text{N excess plant}}{\text{atom }\%15\text{N excess fertilizer}} \cdot 100 \tag{1}$$

$$\%\,Ndfs = 100 - \%\,Ndff \tag{2}$$

$$\text{DM yield }(\text{kg ha}^{-1}) = FW(kg) \cdot \frac{10{,}000\ \left(\text{m}^2\ \text{ha}^{-1}\right)}{area\ harvested(\text{m}^2)} \cdot \frac{SDW\ (kg)}{SFW\ (kg)} \tag{3}$$

$$\text{N yield }(\text{kg ha}^{-1}) = DMyield\ (\text{kg ha}^{-1}) \cdot \frac{\%\,N}{100} \tag{4}$$

$$\text{Fertilizer N yield }(\text{kg ha}^{-1}) = Nyield(\text{kg ha}^{-1}) \cdot \frac{\%\,Ndff}{100} \tag{5}$$

$$\% \text{ Fertilizer N utilization} = \frac{Fertilizer\ N\ yield}{RateofNapplication} \cdot 100 \qquad (6)$$

where Ndff – Fraction of N in the plant derived from the ^{15}N labeled fertilizer; Ndfs – Nitrogen derived from soil; FW – Fresh weight per area harvested; SDW – Subsample dry weight; SFW – Subsample fresh weight; DM – Dry matter Yield.

Statistical analysis: The obtained results were statistically evaluated by the analysis of variance (one-way ANOVA) method. The effects of the different treatments applied are estimated using the statistical software SPSS 25. The comparison of the averages was made by the LSD (Least Significant Difference) test at the threshold α = 5%.

RESULTS AND DISCUSSION

Analysis of climate data

The variations in precipitation and ET0 are shown in Fig. 3, which illustrates the distribution of rainfall during the three years of experience 2014/2015, 2015/2016 and 2016/2017. The cumulative rainfall received between September and August is in the order of 552, 551 and 525 mm respectively. Those corresponding to the experimental seasons (January to April) are close to the averages of 211.4, 303.4 and 332.6 mm. The corresponding potential annual evapotranspiration is in the order of 744.3, 782.6 and 596.3 mm. The ones corresponding to the growing seasons are, respectively, 195.4, 196.5 and 137.5 mm. Despite high rainfall amounts during the second year's experimental season, ET0 remains the highest compared to the other two years of experimentation. This increase is due to the high average temperatures during the corresponding months. Fig. 4 shows the monthly average temperature fluctuations over the three agricultural years. They are between 0.4 and 47 °C.

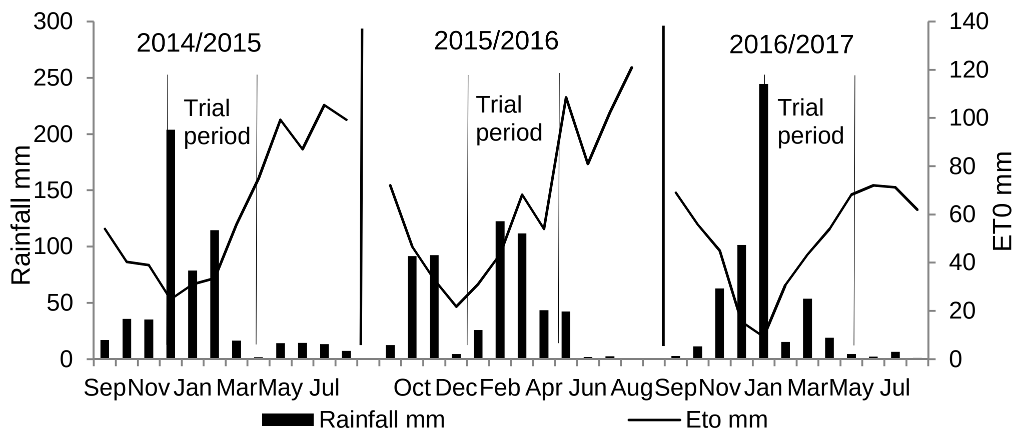

Figure 3. Precipitation, potential evapotranspiration (ET0) at monthly scale for the 2014/2015, 2015/2016 and 2016/2017 test years.

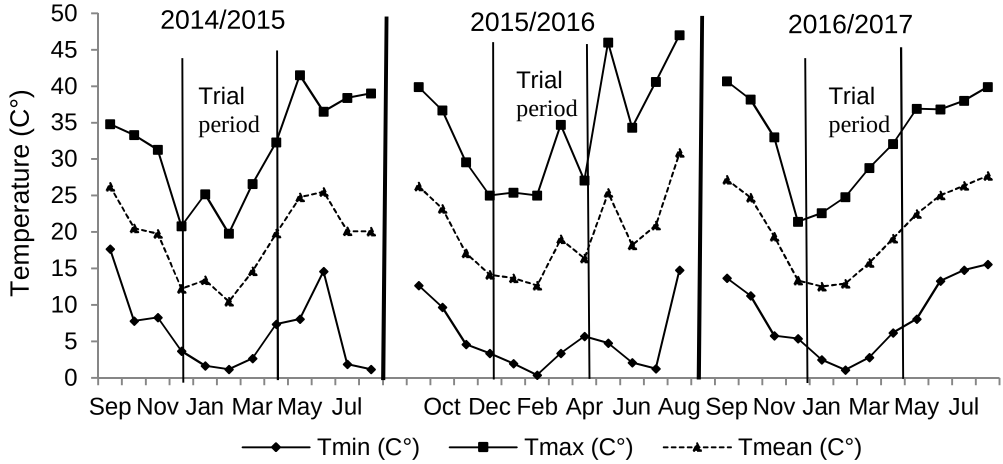

Figure 4. Monthly variations in maximum, minimum and average temperatures for the 2014/2015, 2015/2016 and 2016/2017 test years.

Physical and chemical characteristics of the soil

The granulometric results indicate that the soil is characterized by a silty clay texture (Table 1). Chemical analysis results show that the soil is characterized by a basic pH (about 8). The organic matter content of the soil is low (less than 2%), which causes poor water and mineral retention.

Table 1. Physical and chemical properties of the soil of experimental field

Parameters		Horizon 1 (0–25 cm)	Horizon 2 (25–55) cm)	Horizon 3 (> 55 cm)
pH		7.87	7.77	7.8
Electric conductivity (dS m^{-1})		0.17	0.17	0.17
Bulk density (g cm^{-3})		1.28	1.29	1.29
Saturation humidity (Vol. %)		44.86	43.19	42.5
Field capacity (Vol. %)		33.52	34.50	34.29
Permanent Wilting point (Vol. %)		22.87	23.26	21.60
Total limestone %		0.73	0.48	0.80
Granulometry (%)	Clay	42.81	48.50	51.89
	Silt	48.35	44.67	44.20
	Sand	7.98	7.77	7.80
Soil texture		Silty clay	Silty clay	Silty clay

Effect of fertilization on above-ground biomass and yield

Fig. 5 shows the evolution of nitrogen doses at different phenological stages of the plant. This evolution is supported by the analysis of variance, which showed a very significant effect ($p < 0.001$) of the fresh and dry above-ground biomass, in relation to the increase in nitrogen doses provided. A maximum of fresh and dry biomass is achieved at a rate of 120 kg N ha^{-1}. Above this level, the increase in nitrogen rate is not significant. This result is consistent with that of Maurice et al. (1985) which showed that fertilization at high doses leads to a decrease in above-ground biomass. This is the case for the first year (2014/2015).

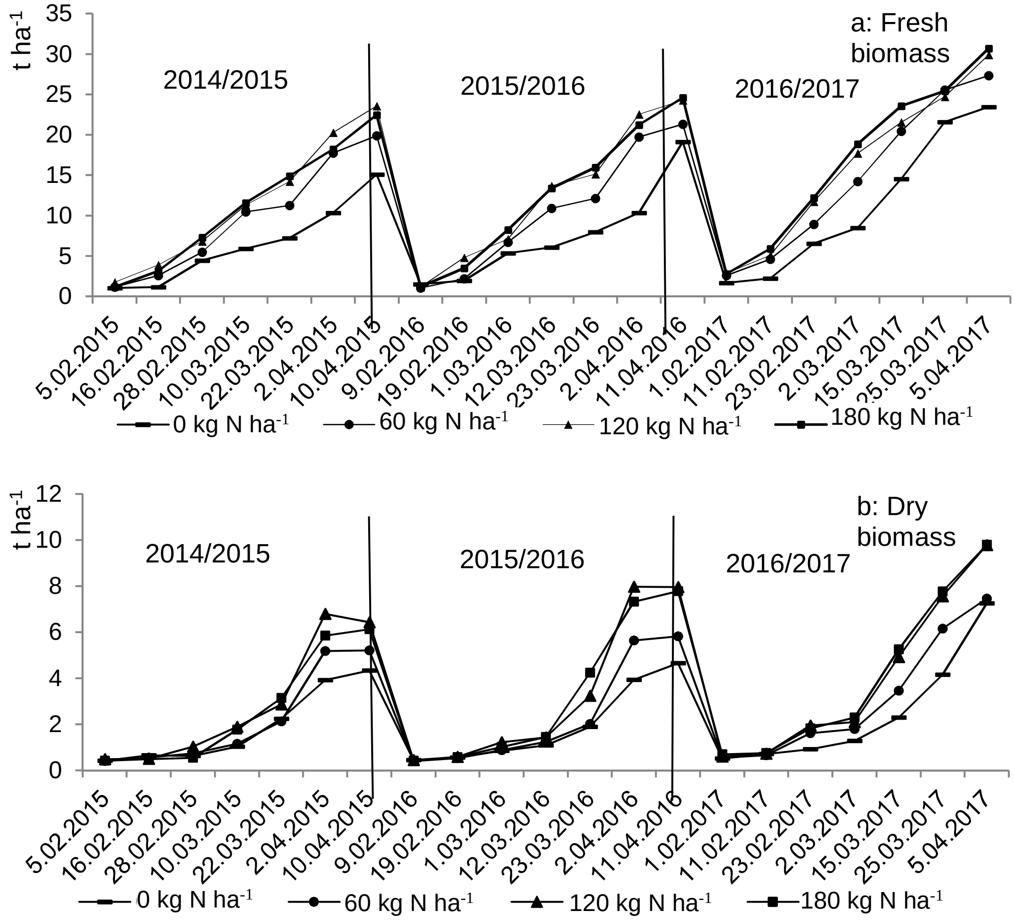

Figure 5. Effect of different fertilization levels on the evolution of fresh (a) and dry (b) above-ground biomass for the three growing seasons.

Fig. 6 shows lettuce yields as a function of the nitrogen rates applied. Indeed, the graph shows that, during the three experimental campaigns, the highest lettuce yields (57.93 and 58.46 t ha^{-1}), are obtained by applying the 120 and 180 kg N ha^{-1} doses. These doses are very highly significant ($p < 0.001$) compared to those obtained (26.27 and 45.49 t ha^{-1}) by providing minimum doses below 60 kg N ha^{-1}.

This result is consistent with Boroujerdnia et al. (2007) and Shahbazie (2005), who reported that increasing nitrogen levels from 0 to 120 kg of N ha^{-1} has a positive effect on lettuce production. Nevertheless, in detail, the T4 treatment, from the 2014/2015 trial, shows a relatively lower yield of about 50.17 t ha^{-1}, compared to that (54.25 t ha^{-1}) of the T3 treatment, from the same year. The difference estimated at 3.08 t ha^{-1}, can be explained by the toxicity of the plants or the non–attraction of nitrogen by the plants resulting from the consumption of excess nitrogen fertilizer, as highlighted by Tabatabaie & Malakoutie (1997). Lettuce's response to yields is considerably higher in 2016 and 2017 than in 2015. This result is related to higher rainfall amounts.

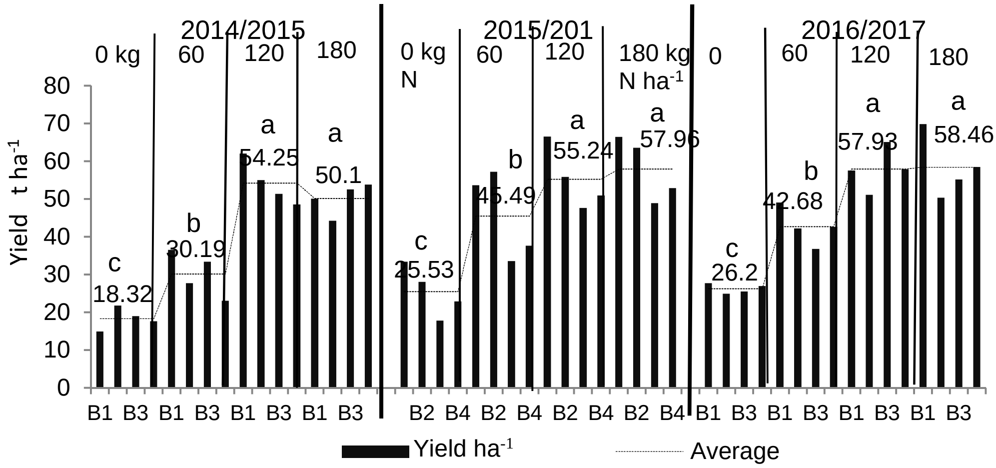

Figure 6. Effect of different fertilization levels on yield for the three growing seasons [a, b and c represent significant differences (p < 0.05)].

In this study, the average yield obtained by the 120 kg N ha^{-1} dose during the three crop years fluctuated between 54.25 and 57.93 t ha^{-1}, or an average of 5.5 kg m^{-2}. Boroujerdnia et al. (2007) obtain a yield of about 7 kg m^{-2} with a rate of 120 kg N ha^{-1}. The difference can be explained by the choice of variety, soil fertility and precipitation. The results of this study suggest that the application of nitrogen in the form of urea at 120 kg N ha^{-1} may be sufficient to cover the N requirements of the lettuce crop. These results are consistent with those obtained by Boroujerdnia et al. (2007), Regional Group of Expertise Nitrates (GREN, 2014), Awaad et al. (2016) and Gonzalez (2017).

Effect of nitrogen fertilization on nitrogen content (%N) in dry matter

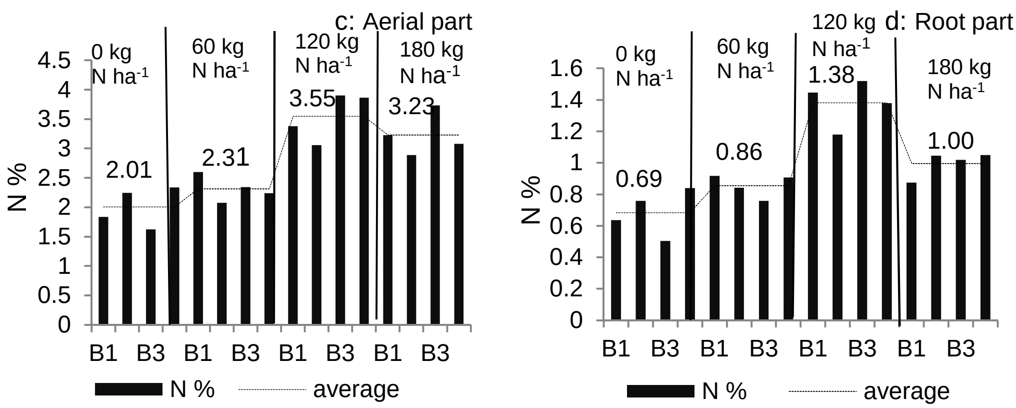

Figure 7. Effect of different fertilization levels on total nitrogen (N %) in lettuce leaves (c) and roots (d).

Fig. 7 shows a fluctuation in the assimilation of nitrogen doses from 0 to 120 kg N ha^{-1} by leaves and roots in the different blocks. Statistically, these results show a very highly significant difference ($p < 0.001$). The average nitrogen assimilation rate increases from 2.01 to 3.55% in the aerial part (c), it is from 0.69 to 1.38% in the root part (d). Above 120 kg N ha^{-1}, the nitrogen content decreases in both the aerial and root parts. At a rate of 180 kg N ha^{-1}, the results show that its use by the plant is ineffective. This result is consistent with that reported by Lawlor et al. (2001). A very close relationship ($r = 0.86$) is observed between nitrogen doses and the content of this element in the whole plant (leaves + roots).

Nitrogen valorization by the crop

The contribution of N15–urea (Ndff) and N–soil (Ndfs) to the total amount of nitrogen absorbed by the aerial part (leaves) and the underground part (root system) is illustrated in Fig. 8. The latter, which shows how isotopic nitrogen is used, determines the real share of nitrogen assimilated by fertilizer inputs (Ndff) in favour of the real share and accurately evaluates the share of soil nitrogen (Ndfs) that contributes to the crop's diet, since, according to Fig. 8 (e and f), it is observed that at a rate of 60 kg N ha^{-1}, the crop values the nitrogen contained in the soil better than the nitrogen supplied.

A better valuation of Ndff by the crop is carried out at a rate of 120 kg N ha^{-1}, it is 70.79% for the leaves, and 59.47% for the roots. Ndfs decreased significantly with increasing nitrogen application rates. These observations are consistent with research by Zhaoming et al. (2016) on winter wheat and Kchaou et al. (2011) on sorghum.

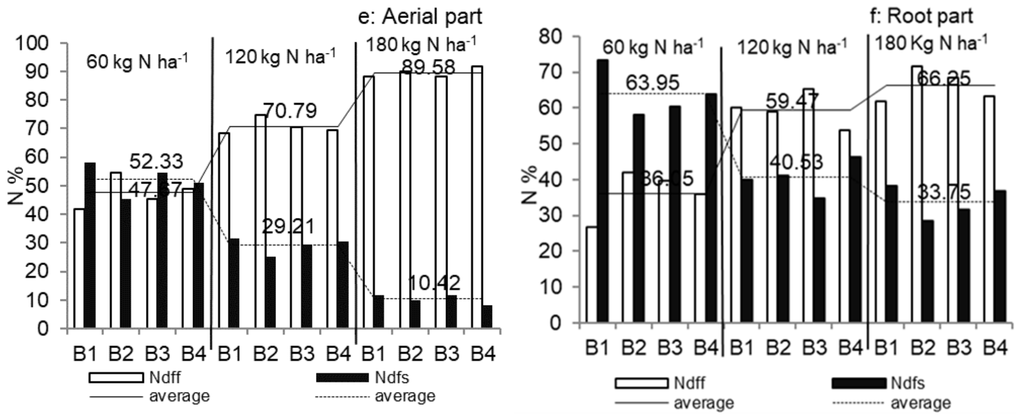

Figure 8. Nitrogen source in the aerial part (e) and root system (f) of lettuce.

Nitrogen use efficiency (NUE)

Nitrogen use efficiency is an important indicator for nitrogen fertilizer application. In this context, Fig. 9 illustrates the variation in the percentage of nitrogen use efficiency as a function of defined thresholds. For doses ranging from 60, 120 to 180 kg N ha^{-1}, the EUN varies, respectively, from 65.42, 74.48 to 68.38%. The percentage of nitrogen use efficiency (NUE), decreased from 74.48% to 68.38% by increasing the dose from 120 to 180 kg N ha^{-1}. These results are similar to those reported by Khelil et al. (2005) and Kchaou et al. (2011). The 120 kg N ha^{-1} dose allows the best efficiencies to be achieved.

That is 74.48% of the fertilizer applied is consumed by lettuce cultivation. The remaining 25.52% of N is either in the soil or lost through leaching. Lettuce is a short-cycle crop; it makes the best use of available nitrogen, as reported by Edith et al. (2017).

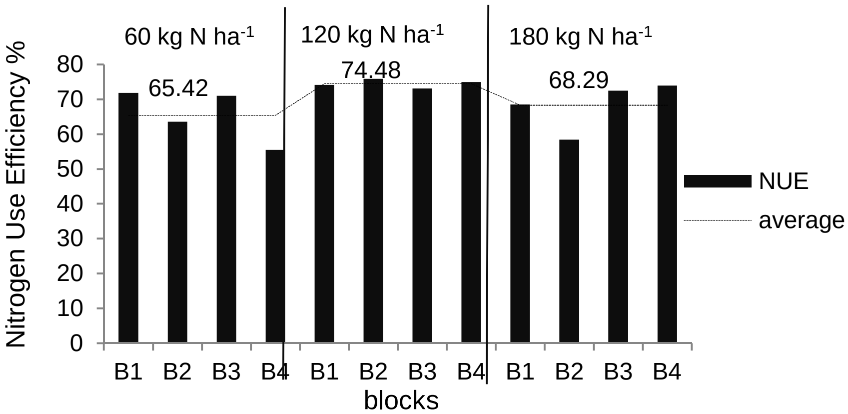

Figure 9. Variation in nitrogen use efficiency by lettuce, expressed as a percentage (%).

CONCLUSIONS

To have a better understanding of the term fertilizer use efficiency, the use of isotopic techniques (^{15}N) proved essential in order to evaluate the different sources of nitrogen assimilated by the lettuce crop. It appears that nitrogen fertilization allowed a good development of the crop, starting from the minimum rate of 60 kg N ha^{-1}. The results obtained from this study showed that the nitrogen fertilizer rate had a significant influence on the evolution of the above-ground biomass and the yield of lettuce. The 120 kg N ha^{-1} dose resulted in a significant yield of 54.25 t ha^{-1}, compared to the other doses provided, with a nitrogen use efficiency of 74.48%. It is recommended as the efficient rate for the crop and those with the same morphological characteristics and that evolve under the same type of climate and soil.

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Review: Soil compaction and controlled traffic farming in arable and grass cropping systems

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Abstract. There is both circumstantial and direct evidence which demonstrates the significant productivity and sustainability benefits associated with adoption of controlled traffic farming (CTF). These benefits may be fully realised when CTF is jointly practiced with no-tillage and assisted by the range of precision agriculture (PA) technologies available. Important contributing factors are those associated with improved trafficability and timeliness of field operations. Adoption of CTF is therefore encouraged as a technically and economically viable option to improve productivity and resource-use efficiency in arable and grass cropping systems. Studies on the economics of CTF consistently show that it is a profitable technological innovation for both grassland and arable land-use. Despite these benefits, global adoption of CTF is still relatively low, with the exception of Australia where approximately 30% of the grain production systems are managed under CTF. The main barriers for adoption of CTF have been equipment incompatibilities and the need to modify machinery to suit a specific system design, often at the own farmers' risk of loss of product warranty. Other barriers include reliance on contracting operations, land tenure systems, and road transport regulations. However, some of the barriers to adoption can be overcome with forward planning when conversion to CTF is built into the machinery replacement programme, and organisations such as ACTFA in Australia and CTF Europe Ltd. in Central and Northern Europe have developed suitable schemes to assist farmers in such a process.

Key words: axle load, fertiliser use efficiency, greenhouse gas emissions, non-controlled traffic, no-tillage cropping, traffic intensity.

INTRODUCTION

In the past few decades, there has been a continuous drive towards the development and adoption of larger, and more powerful, agricultural machinery (Jørgensen, 2012). Larger machinery is often related with timeliness, higher work rates and lower labour requirements, which has contributed to significant improvements in field efficiency and productivity (Vermeulen et al., 2010; Tullberg, 2018). A drawback of this trend has been the associated increase in the overall load of farm machinery, which has, to some extent, offset advances made by the industry in developing improved running gear, such as in tyre (e.g., radial ply tyres) and track technology (e.g., rubber belts) to reduce contact pressures (Ansorge & Godwin, 2008; Antille et al., 2013; Misiewicz et al., 2015). The progressive increase in axle loads, as observed for example with harvesting equipment (e.g., Ansorge & Godwin, 2007; Braunack & Johnston, 2014), means that soil stresses have also continued to increase, extending deeper into the subsoil (e.g., ≥ 0.3 MPa at 400-mm deep) and exceeding historic values, such as those resulting from in-furrow ploughing (Koolen et al., 1992; Chamen, 2015, Fig. 1).

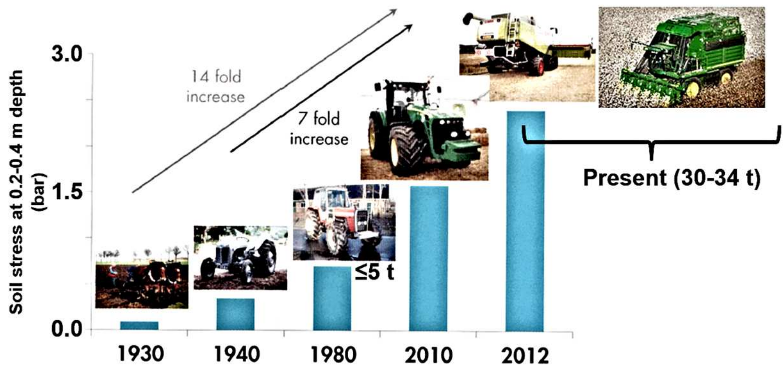

Figure 1. Changes in overall machine load over time and the effect on soil stresses at the 0.2–0.4 m depth interval (modified from Chamen, 2015).

Traffic compaction has adverse effects on the physical, chemical and biological properties of soils; thus, affecting important soil processes and functions, and crop productivity (Soane & van Ouwerkerk, 1995; Wu et al., 1995; Lipiec & Hatano, 2003). Compaction is regarded as one of the main causes of soil degradation and it is addressed in the proposed European Soil Framework Directive (EC, 2006). It compromises water infiltration into soil, increases the frequency and duration of waterlogged conditions, reduces gaseous exchange between soil and the atmosphere, and restricts root penetration and therefore exploitation of water and nutrients in the subsoil (O'Sullivan & Simota, 1995). These effects can, in turn, lead to increased risk of erosion and runoff, and therefore nutrient and sediment transport to water courses (diffuse pollution), and increased risk of flooding (Rickson, 2014; Graves et al., 2015; Alaoui et al., 2018). There is also an elevated risk of greenhouse gas emissions from soils affected by compaction due to poor aeration (Ruser et al., 1998, 2006; Antille et al., 2015a; Tullberg et al., 2018). The effects of soil compaction are often persistent, particularly in the subsoil, and they are intensified with repeated passes (Raghavan et al., 1976, 1977; Botta et al., 2009).

Soil recovery through natural processes varies widely depending on soil type, the extent of wetting and drying, and freezing and thawing cycles (Pollard & Webster 1978; Dexter, 1991). For example, heavy clay soils with shrinking-swelling properties may recover from the effect of compaction to a greater extent than typically medium- and lighter-textured soils with no shrinking-swelling capacity (Radford et al., 2007). However, in all soils, the rate of amelioration of such compaction decreases with an increase in soil depth (Kay, 1990; McHugh et al., 2009), which requires that compaction is avoided, particularly in the subsoil (Spoor et al., 2003). In intensively-managed arable cropping systems, the frequency of traffic with farm machinery does not normally allow for natural soil alleviation; therefore, tillage repair treatments are often required between crop cycles (Alakukku, 1999; Spoor, 2006). Remediation of compaction through tillage is energy-demanding as draught increases significantly with an increase in soil depth (Godwin & O'Dogherty, 2007). Consequently, remediation of deep soil compaction can prove impractical, and often uneconomical, at depths greater than approximately 400-mm (Spoor & Voorhees, 1986; Håkansson & Reeder, 1994; Tullberg, 2000). Deep loosening of soil carries the risk of re-compaction at such depth with subsequent traffic leading to a recurrent compaction-loosening cycle, which aggravates the problem (Soane et al., 1986; Spoor et al., 2003). Botta et al. (2006) showed that on an *Entic Haplustoll* (medium-textured soil) sown with sunflower (*Helianthus annus* L.), the beneficial effects of subsoiling and chiselling in removing soil compaction and reducing soil strength lasted only two years when CTF was not practiced. These effects became negligible after that time when traffic intensity was greater than about 95 Mg km^{-1} ha^{-1} because of re-compaction/re-consolidation of the soil profile; particularly, in the 300 to 600 mm depth interval. Therefore, effective technical solutions lie in ‘traffic management’ rather than ‘tillage management’.

Concerns over the long-term sustainability of arable cropping associated with progressive deterioration of the soil resource have contributed to the development of more efficient field-traffic management strategies; namely, controlled traffic farming (CTF) systems. These systems have evolved in response to evidence of significant soil damage from compaction caused by field traffic. Reviews by Tullberg et al. (2007) and Chamen (2015) provide in-depth analyses of the factors that motivated the development of CTF systems using purposely-modified commercially-available machinery. Research (e.g., Taylor, 1983; Chamen et al., 1992; Tullberg, 2010) and on-farm practice (e.g., Gold, 2013) have shown that CTF systems are effective means of avoiding widespread compaction by confining all load-bearing wheels to the least possible area of permanent traffic lanes. Controlled traffic systems have fundamental advantages in maintaining ‘good’ soil structural conditions of non-trafficked crop beds (e.g., McHugh et al., 2009; Millington et al., 2017), with improved trafficability and timeliness compared with conventional traffic systems.

Review Aim

This article reviews some of the benefits that may result from the adoption of controlled traffic farming in arable and grass production systems, and provides a brief overview of the requirements of such traffic systems. Those benefits are explored in terms of overall ‘system’ efficiency while considering the need for sustainable approaches to soil management in intensive agriculture.

OVERVIEW OF CONTROLLED TRAFFIC FARMING SYSTEMS

Arable Cropping

Controlled traffic farming (CTF) was adopted in commercial-scale farming in the 1990s, initially in Australia (Webb et al., 2004; Tullberg et al., 2007), and subsequently in northern and central Europe (Chamen, 2015; Galambošová et al., 2017), and Canada (CTFA, 2017), respectively. Modification of commercially-available machinery and development of precision (± 0.02-m accuracy) guidance systems (RTK-DGNSS: Real Time Kinematic-Differential Global Navigation Satellite System) greatly facilitated on-farm adoption of CTF (Dijksterhuis et al., 1998; Vermeulen & Chamen, 2010).

The Australian Controlled Traffic Farming Association Inc. (ACTFA, http://actfa.net/) defines CTF as a system in which: (1) all machinery has the same or modular working and track width so that field traffic can be confined to the least possible area of permanent traffic lanes, (2) all machinery is capable of precise guidance along those permanent traffic lanes, and (3) the layout of permanent traffic lanes is designed to optimise surface drainage and operational logistics. These elements are essential components of a CTF system. The following practices are also facilitated by and in agreement with CTF (after ACTFA, 2018): (1) minimal soil disturbance (e.g., shallow tillage and no-tillage). Strategic or occasional tillage may be required in long-term no-tillage systems for mechanical control of herbicide-resistant weeds or to restore optimal growing conditions on some (e.g., hard-setting) soils (Melland et al., 2017; Dang et al., 2018). In sandy soils with hardpans, deep tillage (e.g., 500 mm) with topsoil slotting (soil inclusion plates attached to the rear of deep ripper tines) is an effective technique to prolong the de-compaction response in those soils (Blackwell et al., 2016), (2) increased frequency of rain-fed cropping and cover crops to maximise biomass production, residue returned to soil and therefore greater opportunities for carbon sequestration. In Australia, typical cropping frequencies in CTF systems under no-tillage vary between 1.0 and 1.2, which compares to about 0.7 or less in non-CTF with conventional tillage (Antille et al., 2015a), (3) precise management such as inter-row seeding and accurate placement of agrochemicals and fertilisers, and (4) spatial (subfield-scale) monitoring, mapping and management at progressively finer resolution within a defined spatial framework, which distinguishes between permanent traffic lanes and crop beds (spatially-fixed environment, McPhee et al., 2019). This is assisted by continuous regeneration of soil structure in crop beds (e.g., McHugh et al., 2009; Hulugalle et al., 2017) and elimination of traffic compaction-induced soil variability (Barik et al., 2014).

Conversion from a conventional system, with unmatched machinery and different track gauge widths, to CTF should consider the following (after Isbister et al., 2013, 2018): (1) accurate guidance systems (e.g., GNSS RTK, ± 0.02-m correction) to enable machinery to return consistently and precisely to the same (permanent) traffic lanes, (2) machinery matching so as to match wheel track spacing and also choose a convenient operating width (e.g., seeder and combine harvester-to-sprayer ratio of 3:1) and match in multiples (Fig. 2), (3) optimise the design, management and orientation of permanent traffic lanes, and (4) field layout in regards to risk of erosion and safe discharge of runoff, and subsequent application of variable rate technology.

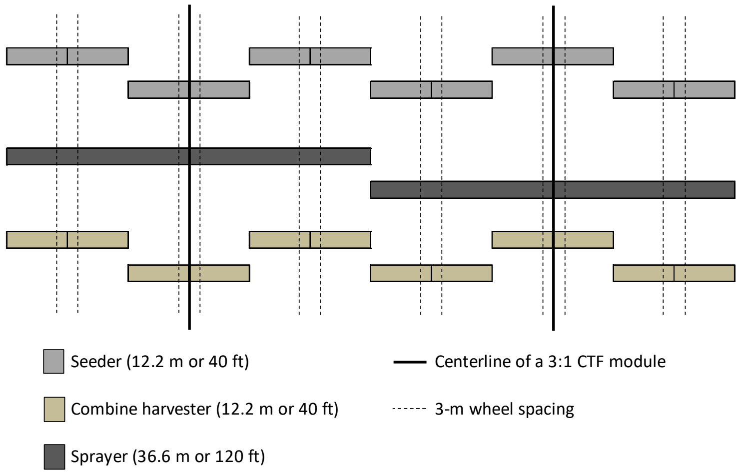

Figure 2. Diagram of a CTF system setup showing a 3-to-1 seeder and combine harvester-to-sprayer matching ratio (re-drawn from Isbister et al., 2018). For all machinery, the wheel spacing shown in this example is 3-m.

In well-designed CTF systems, such as those commonly used in grain-cropping in Australia (e.g., 9 or 12-m module), permanent traffic lanes typically occupy about 15% or less of the cultivated field area, provided that the section width of heavy load-bearing tyres is 500 mm or less (Tullberg et al., 2007; Tullberg, 2014). Without CTF, varying equipment and track gauge widths often translate into disorganised or '*ad hoc*' traffic patterns, which can cover more than 85% of the total cultivated area each time a crop is produced. In non-CTF systems, even when no-tillage is practiced, the field area affected by traffic can be as high as 45%. Alternative CTF systems to the single track width (known as 'Com-Trac') have been also developed, and many of these are more readily adoptable within European farming systems (e.g., Galambošová et al., 2017). For 'Com-Trac' systems, the width of the track matches that of the vehicle that is most costly or difficult to modify, typically the harvesting equipment. For combine harvesters in which the front axle has single tyres configuration, the standard track width is 3-m; hence, all other equipment needs to have equal wheel spacing (Fig. 3).

Figure 3. A 8400-series John Deere CTF-compatible tractor (left) with front and rear axles extended to 3-m. Note the tractor positioned on the permanent traffic lanes of a 9-m module CTF system in no-tillage. The machinery width ratio is 3:1, that is, 9-m front combine harvester and planter bar, and 27-m boom width sprayer (right), also with both axles extended to 3-m.

Fig. 4 shows the output of Trackman® (Newell et al., 1998) used to estimate and illustrate the relative footprint of mechanisation systems representing conventional tillage and zero-tillage with unmatched machinery and track gauge widths, and CTF with 3-m wheel spacing. Trackman® is a wheel-track mapping software, developed to determine both the extent and location of wheelings within a field given the mechanisation system available at the farm. The software can be used for decision-making to investigate 'what if' scenarios when considering conversion to CTF. This is possible by making repetitive adjustments to equipment widths and wheel spacing options until the mechanisation system is optimised to suit the farm-specific application. By providing information on the machinery modifications required, an economic evaluation can be then undertaken to assist decision-making. Different colours in Fig. 4 denote different pieces of farm equipment. In the conventional tillage scenario, the same tractor (red), a front wheel assist (FWA) fitted with dual tyres, is associated with the seeder, scarifer and blade plough. In the CTF and zero-tillage scenarios, the tractors (also in red) are displayed as FWA, but fitted with single instead of duals tyres. The combine harvester (blue) is consistent across all situations. The 'footprint' displayed at the bottom of each section represents the accumulation of all wheel tracks for the associated pieces of equipment and for each scenario (note the footprint colours are consistent with the colours displayed in Fig. 4). When the 'footprints' align as shown in the CTF example, the area of the field affected by compaction is significantly reduced. However, where random traffic occurs with multiple passes of equipment, the 'footprint' or compacted area is significant. In this latter situation, some areas of the field have up to 7 passes of load bearing wheels during a single cropping cycle.

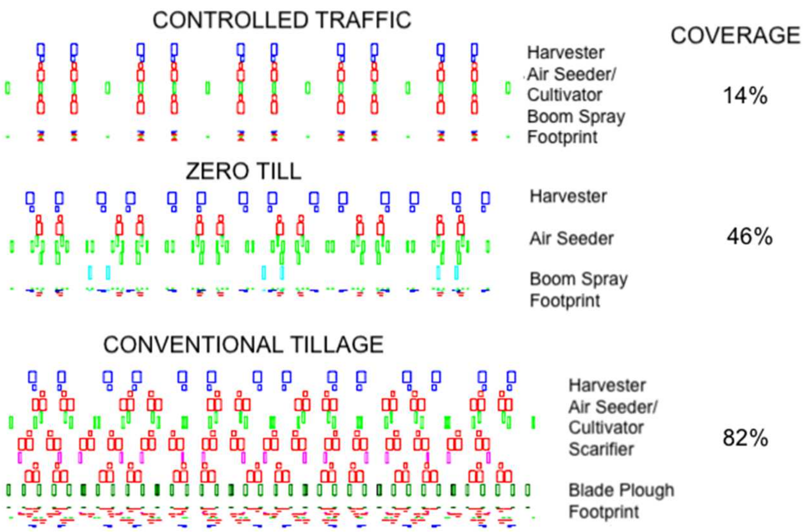

Figure 4. Typical wheeled areas for controlled traffic (3-m centre, 9-m module, zero-tillage), and unmatched machinery in zero-tillage and conventional tillage systems, respectively, determined with the use of Trackman® (Newell et al., 1998).

Alternatives to the common CTF system, in which all vehicles have 3-m wheel spacing, include the following mechanisation arrangements, which are based on the relative widths of farm equipment tracks (after Chamen, 2006; Vermeulen & Chamen, 2010): (1) ‘Half-Trac’: a system with two track widths, one exactly half the width of the other. Implement widths are a direct multiple of one or other of the track widths, (2) ‘Twin-Trac’: a system that uses two track widths; the wider track straddles adjacent passes of the narrower track, and implement width is the addition of the two track widths or a direct multiple of it, (3) ‘Out-Trac’: a system that uses a single common standard track width, but allows the widest vehicle (usually the harvester) to track ‘outwith’ the narrower tracks while centred on them. Implements may be any common width or direct multiple, and (4) ‘Ad-Trac’: a system with two track widths, the narrower using one track of the wider, resulting in an additional track. Implements may be any common width or direct multiple.

Schematic examples of the above arrangements are also shown by Vermeulen & Chamen (2010). For these alternative systems, CTF Europe Ltd. proposed a ‘tier’ approach that aims to encourage farmers to progressively reduce the area of the field subject to vehicular traffic through improvements in the design of the CTF system. This tier system includes the following (as percent of tracked area): 30% to 40% (tier 1), 20% to 30% (tier 2), 10% to 20% (tier 3), and 10% or less (tier 4). Tier 4 may be only achievable with the use of gantry systems (e.g., Chamen et al., 1992, 1994; Taylor, 1994), which have been used in horticulture with satisfactory results (e.g., Pedersen et al., 2015, 2016). Seasonal controlled traffic systems have also been adopted and are designed to confine most field operations, usually with the exception of harvesting, to semi-permanent traffic lanes (Vermeulen & Mosquera, 2009). These systems represent a technical solution for the vegetable, sugar and cotton industries, for example, where incompatibilities between harvesting equipment used with different crops in the rotation are common (Braunack & McGarry, 2006; McPhee & Aird, 2013). Technical manuals (e.g., Webb et al., 2004; Isbister et al., 2013) are available and provide practical guidance on how to match machinery for CTF.

Grass Cropping

Adoption of CTF in grass production systems has been limited. In Scandinavia, Kjeldal (2013) reported the use of CTF for forage production with mower widths from 6 to 12-m, and wheeled areas between 13% and 26% depending on the module. In the U.K., Crathorne Farm, an AHDB (Agriculture and Horticulture Development Board) Dairy demonstration farm located in Yorkshire, has experimented with CTF for clamp silage forage production (James, 2016). A 9-m module width for mower, rake and harvester was used, the spreader was operated at swaths of 18-m, and the wheeled trafficked area was about 24%.

The width of commercially available cutting equipment used for grass silage production restricts the adoption of CTF in grass production systems. These machines tend to be offset rear mounted or trailed, or a combination of front mounted and rear mounted or trailed (triple gang). CTF systems based on combinations of existing machinery (with little or no physical modification or impact on field operations) in the range of common widths of 3, 4, 5, 9 and 12-m are feasible, with trafficked areas of 40%, 28%, 22%, 18%, and 13%, respectively. If arable operations were included, the trafficked areas increase to about 65%, 41%, 31%, 22%, and 18%, respectively (Peets et al., 2017). As a comparison, conservative estimates suggested that the wheeled area under standard, non-controlled traffic management in grass systems can be as high as 80% to 90% of the total field area (Peets et al., 2017). A 3-m system involves machines with little or no modification, but it requires a tractor with a track gauge of 1.5 m and because of its narrow width, the wheeled area is inevitably larger than that of wider systems (Fig. 5, a). The 4- and 5-m systems require a loader wagon, and the mower has heavily loaded wheels running on the non-trafficked bed. The 9- and 12-m systems are achievable based on triple gang mowers (Fig. 6, a) along with standard tedders, swathers, harvester and dribble bar slurry applicator (Fig. 5, b). Harvesting relies on delivery from a self-propelled harvester to a rear hitch trailer (Fig. 6, b) that is swopped on the headland when full or to a specialised trailer on the adjacent traffic lane.

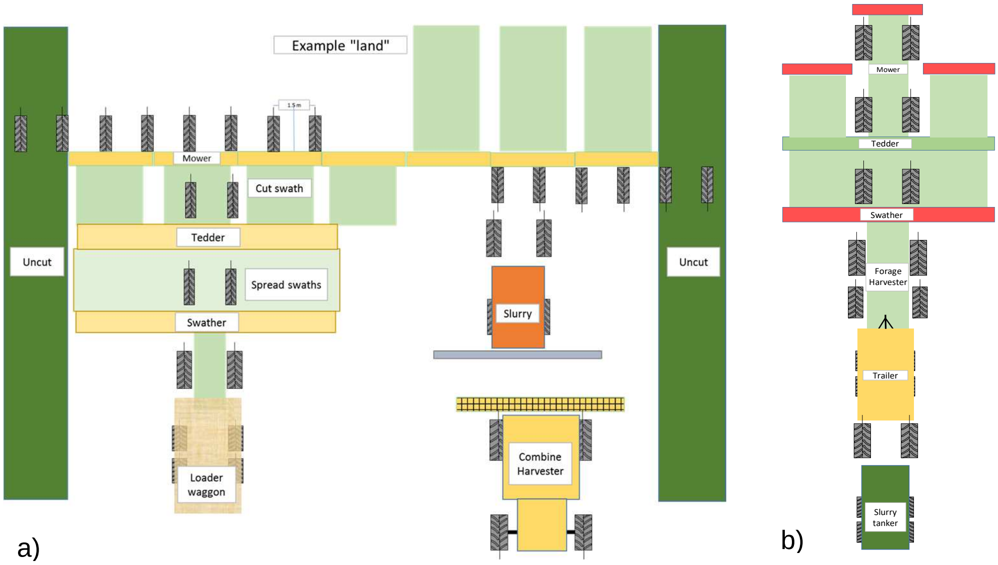

Figure 5. In (a) Tractor on 1.5-m track gauge operating with a 3-m mower, and 9-m tedder and swather. A second tractor on 1.8-m track gauge is used with a loader wagon and to pull a slurry tanker having a 6-m trailing shoe. In (b) Machines and operations in a triple gang mower based (9- and 12-m) controlled traffic forage grass operation.

Figure 6. n (a) Triple gang mower of the type envisaged for 9- and 12-m systems. In (b) Example of a self-propelled harvester loading into a towed trailer.

An important constraint when introducing CTF in grass systems is the associated effect on harvesting work rate with forage trailers running along traffic lanes rather than taking the shortest route to the harvester or field exit. As this may compromise areas of non-trafficked soil, extra discipline and commitment are therefore critical to the success of any CTF system used for grass forage production.

SYSTEM BENEFITS OF CONTROLLED TRAFFIC FARMING

Confinement of field traffic such as in CTF systems has beneficial impacts on: (1) overall soil health, (2) crop performance and yield, (3) fertiliser and water (rainfall and irrigation) use efficiency, and (4) greenhouse gas emissions. Research and farm practice have also shown that the overall improvements in efficiency that can be achieved with CTF usually translate into increased system resilience and therefore profit margins.

Soil Properties and Function

The adverse effects of traffic-induced compaction on overall soil health are well documented (e.g., van Ouwerkerk & Soane, 1995; Soane & van Ouwerkerk, 1995). These effects are cumulative and can lead to a progressive decline in crop productivity (Alakukku, 1996; Shah et al., 2017). Soil compaction affects soil permeability to air and water movement into and through the profile (Vomocil & Flocker, 1961; Lipiec & Hatano, 2003), which is caused by reduced pore size and disruption of pore connectivity, with the associated reduction in surface water infiltration and hydraulic conductivity (Meek et al. 1992; Mossadeghi-Björklund et al., 2016). Hussein et al. (2017) found that differences in terminal infiltration rates in Red Ferrosols were up to ten-fold higher in the crop beds of a CTF system compared with the same soil managed under conventional traffic (non-CTF). The effect of traffic compaction on soil hydraulic properties is exemplified in Fig. 2 of Antille et al. (2016b). This example shows that disruption in the connectivity of soil pores caused by compaction occurs mainly between larger, vertically-oriented drainage pores, and that compaction has relatively little impact on pores holding water at potentials greater than 1,000 kPa; a response that was also shown by Connolly et al. (2001).

Reduced soil (macro)-porosity impairs internal drainage (Vero et al., 2014), which can set conditions for increased runoff and erosion (Rickson, 2014), increase the frequency and duration of waterlogged conditions (Alaoui et al., 2018), and enhance nitrogen (N) losses through denitrification (Torbert & Wood, 1992; Ball et al., 1997; Antille et al., 2015a; Tullberg et al., 2018). Modelling work by Owens et al. (2016, 2019) showed that up to 90% reduction in soil erosion rates from the Great Barrier Reefs catchments, with the associated reduction in sediment, nutrient and pesticide discharge to surface waters, may be achieved when changing management practices from conventional tillage with no traffic control to no-tillage and CTF (Fig. 7). These results agree with those from earlier studies by Tullberg et al. (2001) and Li et al. (2009), which suggested that tillage and traffic effects on runoff and sediment yield appear to be cumulative. Owens' analyses assumed that 15% of the cultivated field area of the CTF system was affected by traffic (permanent traffic lanes) and that recommended management practices for erosion control (e.g., contour banks) were also in place.

Soil structural development in non-trafficked crop beds is also observed when the soil is tilled annually (e.g., Chamen et al., 1990; Vermeulen & Klooster, 1992), but faster rates of natural amelioration are expected when CTF is coupled with no-tillage (Bullock et al., 1985; McHugh et al., 2009). Good soil structural conditions are necessary for adequate functioning of soil organisms (Rabot et al., 2018), and these contribute to aggregate formation and development of biopores, which are largely implicated in soil water retention and transmission in soil (Leeds-Harrison et al., 1986; Kautz, 2015).

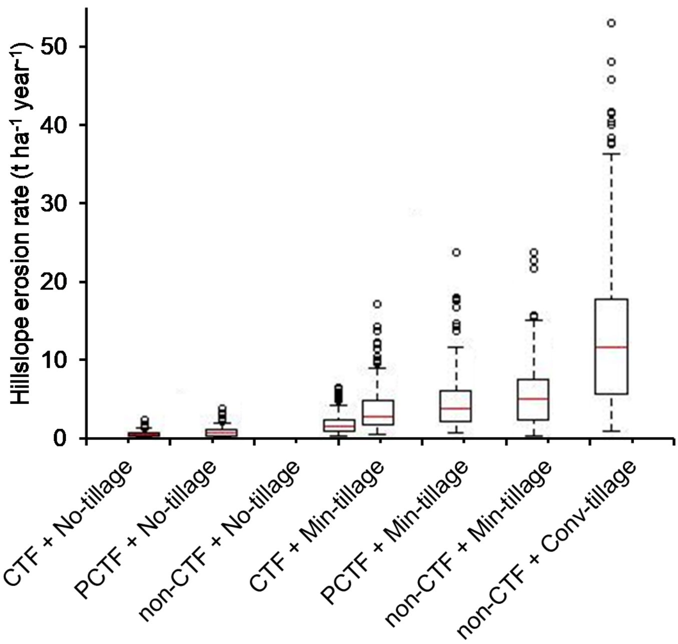

Figure 7. Average annual soil erosion in the Fitzroy Basin (Queensland, Australia) for soil management scenarios that include controlled (CTF) and partially controlled (PCTF) traffic farming, no-tillage, minimum (Min-) and conventional (Conv-) tillage, respectively (after Owens et al., 2016, 2019). Variation for each management scenario denotes inter-annual variation (1970–2015) for soils and climates. Box plots show: Min, Q_1, Med, Q_3, and Max, respectively. Points numerically distant from the rest of the data are outliers.

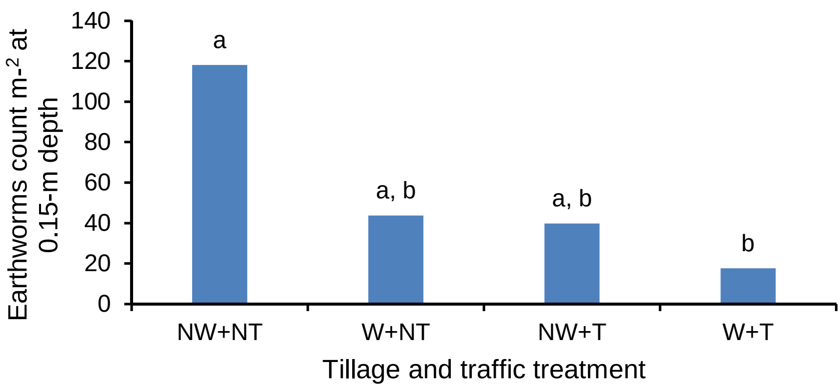

Figure 8. Mean of earthworm counts per m^2 at 0.15 m depth of soil as affected by different combinations of traffic and tillage. NW: non-wheeled soil, NT: no-tillage soil, W: wheeled soil, T: tilled soil. Different letters denote statistically different mean values (after Pangnakorn et al., 2003).

A study by Pangnakorn et al. (2003) in rainfed cropping in southern Queensland showed that earthworm counts under conventional (random) compared with controlled traffic (and no-tillage) were approximately three and eight times higher, respectively, than under annually wheeled, tilled soil (Fig. 8). Wheel traffic reduced earthworm count, but wheeling followed by tillage had significantly less effect. Soil compression during wheeling did not appear to be the main cause of earthworm death, but rather restricted movement and oxygen depletion (Pangnakorn et al., 2003).

Crop Productivity and Nitrogen Use Efficiency

A distinction is made between direct and indirect effects of soil compaction on crop productivity (Chamen, 2006). Direct effects refer to the extent to which crop growth and physiological development are restricted by processes such as water and nutrient uptake, which are adversely affected by soil mechanical impedance (e.g., root expansion and exploration, biomass accumulation and partitioning). By contrast, indirect effects are those that relate to timeliness. This includes the time required to fix pre-existing compaction to enable satisfactory establishment of the next crop in due time, and the ability to complete in-season field operations (e.g., sowing, spraying and fertilisation) due to traffickability conditions (Antille et al., 2015c). In most circumstances, the opportunities to conduct such operations occur within a relatively narrow window as it is determined by the crop (e.g., physiological stage), weather and soil conditions being appropriate (field access, trafficability and workability) for traffic with farm machinery (Earl, 1997; De Toro, 2005; Gut et al., 2015). Failure to conduct in-season operations at the right time will impact crop productivity (e.g., mismatch between fertiliser application and nutrient demand by the crop). Impacts on crop quality may also occur, for example, as a result of delayed spraying for crop protection purposes or late harvest; in all circumstances with an associated impact on crop profit margins (Bednarz et al., 2002). In crops established on soil with 'residual' compaction, such as that originated during harvest of the previous crop, the impact on yield is commonly explained by reduced plant stand and greater plant stand variability. For example, in cotton a 20% reduction in plant stand below a target of about 10–12 plants per m^2 (at 40-inch (1-m) row spacing) due to compaction can result in up to 15% reduction in yield or more if the effect is due to variability in plant stand (Hadas et al., 1985). For Australian broadacre grain production, the daily loss of crop value caused by delays in sowing (outside the optimum) was estimated at approximately 1.5% per day of the total crop value (Tullberg, 2014). Tullberg's analysis was conducted to determine the sowing capacity required to establish a crop within the optimum window for that crop, without significant financial losses. The same concept is applied here to show that delays in 'field access' due to unsuitable trafficability conditions can have financial impacts of the same magnitude. Permanent traffic lanes in CTF largely eliminate this problem. Table 1 summarises reported information on impacts of soil compaction on crop yield. Optimum soil bulk density values are dependent on crop and soil type, and seasonal effects of weather (Negi et al., 1981). Therefore, optimum values for a given crop vary within a range, and these may be narrower or wider depending on year-specific conditions.

Because yield (and dry matter) is affected by compaction, the amount of fertiliser recovered in crop (agronomic efficiency) is concurrently reduced (Wolkowski, 1990), which has financial implications for growers and adverse effects on the environment (Soane & van Ouwerkerk, 1995). The mechanisms by which fertiliser use efficiency is affected by compaction are discussed in several studies (e.g., Lipiec & Stępniewski, 1995; Arvidsson, 1999), and the effect on plant uptake and subsequent recovery in crop is nutrient-specific as it depends on the complex interactions between root growth, soil water and aeration status, and degree of compactness. Generally, factors that restrict water movement within the soil profile (e.g., pore connectivity) and from the soil matrix to the roots will affect nitrogen (N) uptake since the main mechanism implicated in N transport to plant roots is mass flow (Barber et al., 1963; Kirkby et al., 2009). Nitrogen recovered in cereal (grain) and grass (dry matter) correlates well with soil water availability or rather with water used by the crop during the crop cycle (Melaj et al., 2003; Antille et al., 2013, 2015b, 2017). Factors that affect root elongation, such as increased soil mechanical strength, will restrict nutrient absorption through root interception, and this mechanism is particularly important for phosphorus, because of its relatively low mobility within the soil (Wiersum, 1962; Prummel, 1975). Threshold values of soil strength above which root elongation stops vary depending upon the crop, but these typically range between 2 and 2.5 MPa for most arable crops (Taylor & Ratliff, 1969a, 1969b). Traffic with harvesting equipment (overall load: 32–35 Mg) on Vertisols (moisture content: ≈25–30%, w/w) was reported to increase cone index in the 0–500 mm depth range from about 1 MPa prior to traffic to more than 3 MPa after traffic (Braunack & Johnston, 2014). Observations from that work were in close agreement with those reported by Ansorge & Godwin (2007) and Antille et al. (2013), albeit on medium-textured soil with relatively lower moisture content.

Table 1. Yield of common crops achieved in the absence of field traffic relative to yield obtained when the crop was grown under traffic intensities that are typical of the cropping system (100% means no difference). Winter cereals: wheat, barley. Summer cereals: grain sorghum, maize. Grain legumes: soybeans. Oilseeds: oilseed rape, sunflower. Cotton: includes lint or lint + seed

Crop type	Relative yield (or range)	Soil type	Reference
Winter cereals	112%	Red Ferrosol	Hussein et al. (2017)
Winter cereals	104–135%	Loam, Sandy loam	Hamilton et al. (2003); Galambošová et al. (2017); Godwin et al. (2017)
Winter cereals	114–127%	Heavy clay	Radford et al. (2001); Tullberg et al. (2001)
Grain legumes	110–143%	Clay, clay loam, sandy loam	Khalilian et al. (1991); Botta et al. (2007); Kaczorowska-Dolowy et al. (2019)
Summer cereals	100–175%	Loam, Clay	Ngunjiri & Siemens (1995); Radford et al. (2001); Hussein et al. (2018)
Cotton	106–128%	Silt loam, Sandy clay loam, Clay	Hadas et al. (1985); Akinci et al. (2004); Kulkarni et al. (2010); Hulugalle et al. (2017)
Oilseeds	128–195%	Clay loam, Clay	Bayhan et al. (2002); Chan et al. (2006)
Grass (silage)	105–174%	Clay loam, Sandy clay loam, Sandy loam	Peets et al. (2017); Hargreaves et al. (2019)

Hussein et al. (2018) showed significant differences in N fertiliser use efficiency from sorghum (*Sorghum bicolor* L., Moench) established under CTF and non-CTF systems (Fig. 9).

Furthermore, differences in N recovered in grain between the two traffic treatments were irrespective of fertiliser-N formulation. Hussein et al. (2017)'s work agreed closely with Gregorich et al. (2014) demonstrating that significant improvements in fertiliser-N recoveries may not be realized with enhanced N formulations alone (e.g., slow and controlled-released fertilisers) and that avoidance of (random) traffic compaction is a pre-requisite for improved fertilizer use efficiency. This is an important practical consideration for N management as much research effort is currently spent on the role of novel fertiliser formulations in improving nutrient use efficiency (e.g., Watts et al., 2014), without necessarily accounting for the fact that this is largely explained by overall soil condition.

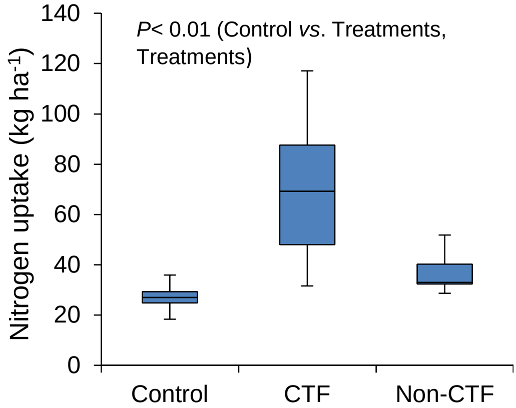

Figure 9. Controlled (CTF) and non-controlled (non-CTF) traffic effects on nitrogen (N) fertiliser use efficiency in sorghum. Box plots show: Min, Q_1, Med, Q_3, and Max, respectively, for N rates between 100 and 300 kg ha^{-1}, except for control (N=0). 'Control' is the zero-N treatment from both CTF and non-CTF traffic systems, respectively, and denotes the contribution of soil N to crop uptake (after Hussein et al., 2018).

Energy Use and Greenhouse Gas Emissions

Crop production systems that reduce the need for tillage will significantly reduce on-farm energy use and associated emissions. These include direct emissions from fuel use during tillage operations (e.g., Burt et al., 1994) and carbon dioxide (CO_2) that is released to the atmosphere through oxidation of soil organic matter (e.g., Chatskikh & Olesen, 2007). This process is enhanced by tillage, particularly in warm and moist environmental conditions (Ding et al., 2002). There exists a relationship between traffic-induced soil compaction and tillage whereby increased traffic intensity leads to increased need for tillage repair treatments (Arndt & Rose, 1966). Consequently, energy requirements of primary and secondary tillage could increase by factors of up to 2.5 and 3.25, respectively, depending on the depth of the operation and the specific soil conditions under which such operations are conducted (Williford, 1980; Hadas et al., 1986; Chamen et al., 1996). In CTF systems, Lamers et al. (1986) reported energy savings of up to approximately 50% due to lower rolling resistance and wheel-slip on permanent traffic lanes compared with trafficking over cultivated and relatively soft soil. Tullberg (2000) showed that the effect of wheeling on the draft of tillage implements (chisel and sweep tines positioned behind a 90 HP tractor in a black Vertisol, 250 mm depth) increased total draft by 30% compared with the same implement operated in non-wheeled soil. Tullberg used these observations to demonstrate that approximately 50% of a tractor's power output can be squandered in the process of creating and subsequently disrupting its own wheel compaction in tillage operations.

Evidence from growers who practice CTF and no-tillage indicates up to 50% reduction in tractor fuel use for field operations. Of the total area used for arable cropping in England (about 1.8M ha), approximately 0.5M ha were established using reduced or no-tillage (DEFRA, 2009). For cereal cropping, where reduced tillage is not practiced, average diesel fuel use was approximately 95 L ha^{-1} (see also Taylor et al., 1993). If CTF and no-tillage allow for a reduction of 50% in fuel use (of 95 L ha^{-1}) by avoiding compaction across the arable cropping area in England, this would save approximately 82×10^6 L of diesel fuel per year, equivalent to 220 Mg CO_2e or 125 kg ha^{-1} of CO_2e per year (assume 1 L of diesel ≈2.7 kg CO_2e). In Australian grain production systems, Tullberg (2014) showed that tillage-based systems required 52 L ha^{-1} of diesel for field operations whereas the most efficient non-CTF system under no-tillage required a minimum of 25 L ha^{-1}. When energy losses due to rolling resistance were minimised by driving over consolidated soil (permanent traffic lanes) of a CTF system, diesel use was reduced to approximately 13 L ha^{-1} (Tullberg, 2014). Note that in Australia, grain production systems that rely on tillage typically practice minimum (‘conservation or non-inverting’) shallow tillage with stubble retention (Reicosky, 2015; Aikins et al., 2019).

For arable systems that rely on tillage, reductions in energy use where traffic is controlled are mainly due to: (1) lower soil specific resistance in the absence of compaction, (2) tillage operations conducted at shallower depths when remediation of deep compaction is not required, (3) fewer tillage operations and reduced power loss in tractive efficiency because of lower motion resistance and reduced wheel-slip (Dickson & Ritchie, 1996; Tullberg, 2000).

Life cycle analyses conducted by Gasso et al. (2014) suggested that potential emissions reductions from adoption of CTF in intensively-managed arable cropping systems would be between 20% and 45% for N_2O, and between 370% and 2100% for CH_4, and that direct emissions from field operations could be reduced by at least 20% compared with non-CTF systems. Such emissions reduction potential agreed with measured data available in the literature, as compiled by Antille et al. (2015a, c). Higher N fertiliser use efficiencies (NUE) typically achieved in CTF systems (Fig. 9) are consistent with the above observations, and suggest disproportionally lower NUE at high N application rates (e.g., ≥ 200 kg ha^{-1} N) in non-CTF systems because of the non-linear response relationship between N rate and (direct) N_2O emissions (Millar et al., 2010; Scheer et al., 2016). A study by Tullberg et al. (2011) investigated short-term (45 days) emissions of N_2O after injection of anhydrous ammonia (82% N) at a rate of 80 kg ha^{-1} N to a black Vertisol sown with wheat in southern Queensland (Australia). Results showed that mean N_2O emissions from simulated ‘random’ traffic were similar to those from permanent traffic lanes of the CTF system, and significantly higher than those from permanent non-trafficked crop beds. A negative sum of CH_4 fluxes (absorption) was observed in permanent crop beds whereas the sum of fluxes from both wheeled soils was positive (emission). Hence, overall traffic treatment effects were significant ($P < 0.05$). Total emissions of N_2O and CH_4 over the measured period post-seeding (45 days) were 58 (permanent crop bed), 325 (permanent traffic lanes) and 370 (random traffic) kg ha^{-1} CO_2e, respectively. This indicates a 45-day post-seeding total CO_2e emission from the CTF system used in the study of 90 kg ha^{-1}, that is, 39 kg ha^{-1} from the 12% cropped area occupied by permanent traffic lanes and 51 kg ha^{-1} from the remaining 88% permanent crop beds. Such losses represent approximately 40% of the emissions of 214 kg ha^{-1}

likely from a randomly-trafficked soil where 50% of the cropped field area is wheeled. Relatively higher N_2O fluxes from the random traffic treatment compared with permanent traffic lanes simply reflects the combined N-fertiliser × traffic effect on emissions. This effect was not observed in permanent traffic lanes because fertiliser is placed at or prior to planting next to the plant row, and in the system used in Tullberg's study, traffic lanes were not cultivated. Further studies by Tullberg et al. (2018) supported those initial observations, and confirmed that adoption of CTF could reduce total soil emissions by 30–50%, which was consistent across a wide range of soil types, crop rotations and environmental conditions.

Economic Considerations

Arable

In Argentina, Botta et al. (2006) showed that over two consecutive crop seasons, soil loosened with a subsoiler resulted in significantly higher sunflower yield than no-tillage and chiselling (Table 2). Yield increases of ≈25% and ≈13% were recorded in the first and second seasons relative to the control (no-tillage), respectively. No statistical differences in yield were observed between the chisel and control treatments.

Table 2. The response of sunflower to tillage over two growing seasons (after Botta et al., 2006). Different letters within each year denote statistical difference between tillage treatments (*P* < 0.01, Duncan's multiple range)

Tillage treatment	No-tillage	Subsoil	Chisel
Crop yield (Mg ha^{-1}, 2003)	2.20^{a}	2.74^{b}	2.38^{a}
Relative increase (%)	–	24.5	8.3
Crop yield (Mg ha^{-1}, 2004)	2.25^{a}	2.54^{b}	2.30^{a}
Relative increase (%)	–	12.8	2.3

From an economic perspective, yield increases observed in year 1 (after the tillage operation) were sufficiently high to offset the cost of subsoiling, which ranged between USD15 and 50 ha^{-1}, but not the chiselling. In the second year, yield increases for the subsoiler treatment represented a benefit of about USD10 ha^{-1}. Further work by Botta et al. (2007) on soybean grown on a *Typical Argiudol* showed that over three crop seasons, field traffic intensities of up to ≈39 Mg km^{-1} ha^{-1} resulted in yield penalties of up to about 8% compared with untrafficked control soil (Table 3). The economics of soybean production based on yield increases for CTF with a traffic intensity of 15.2 Mg km^{-1} ha^{-1} improved by USD102 ha^{-1} in the first year, by USD124 ha^{-1} in the second year, and by USD134 ha^{-1} in the third year, respectively, based on an average soybean price of USD170 tonne^{-1}. Compared with the standard practice (non-CTF), savings of up to USD1.40 ha^{-1} in diesel were possible.

Another study by Botta et al. (2010) also on a *Typical Argiudol*, traffic with heavy equipment (185 kN, tractor and planter) caused a significant reduction in soybean yield, which was observed in all three tillage treatments (no-tillage, chisel, subsoil) used in that study. In the first year of that study, critical values of cone Index for soybean root growth (Riley et al., 1994) were found in the topsoil (0–150 mm). Thus, the yield reduction observed after the first year was attributed to high ground pressure caused by this equipment (> 110 kPa) at relatively shallow depth. In subsequent years, critical values of cone Index were also found in the subsoil (below 150 mm deep). This effect was attributed to high axle loads, which affected the crop performance in subsequent years. The work by Botta et al. (2010) concluded that (crop yield for the 2004 season used as reference for comparison with other years: (2.9 Mg ha^{-1}): (1) subsoiling followed by traffic with light equipment (127 kN), yield increased by about 3% to 21%, depending on the season, which agreed closely with data reported in other studies (Jorajuria et al., 1997; Botta et al., 2004); (2) subsoiling followed by traffic with heavy equipment (185 kN), yield penalties were between 3% and 5%; (3) no-tillage soil trafficked with heavy equipment (185 kN), yield penalties were between 14% and 17%, also depending on the season; (4) chiselling followed by traffic with light equipment (127 kN) showed a 13.7% increase in yield above the reference yield in year 1, and between 1% and 3.5% in the subsequent two years. The overall economic result from the soybean crop that relied on 'light' seeding equipment (127 kN), compared to the heavy equipment (185 kN), showed a relative benefit of USD130 ha^{-1} in the first year, USD65 ha^{-1} in the second year, and USD22 ha^{-1} in third year, respectively, using an average soybean price of USD216 tonne^{-1}.

Table 3. The effect of traffic intensity on soybean yields over three consecutive growing seasons (2003–2005) in Argentina (after Botta et al., 2007). Different letters within each year denote statistical difference between tillage treatments (P < 0.01, Duncan's multiple range)

Traffic intensity	T_1 (38.45 Mg km^{-1} ha^{-1})	T_2 (20.11 Mg km^{-1} ha^{-1})	T_3 (15.2 Mg km^{-1} ha^{-1})
Yield (Mg ha^{-1}, 2003)	2.67^{b}	3.12^{a}	3.30^{a}
Yield (Mg ha^{-1}, 2004)	2.52^{b}	3.14^{a}	3.23^{a}
Yield (Mg ha^{-1}, 2005)	2.48^{b}	3.14^{a}	3.19^{a}

Table 4 summarises costs and revenues involved in conversion from conventional to CTF systems for farming systems representative of central Europe. Revenue is mainly derived from increased crop yield in CTF compared with non-CTF, with potentially additional revenue from improved crop quality that may be possible in some years due to improved timeliness of field operations (Parvin et al., 2005; Chamen, 2015). The long-term profitability of a typical farm can increase by up to 50% when CTF is practiced due to a combination of improved, more stable yields in soils susceptible to compaction with relatively less inter-annual yield variability. About two thirds of the additional profit expected in CTF systems (relative to non-CTF) are explained by increased yield and yield stability (Galambošová et al., 2017). Savings in input costs are possible if CTF is combined with precision agriculture (PA), but may not be significant relative to non-CTF in which PA (e.g., variable rate technology) is also applied (Barát et al., 2017).

Table 4. Relative costs and revenues likely associated with conversion from a conventional system to controlled traffic farming

Category	Item	Anticipated effect	Source
Revenue	Yield	Increased	Chamen (2015).
	Price	Equal or higher	
Capital cost	Investment in modification of machinery, adjustments and replacement of existing by new equipment	Increased	Chamen (2015).
	Investment in RTK and annual fees	Increased if not in use by farmer	
Variable costs, field operations	Fuel, energy (draft)	Decresed	Tullberg (2000); Chamen (2015); Kingwell & Fuchsbichler (2011); Bochtis (2010).
	Field efficiency	Incresed	Galambošová & Rataj (2011).
	Equipment wear and tear	Decresed	

Machinery guidance with high accuracy RTK will have a significant economic impact on the efficiency of the system due to reduced overlap (Galambošová & Rataj, 2011; Jensen et al., 2012). Despite the fact that investment in RTK could be significant, this tends to have a large in-built payback in terms of operational efficiency, savings on inputs and operator stress, as well as forming the basis for automated spatial measurements (Chamen, 2015). The main costs of conversion to a CTF system include: modification (track gauge extension) or replacement of existing machinery by CTF-compatible equipment (Chamen, 2015; Galambošová, 2017). In some circumstances, the transition to CTF may result in zero cost because (deep) tillage equipment becomes redundant and may be sold to pay out the investment in CTF-compatible farm equipment. The 'tier' approach, originally proposed by Vermeulen et al. (2010) to assist farmers wanting to convert to CTF, was used by Galambošová (2017) to exemplify a progressive conversion from non-CTF and unmatched machinery to fully matched CTF. The examples show 'low-cost' CTF systems that simply rely on the re-organisation of field traffic using commercially available machinery to systems that require full modification of the equipment, that is, matching track gauge and module widths (Table 5). Tier 1 is represented by a 6-m 'out-track' system. Here, conventional, non-modified machinery is used and therefore no investment is needed, but simply the re-organisation of in-field traffic.The system uses two or three track gauges and the field area affected by traffic is less than about 45% of the cropped field area. Tier 2 is represented by an 8-m 'out track' system, which uses two different track widths. In this system, implements for primary and secondary tillage would be replaced by 8-m wide implements, as well as the planter. The tractor and sprayer do not need to be replaced or modified. This system would allow for about 75% of the field cropped to

Table 5. The 'tier' system approach for conversion to CTF used in Europe, with the investment costs derived from local dealers (after Galambošová, 2017)

Tier level	Design	Base module	Investment (€)
Tier 1	Out-track	6-m	N/A
Tier 2	Out-track	8-m	247,285
Tier 3	Com-track	8-m	253,585
Tier 4	Com-track	12-m	1,040,396

be free of traffic. Tiers 3 and 4 are represented by ‘Com-track’ systems, which use only one track width. Here, the track width of the tractor has to be modified to match that of the combine harvester. Base modules of 8-m or 12-m are included in the calculations. The 12-m system allows for the non-trafficked area to be as high as 85% of the field cropped area, but this requires modification or replacement of all machinery. Only systems with a base module of 8-m or more are likely to achieve a Tier 4 system and again, only if one of the tracks is used on the adjacent pass. Results derived from a long-term CTF experiment in Slovakia (Galambošová, 2017) are shown in (Table 6). These results show yield, and therefore revenue (€ 59 to 81 ha^{-1} on average), increase proportionally to the reduction in traffic footprint of the CTF system. Given the assumptions made in Galambošová’s 2017 analyses, the breakeven area to overcome the investment needed for conversion to an 8-m CTF system is 528 ha (Table 7).

Table 6. Relative increase in revenue as a result of increased crop yield for different CTF systems (with prices from the Ministry of Agriculture, Slovak Republic) (after Galambošová, 2017)

Year	Retail Price (€ $tonne^{-1}$)	Revenue increase (€ ha^{-1})			
		6-m Out track	8-m Out track	8-m Com track	12-m Com track
2011	196	55	59	73	71
2012	209	82	102	92	107
2013	167	42	72	57	67
Mean revenue		59	78	74	81

Table 7. Breakeven area analyses and return of investment (after Galambošová, 2017)

Tier level	Investment, €	Breakeven area to overcome investment	Return of investment $^{\delta}$
Tier 1: 6-m Out Track	N/A	N/A	N/A
Tier 2: 8-m Out Track	247,285	528	within 4 years for 500 ha of farmed land (or 2.5 for 1,000 ha).
Tier 3: 8-m Com Track	253,585	571	within 4 years for 500 ha of farmed land (or 2.5 years for 1,000 ha)
Tier 4: 12-m Com track	1,040,396	2,140	6 years for 1,000 ha of farmed land (or 4 years for 2,000 ha)

$^{\delta}$The analysis assumes a 2.12% inflation rate (average 2010–2014) and a risk of investment of 10% to discount the returns in the future.

The natural in-field variability means that different areas of the field (or farm) will respond differently to CTF. However, traffic-induced variability is expected to decline with time after adoption of CTF. Sensitivity analyses (Fig. 10) show the required yield increase for different areas that positively respond to CTF technology. The 75% scenario would require an increase in yield of about 0.5 Mg ha^{-1} for farm sizes above 500 ha while the 25% scenario will require a concurrently higher yield increase. For example, considering a realistic 0.5 Mg ha^{-1} yield increase in 50% of the cropped area, the farmed area would have to be at least 50% of the farmed area that positively responded to the system; therefore, CTF would need to be implemented in approximately 800 ha to be profitable.

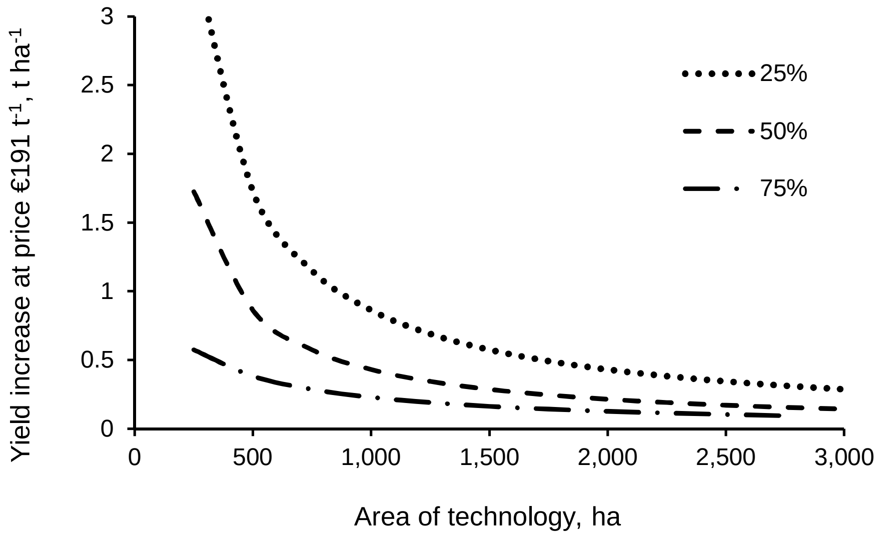

Figure 10. Sensitivity analyses for yield increases needed to convert a standard non-CTF system to an 8-m (out-track) CTF system in central European conditions (after Galambošová, 2017). The different curves show % of farm area which positively respond to CTF.

Grass

Economic analyses of CTF for grass (silage) production in the U.K. by Peets et al. (2017), based on the approach of Godwin et al. (2003), showed that reducing the field trafficked area from about 80% to 45% increased grass silage yield by 0.53 Mg ha^{-1} and 0.73 Mg ha^{-1} for two and three cut systems, respectively. If the field trafficked area was further reduced (to about 15%), this would increase yield by 1.00 Mg ha^{-1} and 1.36 Mg ha^{-1} for the two and three cut systems, respectively. Assuming a dry matter value of € 84 Mg^{-1}, these yield increases represent an additional € 44 to € 114 ha^{-1} and agreed with suggested economic benefits reported in earlier studies (e.g., Stewart et al., 1998) after being adjusted for retail price inflation (Alvemar, 2014). A 1% reduction in the trafficked area increased the benefit of CTF by between € 1.28 ha^{-1} and € 1.74 ha^{-1} for the two and three cut systems, respectively. These results were based upon the assumptions that only the cost of the guidance system would be needed to implement CTF, and that four guidance systems would be required to equip the harvester and the accompanying tractors (Peets et al., 2017). The cost of low accuracy[1] and non-repeatable positioning manually steered systems is less than € 22 ha^{-1} for areas in excess of 100 ha. For fully integrated, high accuracy systems, the cost is about € 100 ha^{-1} for areas in excess of 200 ha reducing to about € 13 ha^{-1} for areas greater than 1,500 ha per cut. The break-even area for implementing CTF ranges from 28 ha for low accuracy, manually steered systems with a 35% trafficked area with three cuts per year, to 250 ha for the fully integrated, high accuracy real-time kinematic navigation systems, reducing to 175 ha with a trafficked area of 15% (Peets et al., 2017).

[1] Low accuracy means that a larger area will be tracked compared with the theoretical.

CONCLUSIONS

There is both circumstantial and direct evidence which demonstrates the significant productivity and sustainability benefits associated with adoption of controlled traffic farming (CTF). These benefits may be fully realised when CTF is jointly practiced with no-tillage and assisted by the range of precision agriculture technologies available. Farmers often recognise the synergistic effect of integrating CTF with no-tillage and PA; hence, producing outcomes that are greater than the sum of the parts. Important contributing factors are those associated with improved trafficability and timeliness of field operations, and those associated with greater precision and uniformity. Adoption of CTF, and its allied technologies, is therefore encouraged as a technically and economically viable option to improve productivity, resource-use efficiency and other dimensions of sustainability in arable and grass cropping systems. Studies on the economics of CTF consistently show that it is a profitable technological innovation for both grassland and arable land-use. Despite these benefits, large-scale adoption of CTF has been low, with the exception of grain production systems in Australia where approximately 30% to 40% of the total grain-producing area is managed under CTF. The main barriers for adoption of CTF have been equipment incompatibilities and the need to modify machinery to suit a specific system design, often at the own farmers' risk of loss of product warranty. Other barriers include reliance on contracting operations and land tenure systems. These structural barriers may be overcome with forward planning when conversion to CTF is built into the machinery replacement programme, and organisations such as ACTFA in Australia and CTF Europe Ltd. in northern Europe have developed suitable schemes to assist farmers in such a process.

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Finding least fragmented holdings with factor analysis and a new methodology: a case study of kargılı land consolidation project from Turkey

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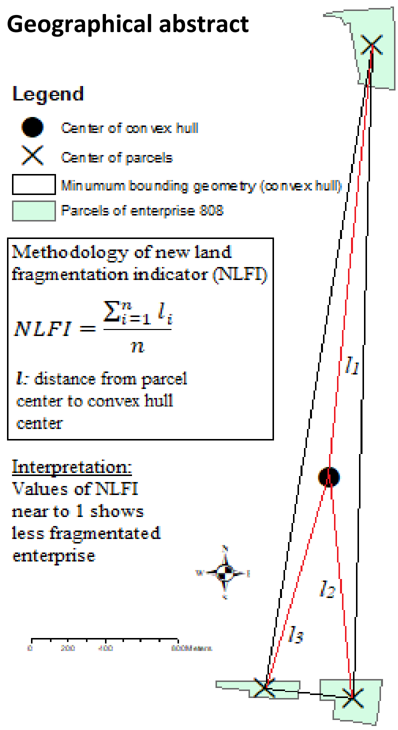
Abstract. Land fragmentation (LF) is a problem restrain agricultural activities and decrease mechanization level, production. Land consolidation (LC) projects are done in the World as well as Turkey to solve LF issues. Researchers created indicators to measure land fragmentation which is important to see success level of LC projects. The use of these indicators is controversial or not accurate. The core aim of the present study is to find new land fragmentation index and to find least fragmented holding with factor analysis using the other indicators which are Simmons, Januszevski, number of parcels, Shmook and Igbozurike besides new land fragmentation index. Kargılı Village land consolidation project in Mersin, Turkey was chosen as a material. Cadastral data before land consolidation, was used to calculate value of indicators, where number of parcels was 932, total area was 1,741.9 ha, the average parcel size was 1.9 ha, number of holdings was 542 and the average parcel size was village had 932 parcels. Data processing were performed with ArcMAP 10.6.1 and SPSS. A total of 18 holdings were identified randomly as sample size which were sufficient to carry out factor analysis including principle component to rank holdings ($P < 0.01$).As a result, new land fragmentation index found correlated with others ($P < 0.01$) and ranking according to new indicator performed better than ranking considering all indicators. In this context, it is possible to use new land fragmentation indicator to determine priority areas for land consolidation.



Key words: GIS, factor analysis, land consolidation, land fragmentation indicators.

INTRODUCTION

The best criteria of agricultural is the high production efficiency increase with low cost. Land fragmentation is the one of problem restrain good agricultural practices to reach the goal (Gonzales, 2004; Hristov, 2009; Vijulie et al., 2012; Kirmikil & Arici, 2013; Küsek, 2014; Looga et al., 2018). For this reason, measuring the land fragmentation level is of considerable importance (Kadigi et al., 2017). In accordance with this purpose, rural areas have been developed under the name land consolidation, land reform and land administration in the world (Burton & King, 1982; Agrawal 1999; Sabates-Wheeler 2002; Niroula & Thapa 2005; Miranda et al., 2006; Sikor et al., 2009; Hartvigsen 2014; Li et al., 2018; Stańczuk-Gałwiaczek et al., 2018). In Turkey, land consolidation projects have been done with investments in high amounts to demolish land fragmentation and irregular shaped parcels. Approximately 5.1 million ha area was consolidated and these projects are conducted on 1.9 million ha in the country. Moreover, it is planned to finish land consolidation projects on 14 million ha until 2023 (TAGEM, 2017). The land consolidation projects have been carried out in Turkey, increases the importance of monitoring and evaluating these projects. One of one important output is decreasing land fragmentation related with agricultural production (Kumbasaroğlu et al., 2007; Tuğay, 2012; Looga et al., 2018), fuel consumption (Polat & Manavbaşı, 2012), rural roads (Kuzu et al., 2019), carbon dioxide emissions (Değirmenci et al., 2017) and mechanization (Küsek, 2014). For the purpose of monitoring and evaluating land management, many indexes have been developed and used to measure land fragmentation (Simmons, 1964; Januszewski, 1968; Ibgozurike, 1974; Schmook, 1976; Demetriou et al., 2011; Looga et al., 2018). In the study of Demetriou et al.(2013) mentioned that land fragmentation indices don't serve the purpose and the new index of Demetriou et al.(2011) may meet the demands for a specific project. Measurement of land fragmentation with existing indices does not give accurate result or have a lot of factors which are spatial distribution of parcels, size of parcels, shape of parcels, accessibility of parcels, type of ownership and shared ownership. For this reason, there is a need for new indexes to measure land fragmentation quickly, easily applicable and effectively.

The core aim of the present study is to develop a new approach to measure land fragmentation for land consolidation projects in terms of spatial distribution of the parcels belong the holdings. We compare the new index with commonly used land fragmentation indices using factor analysis and correlation. The new index is calculated with the help of geographic information systems and is based on land fragmentation level decrease as the distance decrease between the parcels belong the holding.

MATERIALS AND METHODS

Material

Kargılı land consolidation project, which was finished project in Mersin, Turkey, was chosen as a material in the study. Cadastral data before LC, given in Fig. 1, was used to measure land fragmentation indices. Kargılı LC project covers 1,741.9 ha including 932 parcels belong 542 holdings. Data, containing holdings information and map, was obtained from the state-run private company made the project.

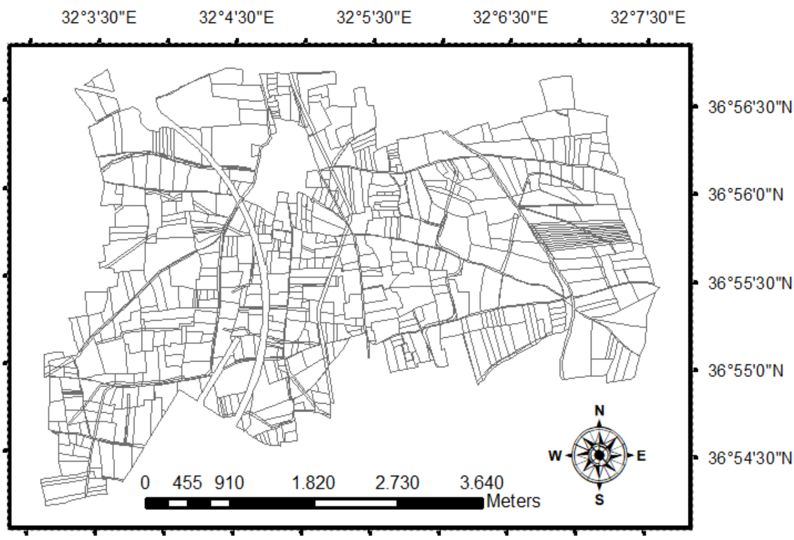


Figure 1. Cadastral map of Kargılı land consolidation project.

Generally, a program NetCAD is used to conduct land consolidation process in Turkey. Land fragmentation level was measured for a number of holdings due data available for calculation methods. The holdings evaluated were chosen randomly. The adequacy of this sample size was measured with Kaiser-Meyer-Olkin (KMO) test which is first step of the factor analysis. Detail of factor analysis stages are given in the methodology part. The features of the holdings evaluated are given in Table 1.

Table 1. Main features of the holdings evaluated

Holdings no*	Total area (ha)	Number parcel
1009	48.83	8
1034	6.3	3
147	0.02	3
209	0.29	2
256	0.05	2
300	34.65	3
369	0.02	2
503	0.01	2
647	734.52	12
717	11.47	4
755	29.30	4
780	6.96	6
785	539.73	15
808	30.73	3
896	326.07	6
919	290.14	21
966	29.17	3
969	1,013.02	15

*Original holding no in the project was used to avoid confusion in the calculations and the rank.

Methodology

Calculation of land fragmentation indicators

The various indices were used to determine land fragmentation level in the project. These indices are Simmons, Januszevski, number of parcels, Shmook, Igozuruke and new land fragmentation index. Formula of the indices, optimum values and correction factor are given below. Correction factor is a parameter which is used to do factor analysis. Indices can be corrected with +1 or -1. Indices are taken correction factor +1 are the indices we want them increase while the indices with correction factor -1 are the indices we want them decrease.

Main idea of the new land fragmentation index is ‘if parcels comes closer, fragmentation level decreasing’ or vice versa. Process of calculation index comprise of a number of steps in ArcMAP 10.6.1. Calculation algorithm of NLFI is given in the graphical abstract and the steps following:

1- Changing parcel feature from polygon to point (feature to point)

2- Creating minimum polygon covering all parcels (minimum bounding geometry with convex hull)

3- Changing the minimum bounding geometry from polygon to point (feature to point)

4- Calculating distance from parcel centre to minimum bounding geometry (point distance)

5- Calculating the new land fragmentation index with the formula

Factor analysis

Factor analysis is used for many purposes such as data reduction, selection of the representative variables from large data set, clustering and ranking. In the present study, factor analysis was used to rank the indices in order of the land fragmentation level. According to the analysis, the land fragmentation level of the holdings were determined using all indicators. In the factor analysis, rotational method were used with varimax which are used mostly (Özdamar, 2017). The overall performance of each holding were obtained and used to rank them.

Applying the factor analysis consist of 8 steps following (Alpar 2017):

1- Calculating min, max and mean values of the land fragmentation indices for all holdings

2- The aim of this step is to normalize the smallest value to 0, the maximum value to 1 and to spread all other data to the range of 0-1. Calculating normalized values of the indices was defined as Eq. (1):

$$NV = \frac{X - \min(X)}{\max(X) - \min(X)} \tag{1}$$

where NV: normalized value¸ X: the observation (a specific value of the land fragmentation index we are calculating for SV); min(X): minimum value of the observation; max(X): maximum value of the observation.

3- Applying principle component analysis with a statistical program to get coefficients of each land fragmentation indicator for the holdings

4- Calculating % weight of the coefficients each land fragmentation indicator for the holdings according to Eq. (2):

$$Coef\% = \frac{100 \times C_i}{\sum_{i=1}^{n} C_i} \tag{2}$$

where Coef% = % weight of the coefficient; Ci: i-th coefficient obtained from principle component analysis.

5- Corrected values of the coefficients (Coef%) according to correction factor of the indices. The correction factors of the indices was given Table 2. Corrected values are calculated with Eq. (3):

$$CV = CF \times Coef\% \tag{3}$$

where CV: corrected values of the indices; CF: correction factor; Coef%: % weight of the coefficient.

6- Calculation of the weighted indicator values for each component formed by principle component analysis according to Eq. (4) below:

$$WIV_{Ci} = \sum_{i=1}^{n} CV_i \times NV_i \qquad (4)$$

where WIVCi: Weighted indice values of i-th component; Ci: i-th component formed by principle component; CVi: corrected calues i-th indice; NVi: normalized value of the i-th indicator.

Calculation of the overall holding scores according to Eq. (5):

$$S = \sum_{i=1}^{n} V_i \times WIV_{Pi} \qquad (5)$$

where S: Score of a holding; Vi: % of variance explained by the component; WIVCi: Weighted indice values of i-th component; Ci: i-th component formed by principle component.

7- Ranking the holdings according to the scores calculated by the set of formula.

Shortly, in statistical evaluation, correlation was used to investigate statistical relation between indicators and factor analysis to rank the holdings according to all indices.

Table 2. Calculation methods of land fragmentation indices

Index	Formula	Resource	Optimum values	Correction factor	Parameters needed
Simmons	$Simmons = \frac{\sum_{i=1}^{n} A_i^2}{A}$	Simmons (1964)	1	+1	**A_i:** Area of *i*th parcel **A:** Total size of the holding **n:** number of parcels belong the holding **Dt:** Total length of round trip distance covering all parcels belong the holding **l_i:** Distance from *i*th parcel centre to convex hull centre
Januszewski	$Januszewski = \frac{\sqrt{A}}{\sum_{i=1}^{n} \sqrt{A_i}}$	Januszewski (1968)	1	+1	
Number of parcels	Total number of parcels of the holding	Anonymous	1	-1	
Schmook	$Schmook = \frac{\sum_{i=1}^{n} A_i}{A}$	Schmook (1976)	0	-1	
Igbozurike	$Igbozurike = \frac{\sum_{i=1}^{n} (\frac{A_i}{100}) \times Dt}{n}$	Igbozurike (1974)	1	+1	
New land fragmentation index	$NLFI = \frac{\sum_{i=1}^{n} l_i}{n}$	-	0	-1	

RESULTS AND DISCUSSION

The descriptive statistics of the indices are given Table 3. The indices have different range. Variation coefficient shows the distribution function of Schmook and Igbozurike indices calculated for the holdings is more heterogeneous than the other indices.

Table 3. Descriptive statistics of the indices

	Minimum	Maximum	Mean	Std. Deviation	Variation coeff (%)
Simmons	0.24	0.83	0.50	0.18	36.00
Januszewski	0.09	0.90	0.37	0.22	59.00
NoP	2.00	21.00	6.33	5.65	89.26
Schmook	0.00	0.13	0.04	0.06	150.00
Igbozurike	0.53	147.00	30.72	35.31	114.94
NLFI	25.21	1,813.30	858.27	594.33	69.25

The correlation matrix given in Table 4 show the index Igbozurike is only correlated negatively with the index and significant at 0.05 level. Igbozurike which calculated with the parameters area and total length of round trip distance covering all parcels belong the holding is differ from the other indices with this parameters. Simmons and Januszewski were found positively correlated and very similar as in the previous studies (Değirmenci et al., 2017; Demetriou et al., 2013). Schmook and NLFI are the only indices correlated with the other indices. As a result, the correlation between the new fragmentation index and other indices is a positive result for its usability.

Table 4. Pearson correlation coefficient matrix

Indicators	Simmons	Januszewski	NoP	Schmook	Igbozurike	NLFI
Simmons	1					
Januszewski	.943**	1				
NoP	-.721**	-.576*	1			
Schmook	.801**	.811**	-.473*	1		
Igbozurike	-.316	-.388	.299	-.530*	1	
NLFI	-.593**	-.560*	.629**	-.715**	.615**	1

**. Correlation is significant at the 0.01 level (2-tailed); *. Correlation is significant at the 0.05 level (2-tailed).

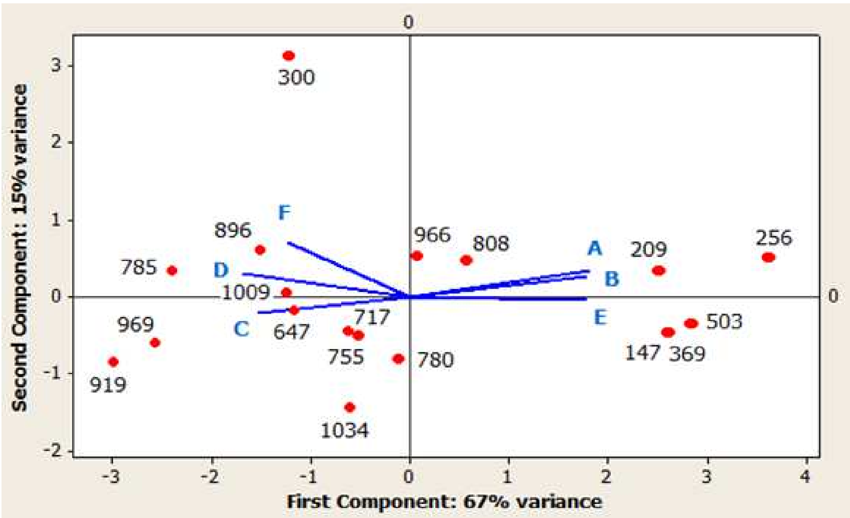
Sample adequacy of the factor analysis was measured with Kaiser Meyer Olkin and Barlett test and was found 0.68 and 86.50, respectively ($P < 0.01$). As a result of factor analysis, 3 components were formed explain 92% of the total variance. The rotated component matrix is given Table 5.

Table 5. Rotated component matrix

Index code	Index	PC1	PC2	PC3
A	Simmons	0.454	0.384	0.117
B	Januszewski	0.443	0.289	0.357
C	NoP	-0.374	-0.242	0.763
D	NLFI	-0.412	0.336	0.315
E	Schmook	0.443	-0.05	0.418
F	Ibgozurike	-0.301	0.771	-0.063
Variation explained (%)		0.67	0.15	0.10

We can see from Fig. 2, the fragmentation indices with principle component coefficients close each other are cumulated together in terms of similar values of land fragmentation indices. For instance, the holdings with no 147, 369 and 503 are cumulated and have similar values of land fragmentation. The distance increase between the holdings means their values of land fragmentation differ while distance decrease between the holdings means they have more similar features.

The holdings closer to tip of the index line illustrate they related more each other. And it also means they have more optimum value in terms of the indices which they are closer to the end of the index lines (blue). In the graph, on the left side number of parcels, new land fragmentation index and Ibgozurike are more similar than the indices on the right side (Simmons, Januszewski and Schmook). Another feature the graph is that we can easily examine the correlation between the indicators supporting Table 5. The acute angle between indicators show positive linear correlation while the wide angles show relation between the indices decrease. The holdings close each other have similar values, the holdings asunder have different values. We can also see from success rating, these holdings are also close each other (Table 5).



●Enterprise, A: Simmons, B: Januszewski, C: Number of parcels, D: New land fragmentation index, E: Schmook, F: Ibgozurike

Figure 2. Biplot graph.

Table 6 clarify ranking the holdings with overall score besides new land fragmentation index. The least fragmented holdings are on the top of the list when the most are on the end of the list. The overall ranking is similar with the NLFI ranking, even the top 4 holdings are same but the order is different. The holding no 256 is top of the overall ranking when it is the 4th in the other ranking. When we investigate the parcels of the holding no 256, we can clearly see the holdings with 503, 369 and 147 are less fragmented than the holding 256. It can be said that these holdings are not fragmented due to no gap exist between the parcels. This prove NLFI perform better than the others. When we focus on the most fragmented holding with no 919 according to overall performance is not on the bottom of the NLFI rank. Indeed, the holding with no 969 which is the most fragmented holding in reference to NLFI is examined, it was more fragmented than the holding 919. According to ranking of NLFI and the overall ranking of all indices, we can say that we can use the new index instead of using a lot of factors. It may be possible use NLFI interchangeably.

Table 6. Overall ranking of the holdings and comparison with new land fragmentation

Overall			New land fragmentation index		
Holding no	Score	Rank	Holding no	NLFI	Rank
256	4,113.25	1	503	25.21	1
503	3,323.18	2	369	40.63	2
369	3,161.72	3	147	66.29	3
147	3,101.84	4	256	130.06	4
209	2,961.80	5	1034	291.14	5
808	771.69	6	780	415.47	6
966	295.46	7	717	629.15	7
780	203.78	8	209	724.46	8
717	-214.64	9	808	985.62	9
1034	-233.17	10	755	994.62	10
755	-343.53	11	966	1,061.69	11
647	-939.21	12	1,009	1,122.02	12
1009	-994.05	13	647	1,262.37	13
300	-1104.63	14	919	1,272.89	14
896	-1,305.83	15	300	1,295.40	15
785	-2,180.84	16	785	1,538.14	16
969	-2,305.62	17	896	1,780.41	17
919	-2,678.12	18	969	1,813.30	18

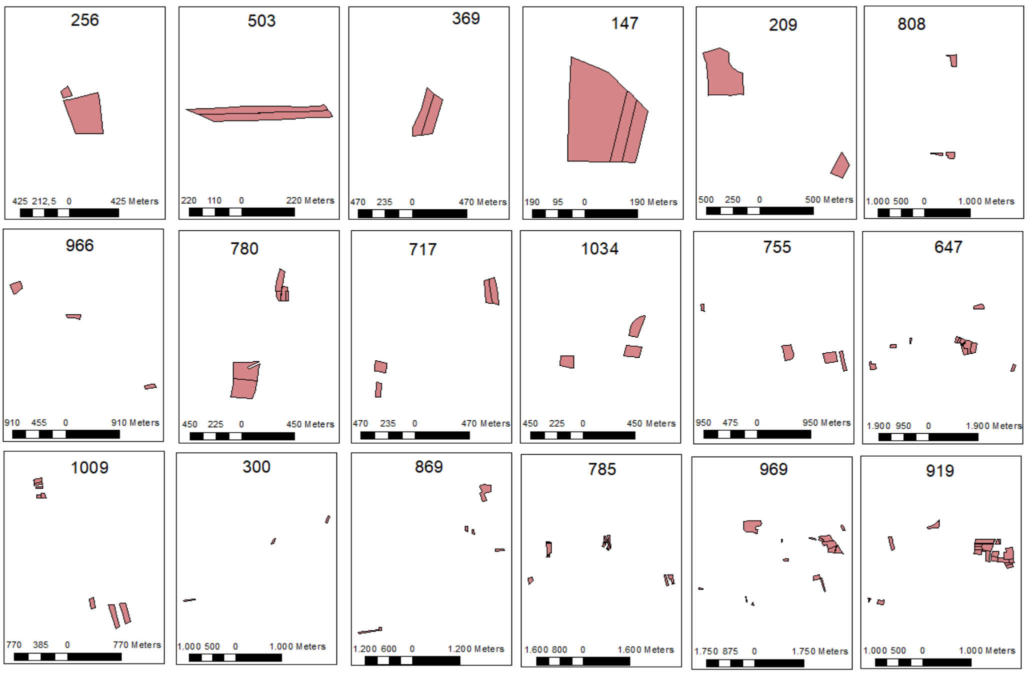


Figure 3. Spatial distribution of the parcels belongs the holdings.

Land fragmentation is effected by various parameters including holding size, number of parcels, size of parcels, shape of parcels, spatial distribution of the parcels, size distribution of parcels and internal fragmentation (Platonova et al., 2011; Demetriou et al., 2011; Aasmäe & Maasikamäe, 2014; Siik & Maasikamäe, 2015; Looga et al., 2018; Kirmikil et al., 2017). In this studies, shortly it is explained that fragmentation measurement is the substantial matter and can be measured with many factors. The correlation, principle component results and overall rank indicate that new index can be used interchangeably. The new index doesn't show shape measurement and hidden land fragmentation but spatial distribution of the parcels belong the holdings.

CONCLUSIONS

The main purpose of the present study was to investigate a new methodology to measure land fragmentation which has various effect on agricultural production. In this context, new land fragmentation index was created and compared with the other indices including Simmons, Januszewski, number of parcels, Schmook and Ibgozurike. These indices was calculated for 18 holdings in Kargılı before land consolidation project in Turkey. The overall performance score of the previous indices was calculated with factor analysis and were used to rank the holdings. The ranking occurred as a result of factor analysis was compared with the ranking of the new index. As a conclusion, new land fragmentation index showed similar performance in some cases with the other indices and it was found correlated with the other indices. However, in most cases we may say new land fragmentation index show better performance explain scattered parcels. This new index has value in terms of measurement of agricultural productivity and priority areas of land consolidation. On the other hand, it is also need to add indices have difficulties to measure accurate land fragmentation level. Therefore, in the future studies, optimum parcel size, parcel shape and road distance from parcel residence to the parcels can be investigated according to agricultural activities depend on the crops cultivated, machinery used, irrigation and pesticide applications.

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Numerical modelling of process of cleaning potatoes in spiral separator

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Abstract. Cleaning potato tubers from soil and plant residues after their digging from the soil is a topical problem in the industrial production of potatoes. Taking into account the fact that the cleaning spirals are positioned with overlapping and rotate in the same sense, the potato tuber that has landed on the surface of the spiral separator in the trough between two adjacent spirals will perform translational motion towards the output ends of the spirals. As a result of solving the said system of equations, the graphical relations between the values of the normal reactions and friction forces generated during the translation of the potato tuber along the mentioned spirals, on the one hand, and the design and kinematic parameters, on the other hand, based on the requirement of not damaging tubers when performing the said work process of transportation and cleaning, have been obtained. The limitations for the normal reactions and friction forces at the points of contact between the tuber and the surface of the cleaning spiral are set in accordance with the requirement that they do not exceed the force of scraping (damaging) the tuber's external surface permissible for potato tubers. That has provided an opportunity to obtain the rational values of the design and kinematic parameters of the separator's operating spirals, in particular, the value of the angular velocity of the rotating cleaning spirals as well as their radius and helix lead.

Key words: post-harvest processing, potato, rational parameters, surface of the spiral separator.

INTRODUCTION

The advancement of the work process of potato production is a topical problem worldwide. One of the most important phases in the said work process is the cleaning of potato tubers from soil and plant residues after their digging out from the soil (Misener & McLeod, 1989; Peters, 1997; Veerman & Wustman, 2005; Bishop et al., 2012; Ichiki et al., 2013; Gou & Campanella, 2017; Wang et al., 2017). This phase provides for the high quality of the harvested product, while the possibility of damaging the product in it must be ruled out (Petrov, 2004).

The spiral separator of our design (Bulgakov et al., 2018a & 2018b) delivers, according to the results of the implemented experimental investigations, a sufficiently high level of cleaning the potato tubers from soil impurities and plant debris and at the same time ensures not damaging the tubers in terms of the established agricultural technology requirements. The simple design together with the low metal and energy intensity make this potato heap separator a promising engineering solution.

However, the varying conditions of harvesting, including the condition of the dug potato bed (the humidity and hardness of the soil in the ridge area, the presence of rhizomae, stones and hardened soil bodies, haulm residues) as well as the quantity of potato tubers differing in their weights, dimensions and shapes, necessitate repeatedly changing the engineering and process characteristics of the above-mentioned separator in order to ensure the achievement of the described performance of the work process of cleaning (Feller et al., 1987).

Such a situation gives rise to a problem of scientific substantiation of such rational design and kinematic parameters of the spiral potato heap separator under consideration that would provide for the high quality of cleaning under different physical and mechanical properties of the soil and the potato tubers themselves. Carrying out fundamental theoretical research into the process of interaction between the potato heap and, in particular, the potato tubers and the operating components of the spiral separator under consideration is an important step towards solving the above-mentioned problem (Krause & Minkin, 2015). Therefore, earlier in paper (Bulgakov et al., 2018c), we developed a mathematical model of cleaning potato tubers from soil and plant residues with the use of the spiral separator subject to the requirement of not damaging the potato tubers. In particular, the conditions, in which a single potato tuber approximated by a body shaped similar to a sphere was situated in the space between two adjacent spiral springs of the separator, were determined. All the relevant existing forces were applied to the potato tuber's body and the conditions were determined for the movement of the potato tuber in the said space as in the only place, where its displacement along the axes of the spiral cleaning springs, i.e. its cleaning from impurities and discharge from the area of cleaning, is ensured. As a result of the mathematical modelling, a system of differential equations was generated, its transformations were carried out and the necessary conditions were found that provide for the guaranteed movement of a single potato tuber on the cleaning surface of the spiral separator under consideration.

In the present study, the mathematical model developed in paper (Bulgaov et al., 2018c) has been used to perform the numerical calculations on a PC in order to substantiate the rational and practical parameters of the earlier developed new design of a spiral separator. At the same time, in the said calculations provisions have been made for the movement of the potato tuber without being damaged.

The aim of the study is to raise the quality of the cleaning of potato tubers from soil and plant impurities taking into account the requirement of not damaging them by means of analytically substantiating the design and kinematic parameters of the spiral separator on the basis of the calculation and analysis of the mathematical model of the interaction between the potato heap and the separator's operating surface.

MATREIALS AND METHODS

The investigations have been carried out with the use of techniques from the theoretical mechanics (Vasilenko, 1996), in particular, the dynamics of constrained particle, the higher mathematics, the techniques of designing computer programmes and performing numerical calculations on a PC as well as analysing the obtained results.

As already mentioned, in paper (Bulgakov et al., 2018c) a new mathematical model of the movement of a single tuber in the space between two adjacent cleaning spiral springs was developed on the basis of the earlier elaborated pattern of forces acting in the interaction between a potato tuber and the operating surface of a spiral separator. Nevertheless, in that study the process of the movement of the potato tuber approximated by a spherical body on the surface of the spiral separator was not investigated fully, because the conditions of such a movement were not represented in their final form and PC-assisted calculations were not carried out for the generated differential equations of motion.

In order to perform further analytical investigations, the equivalent schematic model of a potato tuber's motion has been refined in order to most fully take into account all the forces supporting the movement of a single potato tuber in the trough between two spiral springs. The resulting equivalent schematic model is shown in Fig. 1.

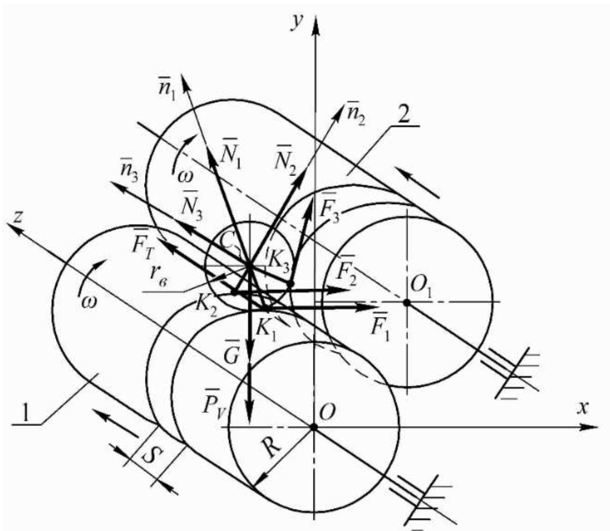

Figure 1. Equivalent schematic model of interaction between single potato tuber and two spiral springs, when tuber is situated in trough between springs

As is seen from the presented refined equivalent schematic model, the motion of the single potato tuber along the longitudinal axes of the spirals has to be guaranteed by the main propelling force $\overline{F}_T$ that appears at the point of contact K_1 with supporting spiral turn 1. At the same time, forces propelling the tuber can arise to some extent also at other points of contact between the single potato tuber and the spirals, such as K_2 on spiral 1 and point K_3 on the supporting turn of spiral 2. But, for the purposes of solving this particular problem, the potato tuber propelling forces that appear on the coils at points

K_2 and K_3, by reason of their smallness, can be neglected at a first approximation and it can be assumed that it is exactly point K_1 where the force $\bar{F}_T$ must be applied. It is also assumed that the vector of the said force $\bar{F}_T$ is parallel to the longitudinal axes of spirals 1 and 2.

Complex mechanical and mathematical investigations and transformations have been carried out and on their basis a mathematical model of a single potato tuber's motion comprising three differential equations of motion has been developed. The model appears as follows (Bulgakov et al., 2018c):

$$\left.\begin{aligned}
&m\ddot{x} = \left(N_1 + N_2 - N_3\right)\times \\
&\times\frac{A\sin(\omega t) + B\cos(\omega t)\cdot\sin(2\omega t)}{\sqrt{\left[A\sin(\omega t) + B\cos(\omega t)\cdot\sin(2\omega t)\right]^2 + \left[A\cos(\omega t) + B\sin(\omega t)\cdot\sin(2\omega t)\right]^2 + C^2\cos^2(2\omega t)}} - \\
&-\left(F_1 + F_2 + F_3\right)\frac{2\pi R\sin(\omega t)}{\sqrt{4\pi^2R^2 + S^2}}, \\
&m\ddot{y} = \left(N_1 + N_2 + N_3\right)\times \\
&\times\frac{A\cos(\omega t) + B\sin(\omega t)\cdot\sin(2\omega t)}{\sqrt{\left[A\sin(\omega t) + B\cos(\omega t)\cdot\sin(2\omega t)\right]^2 + \left[A\cos(\omega t) + B\sin(\omega t)\cdot\sin(2\omega t)\right]^2 + C^2\cos^2(2\omega t)}} - \\
&-\left(-F_1 - F_2 + F_3\right)\frac{2\pi R\cos(\omega t)}{\sqrt{4\pi^2R^2 + S^2}} - mg - P_V, \\
&m\ddot{z} = \left(N_1 - N_2 + N_3\right)\times \\
&\times\frac{C\cos(2\omega t)}{\sqrt{\left[A\sin(\omega t) + B\cos(\omega t)\cdot\sin(2\omega t)\right]^2 + \left[A\cos(\omega t) + B\sin(\omega t)\cdot\sin(2\omega t)\right]^2 + C^2\cos^2(2\omega t)}} - \\
&-\left(F_1 + F_2 + F_3\right)\frac{S}{\sqrt{4\pi^2R^2 + S^2}},
\end{aligned}\right\} \qquad (1)$$

where

$$A = -\frac{S^2}{4\pi^2 R}\cdot\cos\left(\frac{S}{2\pi R}\right)$$

$$B = \frac{S^2}{4\pi^2 R}\cdot\cos\left(\frac{S}{2\pi R}\right) - \frac{S^3}{8\pi^3 R^2}\cdot\sin\left(\frac{S}{2\pi R}\right)$$

$$C = \frac{S}{2\pi}\cdot\cos\left(\frac{S}{2\pi R}\right)$$

R – radius of spiral; S – lead of helix; m – mass of potato tuber; f – coefficient of sliding friction of the potato tuber's surface on the operating surface of the spiral; g – acceleration of gravity; P_V – force of impact of the fed potato heap on the spiral separator (vectored vertically down); ω – angular velocity of the rotating spiral about its figure axis; N_1, N_2 – normal reaction forces generated by the two adjacent turns of the first spiral, with which the potato tuber is in contact, when it is situated in the trough between the two adjacent spirals; N_3 – normal reaction force generated by the turn of the second spiral, with which the tuber is in contact at the given moment; F_1, F_2 and F_3 – forces of friction acting at the respective points of contact K_1, K_2 and K_3.

RESULTS AND DISCUSSION

The analysis of the obtained mathematical model includes first of all the solving of the system of differential Eqs (1) for the unknown functions $x = x(t)$, $y = y(t)$ and $z = z(t)$. The values of the normal reactions N_1, N_2 and N_3 can be determined on the basis of the conditions of the equilibrium of the potato tuber situated in the trough between the two adjacent spirals. These conditions were obtained earlier in (Bulgakov et al., 2018b) in the form of a system of linear equations with variable coefficients and unknown quantities N_1, N_2 and N_3. The solving of the mentioned system of linear equations could provide the values of the normal reactions N_1, N_2 and N_3 with an accuracy that is sufficient for practical purposes.

The solving of the above equations was carried out with the use of a PC, which resulted in obtaining the following mean values of the normal reactions: N_1 = 1.50 N, N_2 = 1.50 N and N_3 = 1.00 N. These theoretically obtained mean values of the normal reactions were later proved by the respective experimental investigations.

Also, experimental investigations and theoretical research have been undertaken in order to determine the value of the propelling force F_T that is responsible for the displacement of the potato tuber along the longitudinal axis of the cleaning spiral. Thus, from the results of the accomplished field experiment research into the operation of the spiral separator, its energy characteristics have been determined, in particular, the power consumption P by the drive of the spiral separator as during its idle run, so when the heap of cleaned potato tubers is fed onto the cleaning surface at a rate of 30 kg s^{-1} (Bulgakov et al., 2017).

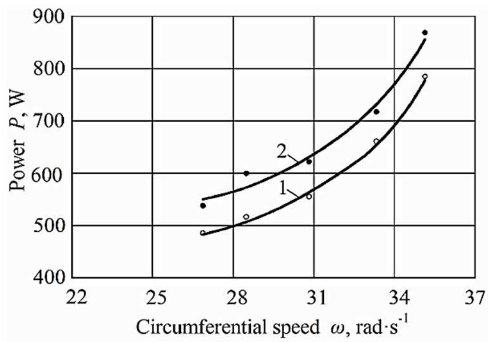

Figure 2. Relation between consumed power P required for driving rotational motion of three spirals of separator and angular velocity ω of its rotating spirals: 1 – idle running; 2 – heap feeding at a rate of 30 kg·s^{-1}.

The results obtained in the course of the experimental investigations and processed with the use of a PC have made it possible to determine the relation between the consumed power P and the angular velocity ω of the cleaning spiral rolls and plot the diagrams showing the relation (Fig. 2).

As is seen from the diagrams (Fig. 2), the power P consumed for driving the spiral rolls (3 pcs) under the operating load can reach the order of 850 W at an angular velocity

ω of the rotating rolls of about 40 rad·s^{-1}, when the heap of the cleaned potato tubers is fed to the rolls at a rate of 30 kg s^{-1}.

Meanwhile, in order to determine the value of the power P needed for the calculation of the propelling force F_T applied by only one turn of one spiral, it is necessary to subtract the power consumed by the separator during its idle running from the total power consumed by the separator, take the adjusted value of the power into account in the feeding of the potato heap to the complete cleaning surface of the separator and then, on the basis of the fact that the propelling force is generated by only one of the spiral rolls, the maximum value of the power P needed for the calculation of the propelling force F_T is assumed to be not exceeding 85.00 W on an average.

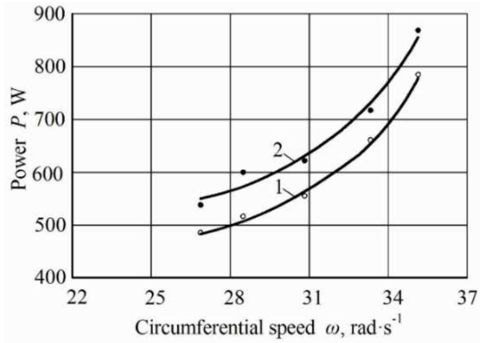

Figure 2. Relation between consumed power P required for driving rotational motion of three spirals of separator and angular velocity ω of its rotating spirals: 1 – idle running; 2 – heap feeding at a rate of 30 kg·s^{-1}.

Proceeding from the value of the consumed power P determined from the results of the experimental investigations, it is necessary to find the torque M_{kw} of the drive shaft of one of the separator's spirals. For that purpose, the following relation can be used:

$$M_{kw} = \frac{P}{\omega}, \tag{2}$$

where M_{kw} – torque of the drive shaft of a single cleaning spiral; ω – angular velocity of the rotating spiral.

Hence, taking into account (2), the value of the propelling force F_T is equal to:

$$F_T = \frac{M_{kw}}{R}\sin\gamma = \frac{P}{\omega \cdot R}\sin\gamma, \tag{3}$$

where R – spiral's radius; γ – lead angle of the helical line of the separator's spiral.

Further, the results of the experimental investigations have been used to determine the value of the force P_V that is a member of the system of differential Eqs (1). It has been proved by the results of the experimental investigations that the maximum mass of a soil lump that can be found in the potato heap coming into the separator is in the majority of cases two times greater than the average mass of a potato tuber (Bulgakov et al., 2017). Therefore, following the results of the done measurements, the force P_V of the impact of the fed potato heap on a single potato tuber situated in the trough between two adjacent spirals is assumed to be equal to:

$$P_V = 2mg, \tag{4}$$

where m – mass of the potato tuber.

Thus, all the data necessary for the transformation of the system of differential Eqs (1) into the following new form have been finally obtained:

$$\left.\begin{aligned}
&m\ddot{x} = \left(N_1 + N_2 - N_3\right)\times \\
&\times\frac{A\sin\left(\omega t\right) + B\cos\left(\omega t\right)\cdot\sin\left(2\omega t\right)}{\sqrt{\left[A\sin\left(\omega t\right) + B\cos\left(\omega t\right)\cdot\sin\left(2\omega t\right)\right]^2 + \left[A\cos\left(\omega t\right) + B\sin\left(\omega t\right)\cdot\sin\left(2\omega t\right)\right]^2 + C^2\cos^2\left(2\omega t\right)}} - \\
&-\left(F_1 + F_2 + F_3\right)\frac{2\pi R\sin\left(\omega t\right)}{\sqrt{4\pi^2R^2 + S^2}}, \\
&m\ddot{y} = \left(N_1 + N_2 + N_3\right)\times \\
&\times\frac{A\cos\left(\omega t\right) + B\sin\left(\omega t\right)\cdot\sin\left(2\omega t\right)}{\sqrt{\left[A\sin\left(\omega t\right) + B\cos\left(\omega t\right)\cdot\sin\left(2\omega t\right)\right]^2 + \left[A\cos\left(\omega t\right) + B\sin\left(\omega t\right)\cdot\sin\left(2\omega t\right)\right]^2 + C^2\cos^2\left(2\omega t\right)}} - \\
&-\left(-F_1 - F_2 + F_3\right)\frac{2\pi R\cos\left(\omega t\right)}{\sqrt{4\pi^2R^2 + S^2}} - 3mg, \\
&m\ddot{z} = \frac{P}{\omega\cdot R}\sin\gamma + \left(N_1 - N_2 + N_3\right)\times \\
&\times\frac{C\cos\left(2\omega t\right)}{\sqrt{\left[A\sin\left(\omega t\right) + B\cos\left(\omega t\right)\cdot\sin\left(2\omega t\right)\right]^2 + \left[A\cos\left(\omega t\right) + B\sin\left(\omega t\right)\cdot\sin\left(2\omega t\right)\right]^2 + C^2\cos^2\left(2\omega t\right)}} - \\
&-\left(F_1 + F_2 + F_3\right)\frac{S}{\sqrt{4\pi^2R^2 + S^2}},
\end{aligned}\right\} \tag{5}$$

Specifically for our design of the spiral potato heap separator (Bulgakov, et al., 2018a), the system of differential Eqs (5) has been solved using the following values of the design and kinematic parameters included in the said system of equations: $R = 0.025…0.25$ m; $S = 0.035$ m; $m = 0.40$ kg; $g = 9.81$ m·s^{-2}; $f = 0.2$; $\omega = 20…40$ rad·s^{-1}; $N_1 = 1.50$ N; $N_2 = 1.50$ N; $N_3 = 1.00$ N; $P_V = 85$ N; $\gamma = 20°$.

As a result of solving the above system of Eqs (5) with the use of the Runge-Kutta method on a PC in the MathCad environment, the graphical representations of the relations between the values of the variables $x = x(t)$, $y = y(t)$ and $z = z(t)$, on the one hand, and a number of values of the initial design and kinematic parameters of the spiral separator, on the other hand, which show the displacements of the potato tuber along the *Ox*, *Oy* and *Oz* axes at an arbitrary instant of time *t*, have been obtained.

The obtained graphical relations are presented in Fig. 3, Fig. 4, Fig. 5 and Fig. 6. In Fig. 3, the variation of the *z* coordinate of the potato tuber's centre of mass *C* with the time *t* for different values of the angular velocity ω of the rotating spiral is shown.

In Fig. 4, the variation of the *z* coordinate of the potato tuber's centre of mass *C* with the time *t* is plotted for different values of the spiral's radius *R*.

According to the diagrams in Fig. 3, under the above-mentioned parameters of the spiral separator, the displacement of the potato tuber along the *Oz* axis, i.e. longitudinally, in $t = 0.3$ s is equal to 0.60 m at an angular velocity value equal to $\omega = 30$ rad s^{-1}. At an angular velocity equal to $\omega = 30$ rad s^{-1}, the said displacement is equal to 0.44 m, at an angular velocity of $\omega = 40$ rad s^{-1} – 0.33 m.

Also, as is seen from the presented graphical relations, the displacement of the potato tuber along the *Oz* axis, i.e. along the spiral's figure axis, changes following a law that is close to parabolic. Moreover, when the angular velocity ω of the rotating spirals increases, the value of the tuber's displacement in the same time *t* decreases.

That is due to the fact that, at the pre-set consumed power *P*, the value of the torque M_{kw} produced by the spiral's drive shaft and, accordingly, of the propelling force F_T generated by the spiral's supporting turn decreases with the increase of the angular velocity ω, which results in the reduction also of the velocity and displacement of the potato tuber along the line under consideration.

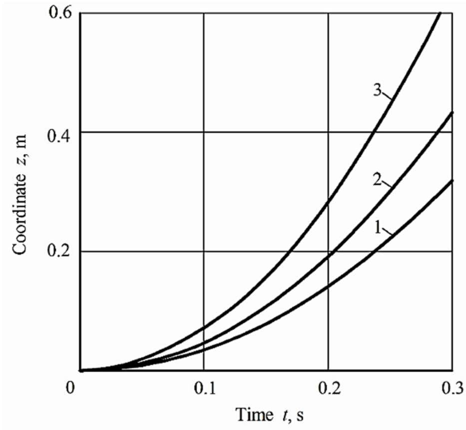

Figure 3. Cases of variation of *z* coordinate, i.e. displacement of potato tuber's centre of mass *C* along longitudinal axis of spiral spring with time *t*, for: 1) $\omega = 20$ rad·s^{-1}; 2) $\omega = 30$ rad·s^{-1}; 3) $\omega = 40$ rad s^{-1}.

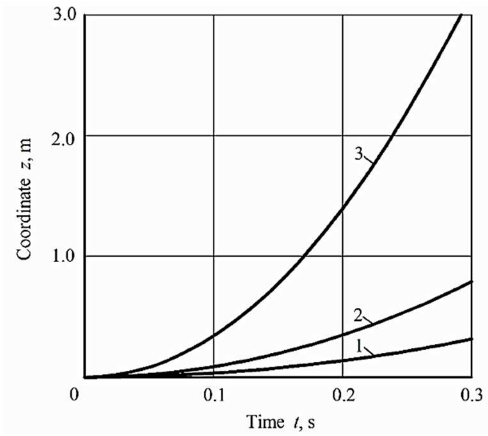

Figure 4. Cases of variation of *z* coordinate, i.e. displacement of potato tuber's centre of mass *C* along longitudinal axis of spiral spring, with time *t* for: 1) $R = 0.025$ m; 2) $R = 0.10$ m; 3) $R = 0.25$ m.

The diagrams in Fig. 4 show that the displacement of the potato tuber along the *Oz* axis, i.e. along the spiral's figure axis, in a time interval of $t = 0.3$ s is equal to 3.2 m, when the spiral's radius has a value of $R = 0.025$ m, in case of $R = 0.10$ m it is equal to 0.75 m, in case of $R = 0.25$ m– 0.30 m. Hence, the increase of the spiral's radius *R* results in the decrease of the value of the tuber's displacement along the spiral's longitudinal axis.

The reason for such a relation is the fact that the increase of the spiral's radius *R* causes the torque M_{kw} of the spiral's drive shaft and, accordingly, the propelling force F_T to decrease, which results in the reduction of both the velocity and displacement of the potato tuber along the trough between the two adjacent spirals.

The analysis of the diagrams presented in Fig. 3 and Fig. 4 provides evidence that the spiral potato heap separator under consideration possesses a high transporting capability along the longitudinal axes of its spirals.

In Fig. 5 and Fig. 6, the diagrams are shown for the variation of the *y* and *x* coordinates of the potato tuber's centre of mass *C* with the time *t*, i.e. the displacement of the potato tuber across the trough between the two adjacent spirals.

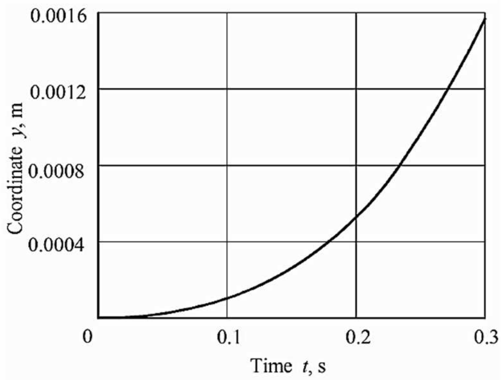

Figure 5. Variation of *y* coordinate, i.e. vertical displacement of potato tuber's centre of mass *C*, with time *t*.

As is seen from the graphical relation presented in Fig. 5, the vertical displacement of the potato tuber, i.e. its motion along the *Oy* axis in a time interval of $t = 0.3$ s is equal to 0.0016 m, which implies that the tuber moves virtually without losing the contact with the turns of the spirals.

The diagram in Fig. 6 shows that the displacement of the potato tuber along the *Ox* axis in the same time $t = 0.3$ s is negligible, being equal to mere 0.0018 m.

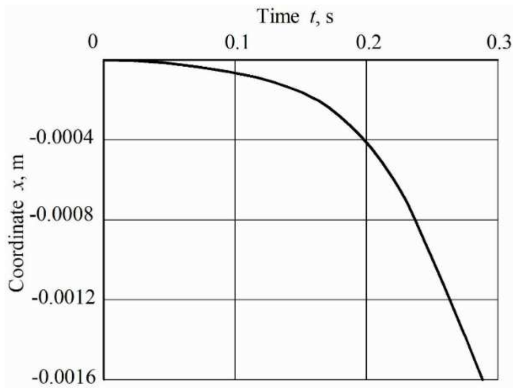

Figure 6. Variation of *x* coordinate, i.e. lateral displacement of potato tuber's centre of mass *C*, with time *t*.

Therefore, as can be concluded from the diagrams shown in Fig. 3–Fig. 6, the potato tuber moves along the trough between the two adjacent spirals smoothly, in virtually constant contact with the spirals and with great stability. The results of the PC-assisted calculations prove that the potato tuber in no case can be trapped or compressed between the turns of adjacent spirals. That, in its turn, ensures not damaging potato tubers during their cleaning in the spiral separator under discussion.

CONCLUSIONS

1. The PC-assisted analysis of the mathematical model of the process of cleaning potato tubers from soil and plant impurities with the use of a spiral separator subject to not damaging them has been completed. As a result of the analysis, the rational design and kinematic parameters of the separator have been substantiated.

2. The graphical relations between the displacement of a potato tuber situated in the trough between two adjacent spirals at an arbitrary instant of time and the design and kinematic parameters of the separator have been obtained.

3. The longitudinal displacement of the potato tuber (along the *Oz* axis) in 0.3 s at $\omega = 20…40$ rad s^{-1} is proved to be equal to 0.60…0.33 m, at the spiral's radius of $R = 0.025…0.250$ m – 3.20…0.30 m respectively, which implies the good transportation capability of the developed spiral separator of a new design.

4. As is seen from the obtained graphical relations, the vertical (along the *Oy* axis) and transverse (along the *Ox* axis) displacements of the potato tuber are fairly negligible and are equal to 0.0016 m and 0.0018 m respectively. That signifies that the movement of the potato tuber along the trough between the two adjacent spirals is stable and smooth, which ensures not damaging the tuber.

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Behavioural and physiological responses of rabbits

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Abstract. The profitability of a rabbit farming system must consider the thermal environment that the animal will be exposed during the productive period. The goal of this study was to evaluate the physiological responses and behaviours of 26 New Zealand rabbits during seven days of their lives at three times a day. The experiment was carried out in rabbit house in the Federal University of Lavras at Lavras, Brazil. To characterize the thermal environment sensors were used to measure the dry bulb temperature and relative humidity at 48 points inside the rabbit house, at 6:00 a.m., 12:00 a.m. and 6:00 p.m. In addition, the temperature and humidity index (THI) was calculated. The respiratory rate and the superficial temperature of the rabbits' ears were measured. Behaviour evaluations were monitored in punctual record, with duration of two min/cage. Later an ethogram was made with the main behaviours identified. Similar data of behaviour and data of physiological responses were identified by using Ward's method of cluster analysis. It was observed the period of 6 a.m. showed more comfortable conditions of THI values than the others analysed. Besides, physiological responses presented better values at 6:00 a.m. in comparison to 12:00 and 6:00 p.m. Furthermore, in general, a similar behaviour was observed in the rabbits at 12:00 and 6:00 p.m., while at 6:00 a.m. was different. But rabbits demonstrated to be more comfortable at 6 a.m. maybe because at this time environment conditions were better than the rest of the day. Besides, it can be observed that rabbits were more active in sunrise and sunset than in the rest of the day.

Key words: thermal environment, dendrogram, grouping of data, animal welfare.

INTRODUCTION

Brazil has incredible agricultural potential due to its extensive land area, which benefits the establishment of several types of production systems, especially animal production systems, including rabbit production.

Several products derived from rabbits can be commercialized, such as meat, fur, urine, and handicrafts, among other products. However, this branch of agribusiness is underdeveloped in Brazil considering its high agricultural and rabbit production potential (Santos, 2010).

Rabbit production is considered a strategic production activity because it generates a large number of products, co-products, and by-products of high added value in a short time; furthermore, it is considered a sustainable activity due to its carbon and water savings and consequent low environmental impacts due to reduced production time (Machado & Ferreira, 2012).

In human nutrition, foods derived from animal products are important sources of protein and other nutrients. Thus, rabbit meat is considered an excellent source of protein and nutrients because it is considered to be a leaner and healthier meat than beef, sheep meat, and pork (Hernández et al., 2000). In addition, it is a tasty meat that is easy to digest, low in fat and cholesterol, and often recommended by nutritionists for the elderly and children (Hernández et al., 2000).

However, the rabbit breeding industry in Brazil is typically disorganized and subjected to many challenges related to production technology, which increases production costs (Machado, 2012). Therefore, it is of the utmost importance to understand the parameters that affect rabbit production to obtain and combine maximum rabbit productivity with lower production costs (Machado, 2012).

Among these parameters, rabbit welfare analysis deserves attention, and many studies aim to evaluate alternatives to improve existing housing systems (Verga et al., 2007).

Analysing the interaction between genetic, nutritional, and especially environmental factors are of the utmost importance for establishing an efficient rabbit production system. Thus, according to Lebas et al. (1996), for rabbit production to be efficient, the ideal air temperature to raise rabbits after weaning (after 30 days of age) should range between 15 and 20 °C, and the relative humidity (RH, %) should be approximately 60 to 70%.

According to Arveaux (1991), the welfare of rabbits depends to a large extent on the available space, and cages that are too small or characterized by overcrowding rates have immediate consequences, such as changes in hygiene, sanitary conditions, and behaviour, that negatively affect the performance of animals.

Reduced rabbit welfare may lead to atypical behaviours that may be signs of frustration and anxiety (Barros, 2011). Thus, according to Morisse et al. (1999), abnormal aspects of social, maternal, and food intake behaviour can be indicative of thermal stress.

Rabbits are homoeothermic animals and are more sensitive to high air temperature conditions because they cannot perform thermoregulatory sweating (McNitt et al., 1996), thereby limiting their ability to eliminate excess body heat.

Therefore, when behavioural changes no longer have an effect on the maintenance of homeothermy, increased respiratory rate (RR) becomes one of the mechanisms necessary to stimulate evaporative heat loss (Zeferino et al., 2011).

According to Zeferino et al. (2011), in addition to RR, ear temperature (ET) is another physiological mechanism used by rabbits to dissipate surplus heat.

In this context, it is possible to use methods that analyse the rabbit breeding system to serve as a tool for the producer to make quick and accurate decisions. Hierarchical agglomerative clustering (HAC) analysis can be a simple and effective method because it is based on the simple idea of placing objects that are similar according to some pre-determined criteria in the same group; thus, HAC is suitable for the analysis of data that represent many different situations (Linden, 2009).

This technique also allows the results to be visualized and classified using dendrograms that hierarchically illustrate the degree of similarity between clusters. Within each cluster, the objects are similar to each other, whereas objects located in other clusters are different from each other (Dominick et al., 2012).

Dendrograms are especially useful in visualizing similarities between samples or objects represented by points in space where conventional plotting is not possible (Lau et al., 2009).

To evaluate the thermal environment to which the rabbits were exposed, the temperature- humidity index (THI) proposed by Thom (1958) was used. This index can be used to evaluate the thermal comfort of commercial rabbits within their environment.

Thus, the present study aimed to evaluate the physiological responses and behaviours of 26 New Zealand White (NZB) rabbits three times a day for seven days by making technical dendrograms.

MATERIALS AND METHODS

The experiment was conducted in a house of the rabbit production unit of the Department of Animal Science of the Federal University of Lavras (UFLA), in Lavras, Brazil, during May 2016. Twenty-six NZB rabbits (14 males and 12 females) aged 58 days were housed at random in 13 collective galvanized wire cages. During the experimental period, the animals had *ad libitum* access to balanced feed and drinking water.

Behaviour was monitored and logged by an observer at a distance of 1 m from the cages for two minutes per cage at 6 am, 12 pm, and 6 pm every day for seven days.

The list of the types of behaviours monitored during the experiment as well as the definition of each observed item is listed below (Table 1).

Table 1. Ethogram of primary rabbit behaviours and their description

Behaviour	Definition
Exploratory	Smell the surrounding environment, bite.
Intake	Feed in the feeder or drink water.
Playful	Jumps; Dig the floor of the cage frequently and insistently; Performing body care (cleaning the ears).
Stereotypies	Biting or licking cage bars; Roer frequently and insistently.
Indicative of heat stress	Lying; sitting, prostrate, excessive body care

After the behavioural analysis, the physiological indicators were analysed. The respiratory rate was assessed by visually counting the flank movements using a digital timer (± 0.01 s). The respiratory movements were monitored for 15 s and then multiplied by four to obtain breaths per minute. ET was measured at three different points with the use of a thermometer (laser).

To characterise the thermal environment inside the rabbit shed, the dry bulb temperature (t_{db}, °C), dew point temperature (t_d), and relative humidity (RH, %) were measured at a height of 1 m (from the ground) to the centre of the cage and evaluated three times during the seven days of observation.

To measure $t_{db,}$ t_d, and RH, a sensor (base station) with an accuracy of 0.1 °C and 1% was used. These values were then converted to THI, according to the equation by Thom (1958).

The HAC analysis and the dendrograms of the THI and behaviour averages were performed using the statistical computer system R (R Development Core Team, 2018), and the cophenetic correlation coefficient fit was also estimated using the same software.

RESULTS AND DISCUSSIONS

THI values and the dendrogram with clustering analysis in the morning (6 am), afternoon (12 pm), and evening (6 pm) periods during the seven-day study (Fig. 1).

According to Lebas et al. (1996), the ideal tdb values for rabbit breeding vary between 15 to 20 °C, and the ideal RH value is 60 to 70%, according to Ferreira et al. (2012). Based on this information, if we calculate the ideal THI values using the equation proposed by Thom (1958), we can calculate that the ideal minimum and maximum THI for the rabbit breeding environment will be 59 and 61, respectively.

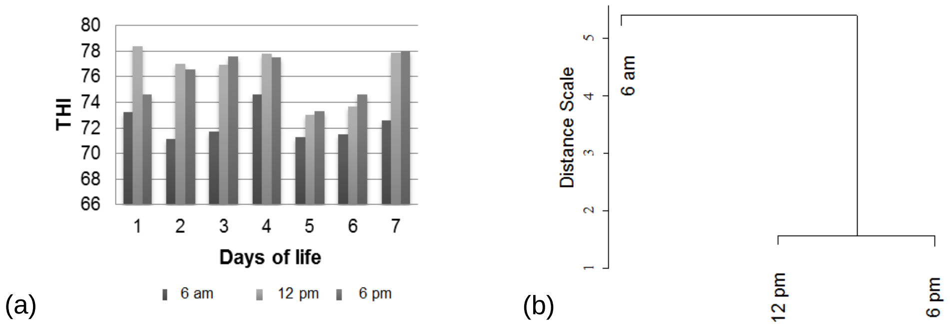


Figure 1. Graphs: (a) with THI values and (b) dendrogram analysis in the morning (6 am), afternoon (12 pm), and evening (6 pm) periods during the seven-day study.

Fig. 1 (a) shows that during the experimental period, the THI ranged from 66 to 78; these values are much higher than the ideal values. The assessment of THI values during the three periods (6 am, 12 pm, and 6 pm) using HAC (Fig. 1, b) revealed that the THI values were similar between 12 pm and 6 pm (mean THI value of 76) but were different from the values at 6 am (mean THI value of 72). In other words, the 6 am time exhibited the best conditions with the lowest THI values ranging from 71 to 75, but the THI was not within what is considered the optimal range. The cophenetic correlation coefficient of Fig. 1 (b) was 0.99, indicating a high accuracy of analysis.

The dendrograms comparing the physiological responses at the three time periods (6 am, 12 pm, and 6 pm): ET (Fig. 2, a) and RR (Fig. 2, b) for the seven days of the study period (Fig. 2).

Thus, as in Fig. 1 (b), the rabbits were under better thermal comfort conditions at 6 am, which resulted in a lower ET (23.8 °C) and RR (76 mov min^{-1}), whereas at 12 pm and 6 pm, ET and RR exhibited similar averages (27.7 °C and 88 mov min^{-1}, respectively). Rabbits are more sensitive to heat than to cold, and abrupt temperature variations are more harmful than a gradual change in temperature outside the comfort zone (Ferreira et al., 2012).

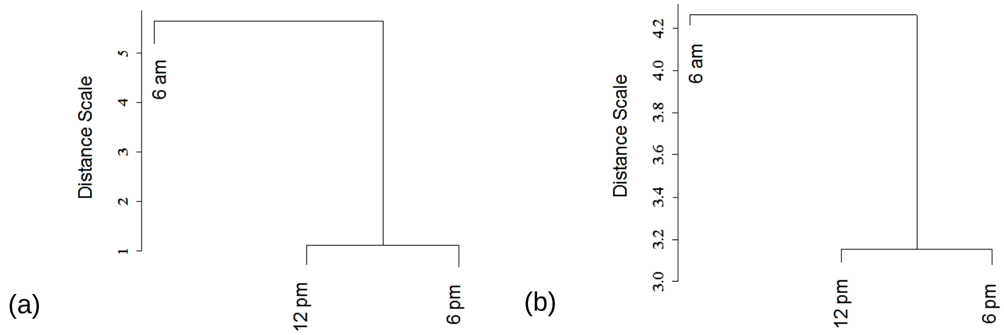
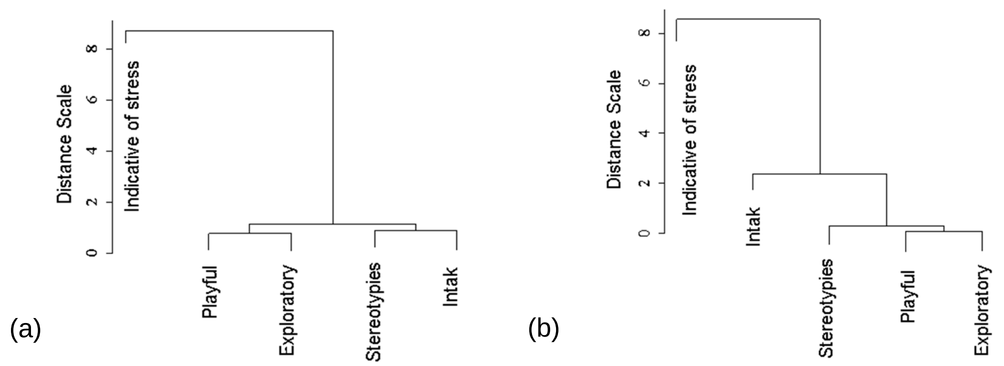


Figure 2. Dendrograms of physiological responses of rabbits during the experimental period: (a) ear surface temperature (ET, °C) and (b) respiratory rate (RR, mov min^{-1}).

Animals under thermal stress tend to exhibit behavioural changes to try to minimize this effect. Thus, Fig. 3 presents the behaviours logged at each observation period during the seven experimental days. The cophenetic coefficients of Fig. 3 were 0.99 for Fig. 3(a) and 0.98 for Fig. 3, b, c.



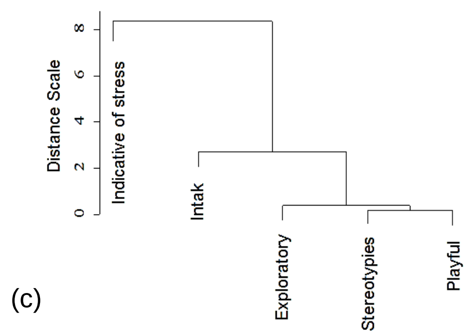


Figure 3. Dendrogram of rabbit behaviour during seven days at different times of the day: 6 am (a), 12 pm (b), and 6 pm (c).

The time the rabbits spent exhibiting playful and exploratory behaviours or stereotypies was very similar during the three observed periods (6 am, 12 pm, and 6 pm) and accounted for less than 10% of the total time observed (Fig. 3). However, the time they spent on behaviours indicative of heat stress was much higher than the time spent on other behaviours (approximately 75% of the time), especially in the afternoon (Fig. 4).

At 6 am, there was lower food and water intake compared to other observation times (approximately 10%, 19%, and 21% of the time at 6 am, 12 pm, and 6 pm, respectively). In addition, at 6 am, the animals were calmer. This observation is in accordance to Diez et al. (2013) that affirm that less activity during the day in experimented rabbits could be resulted not only by temperature reason, but also by rabbits behavioral pattern. According to the same authors rabbits are active in sunrise and sunset period and totally no active during the day. At 12 and 6 pm, the THI values were higher, as shown in Fig. 1, and this may have influenced the greater intake, primarily of water, at these times.

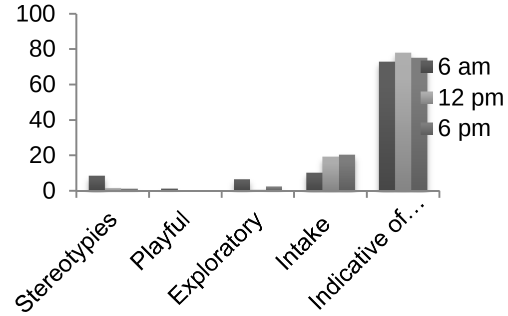


Figure 4. Frequency of occurrence of behaviours (%) during the three evaluated periods.

Adverse climatic conditions are important stressors that negatively affect the environmental quality in which a rabbit is raised, its behaviour, and its productive and physiological responses (Verga et al., 2007).

CONCLUSIONS

During the experimental period, thermal conditions inside the rabbit house, represented by the THI, were milder at 6 am than at 12 pm and 6 pm. This pattern was also reflected in the ET and RR of these animals, which were lower at 6 am. Regarding the behaviours observed, it was clear that the animals exhibited a higher frequency of behaviours indicative of thermal stress for most of the day, as they were housed in conditions outside their thermoneutral zone.

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Possibilities for the biological control of yellow rust (*Puccinia striiformis* f. sp. *tritici*) in winter wheat in Latvia in 2017–2018

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Abstract. Yellow rust, caused by *Puccinia striiformis* f. sp. *tritici*, is a significant wheat disease worldwide. In Latvia, the distribution of yellow rust has increased recently and new aggressive races have been identified. The aim of this research was to investigate the possibilities for the biological control of yellow rust in winter wheat. A field trial was established in a biological field of winter wheat in Latvia in 2017 and 2018. Biological products that contained *Bacillus* spp., *Pseudomonas aurantiaca*, *Brevibacillus* spp., *Acinetobacter* spp., and chitosan were used for treatments, and one variant was left untreated. The efficacy of products was evaluated by the AUDPC (area under the disease progress curve) comparison. Differences in the severity of yellow rust between the trial years were observed. In 2018, the severity of yellow rust was lower than in 2017. In untreated plots, on flag leaf, the severity varied from 10.9% to 32.5% in 2017 and from 1.4% to 6.5% in 2018. In 2017, the severity of yellow rust reached its maximum on 05.07. at wheat growth stage (GS) 79, and in 2018 – on 20.06. GS 79. Both in 2017 and 2018, no significant differences ($p > 0.05$) were found in AUDPC values among the variants. After two years of investigations, the results were not convincing; therefore, further research is needed.

Key words: disease severity, biological control, *Bacillus* spp.

INTRODUCTION

Wheat is the main cereal grown in Latvia. In 2017, the total sown area of winter wheat was 375.7 thousand hectares with the average yield of 51.5 t ha^{-1} (Central Statistical Bureau of Latvia, 2018). One of the main risks in wheat cultivation is wheat leaf diseases such as Septoria tritici blotch, tan spot, and yellow rust.

Yellow rust, caused by *Puccinia striiformis* f. sp. *tritici*, has been considered one of the major threats for wheat growers for the last centuries (Singh et al., 2004; Wellings, 2011). Yellow rust is distributed all over the world, except Antarctica (Stubs, 1985; Chen, 2005).

P. striiformis f. sp. *tritici* is a biotrophic fungus that develops on live plant cells, negatively impacts plant photosynthesis, and uses host nutritions (Chen et al., 2014), thus provoking slower plant growth, yield reduction, and poor grain quality (Waqar et al., 2018). Yellow rust can reduce the amount of yield for 10–70% (Chen, 2005) if the wheat variety is susceptible and climate conditions are suitable for the development of yellow rust.

The situation about the distribution of yellow rust in Latvia is uncertain. In Latvia, detailed researches about the severity of yellow rust and its influence on winter wheat yield have not yet been performed; however, periodical observations have been made and the disease has been recently recorded in the northwest part of the country (Feodorova-Fedotova & Bankina, 2018).

It has been considered that *P. striiformis* f. sp. *tritici* is a temperate-climate zone pathogen (Chen et al., 2014); however, in the last decades, new epidemics of yellow rust were established in the regions where the disease had not been found before (Chen et al., 2000; Hovmøller et al., 2010). It was discovered that the causal agent of yellow rust is adapted to high temperatures (Milus et al., 2009). Air temperatures from 0 °C to 26 °C are suitable for successful development of yellow rust (Chen et al., 2014), and the minimum lasting dew period for successful development of yellow rust is from 4 to 6 hours at an optimal temperature (8 °C) (de Vallavieille-Pope et al., 1994). New, aggressive races with a shorter latent period and ability to produce more spores have appeared (Markell & Milus, 2008; Milus et al., 2009; Hovmøller et al., 2011).

An effective way to avoid yield losses caused by wheat diseases is the application of fungicides. Although chemical control is effective against yellow rust (Jørgensen et al., 2018), regular usage of fungicides can lead to the development of resistance (Oliver, 2014). Other, more environmentally friendly measures are necessary for the control of yellow rust.

Only a few kinds of researches about the applications of biological fungicides under field and greenhouse conditions regarding wheat diseases have been made. Products containing the bacteria are used for cereal disease control. *Bacillus* spp. cultures are used for the biocontrol of *Fusarium graminearum* in wheat. Several isolates can effectively reduce the growth of *Fusarium graminearum* in vitro (Stumbriene et al., 2018). *Bacillus subtilis* strain E1R-j can be used for the biocontrol of powdery mildew *Blumeria graminis* in wheat under greenhouse conditions (Gao et al., 2015). E1R-j inhibited the development of conidia, haustoria, and the extension of mycelia of powdery mildew. Li et al. (2013) concluded that *Bacillus subtilis* strain E1R-j inhibited the uredospore germination and reduced the severity of yellow rust under greenhouse conditions.

Serenade ASO, produced by the company ‘Bayer CropScience’, is a biofungicide containing *Bacillus subtilis* strain QST 713 and is mainly used in Europe for *Botrytis cinerea* control in strawberries, lettuce, and a broad spectrum of vegetables. Serenade ASO can reduce the severity of yellow rust in winter wheat, but, for a better result, it should be used together with other products (Reiss & Jørgensen, 2017).

The results obtained are contradictory. The severity of yellow rust and efficacy of biological plant protection products varied between the years of research. More researches regarding biocontrol of yellow rust under field conditions are required.

Authors of this research proposed a hypothesis that the usage of biological plant protection products in winter wheat control the severity of yellow rust, the efficacy of each biological plant protection product is different.

The aim of this research was to investigate the possibilities for the biological control of yellow rust in winter wheat.

MATERIALS AND METHODS

A field trial was established for winter wheat variety 'Edvins' in a biological field in the southwest part of Latvia (Institute of Agricultural Resources and Economics, Stende Research Centre, 57.189493 N, 22.561066 E) in 2017 and 2018. Winter wheat 'Edvins' is moderately middle susceptible to yellow rust (V. Strazdina, personal communication, 2 April 2018).

Sample plots were randomized, and the size of each plot was 2.5 m width and 10 m length. The space between rows was 0.125 m and space between plots – 0.5 m in both years of research. The seeding rate was 200 kg ha^{-1} in 2016 and 250 kg ha^{-1} in 2017. Sowing date was 14.09. and seedling growth started at 23.09. in 2016. Sowing date was 07.09. and seedling growth started at 16.09. in 2017. The soil was suitable for wheat cultivation, and crop management was used according to the practice under the conditions of wheat production in Stende Research Centre. Wheat seed was not treated before the sowing. The field trials consisted of seven variants in four replications.

Several biological products were used for applications (Table 1), and one variant was left untreated as a control. Plant protection products were used according to the producer reference.

Table 1. Biological products used in field trials in 2017–2018

No.	Biological products	Active substance	Dosage, L ha^{-1}, in 2017	Dosage, L ha^{-1}, in 2018
1.	Untreated	-	-	-
2.	Serenade ASO	*Bacillus subtilis* QST 713 13.96 g L^{-1}	4.0	6.0
3.	Bactoforce	*Bacillus spp.*	4.0	6.0
4.	BactoMix	*Bacillus subtilis* D V-845 and V-843 D, *Pseudomonas aurantiaca*, *Brevibacillus*, *Acinetobacter*, 1.3 × 109 KVV/ml	4.0	6.0
5.	Albit	Poli-beta-hydroksybutyrate 0.62%, organic matter 22%, NPK 7.5-6-4.5	0.04	0.08
6.	ChitoPlant	Chitosan 99.9%	0.2 kg ha^{-1}	0.4 kg ha^{-1}
7.	Serenade ASO + ChitoPlant	*Bacillus subtilis* QST 713 1.34% + Chitosan 99.9%	4.0 + 0.2 kg ha^{-1}	6.0 + 0.4 kg ha^{-1}

The field trial was treated with biological products four times in 2017. As results in 2017 showed that the severity of yellow rust on flag leaf at the end of vegetation was high – 32.5% (Fig. 1), for more efficient yellow rust control it was decided to enlarge treatment times to six in 2018. Treatment dates and plant growth stages (GS) according to BBCH scale (Hack et. al., 1992) are shown in Table 2.

Table 2. Treatment dates and plant growth stages in 2017–2018

2017		2018	
date of treatments	GS	date of treatments	GS
28.04.2017	29–31	10.05.2018	31–33
08.05.2017	31–33	17.05.2018	37
18.05.2017	33–34	24.05.2018	41
29.05.2017	39	31.05.2018	55–57
		07.06.2018	65
		14.06.2018	73

The severity of yellow rust was assessed during the vegetation, starting from first symptoms until leaf yellowing and shrivelling at GS 79 (Table 3). The severity of yellow rust was assessed on 10 randomly selected leaves from each plot and expressed in percentages. Each leaf level was evaluated separately.

Meteorological conditions representing 2017 and 2018 are shown in Table 4. Average air temperature and amount of percipitation was determined.

Table 3. Assessment times and plant growth stages in 2017–2018

2017		2018	
Date of assessments	GS	Date of assessments	GS
14.06.2017	57–59	17.05.2018	37
20.06.2017	65	24.05.2018	41
27.06.2017	73–75	31.05.2018	55–57
05.07.2017	79	07.06.2018	65
		14.06.2018	73
		20.06.2018	75
		26.06.2018	77–79

Table 4. Meteorological conditions during the years of research (data from Stende Research Centre meteorological station)

	Average temperature, °C					Amount of precipitation, mm				
Month	I	II	III	average in a month	norm	I	II	III	in a month	norm
2017										
April	6.4	1.0	3.7	3.7	4.3	4.0	29.0	42.7	75.7	37.0
May	6.3	11.5	13.1	10.3	10.2	1.2	2.6	10.7	14.5	45.0
June	12.4	15.3	13.9	13.9	14.2	17.7	18.2	22.7	58.6	57.0
July	14.3	15.1	17.2	15.5	16.3	19.9	28.7	6.9	55.5	87.0
August	17.3	17.4	14.1	16.3	15.5	18.5	16.9	16.0	51.4	87.0
2018										
April	5.0	9.5	8.5	7.7	4.3	28.6	12.4	6.7	47.7	37.0
May	12.5	16.4	17.5	15.5	10.2	14.0	0.0	0.0	14.0	45.0
June	15.4	16.7	14.4	15.5	14.2	0.2	8.9	26.7	35.8	57.0
July	15.1	22.0	22.2	19.8	16.3	17.3	6.5	8.8	32.6	87.0
August	22.2	17.3	15.7	18.4	15.5	25.7	56.0	12.4	94.1	87.0

The impact of yellow rust was detected by calculating the AUDPC (area under the disease progress curve). It shows combined disease influence on plants during the vegetation (Simko & Piepho, 2012). The AUDPC was calculated using the formula (Simko & Piepho, 2012) (1):

$$A_k = \sum_{\mathrm{i}=1}^{\mathrm{N}_{i-1}} \frac{(y_i + y_{i+1})}{2} (\mathrm{t}_{i+1} - \mathrm{t}_i) \qquad (1)$$

where N is assessment times, y is disease severity at the moment of assessment, and $\mathrm{t}_{i+1} - \mathrm{t}_i$ is the time period between assessment times.

The effectiveness of biological products was calculated according to the formula (2):

$$\mathrm{T} = \frac{(k - v) \cdot 100}{k} \qquad (2)$$

where k is the severity (incidence, AUDPC) of the disease in the untreated variant, v is the severity (incidence, AUDPC) of the disease in the treated variant. Similar calculations has been made in Barro et al. (2017) research.

The yield and grain quality parameters (thousand kernel weight (TKW), g; protein content, %) were evaluated after the harvest.

For statistical analysis, 'MS Excel 2010' and 'R' programs were used. Correlation analysis, regression analysis, analysis of variance, analysis of covariance were used for the calculation of results.

RESULTS AND DISCUSSION

Peculiarities of the dynamics of the development of yellow rust was observed in untreated plots in both years of investigation. In 2017, the first symptoms of yellow rust were observed on 14.06. – on the second leaf of wheat GS 57. Six days later, on 20.06., yellow rust was found on the flag leaf of wheat GS 65. A rapid development of yellow rust during grain formation was observed (Fig. 1). Meteorological conditions in June 2017 (Table 4) were favourable for the development of yellow rust. Sufficient amount of precipitation (58.6 mm per month) and the average air temperature of 13.9 °C enabled yellow rust to grow and produce spores successfully. The identification of yellow rust was made according to well recognizable visual symptoms on wheat leaves. At the end of vegetation, at GS 79, the severity of yellow rust reached its maximum in untreated plots – 32.5% on the flag leaf and 24% on the second leaf (Fig. 1).

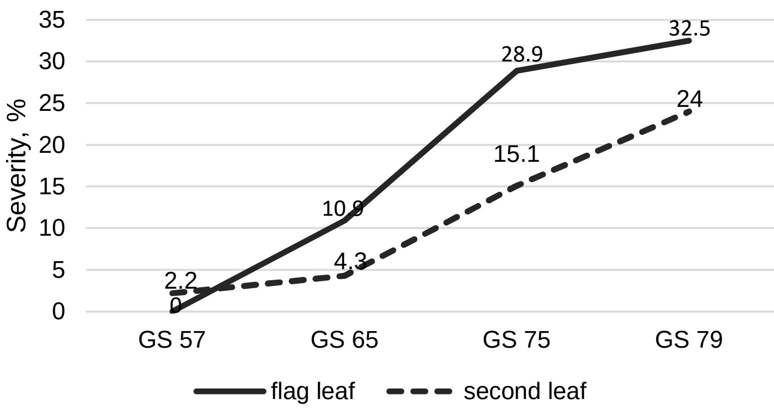

Figure 1. Severity of yellow rust on flag leaf and second leaf in untreated plots in 2017.

In 2018, the severity of yellow rust in untreated plots was lower compared to 2017. In 2018, the first symptoms of yellow rust were observed on the second leaf on 31.05. GS 55–57. Yellow rust for the first time was observed on the flag leaf on 07.06. GS 65. Meteorological conditions – lack of rain in the first and second ten-day period of May (Table 4) – were not favourable for the development of yellow rust. De Vallavieille-Pope et al. (1994) ascertained that dry period has a negative impact on spore germination.

After rainfall in the second and third ten-day period, the severity of yellow rust reached its maximum (6.5%) on the flag leaf in untreated plots (Fig. 2).

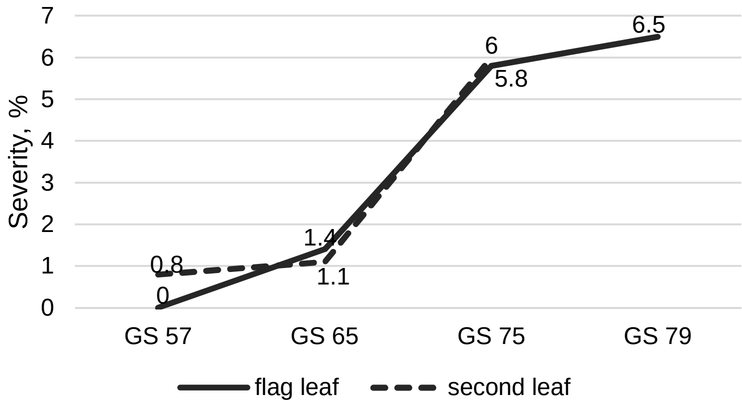

Figure 2. Severity of yellow rust on flag leaf and second leaf in untreated plots in 2018.

The AUDPC values were compared to assess the efficacy of treatments both in 2017 and 2018. Treatment with biological products did not significantly ($p > 0.05$) decrease the level of yellow rust. In 2017, a slight tendency to reduce the impact of yellow rust both on flag leaf and second leaf was observed by using the biological product 'Albit' at the dosage of 0.04 L ha^{-1}. The variant treated with 4.0 L ha^{-1} of 'BactoMix 5' exhibited the highest AUDPC value in 2017 (Fig. 3); in contrast, in 2018, the dosage of 6.0 L ha^{-1} of 'BaxtoMix 5' showed a tendency to reduce the impact of yellow rust (Fig. 4). Yellow rust migrates with the help of wind (Chen et al., 2014) and this could be a reason of irregular incidence of yellow rust in research sample plots. Irregular incidence of yellow rust could influence the efficacy of biological products.

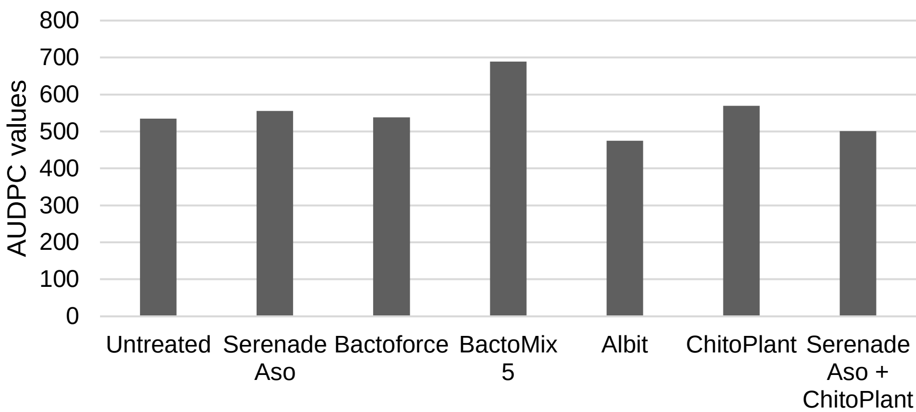

Figure 3. The development of yellow rust depending on biological control variants in 2017.

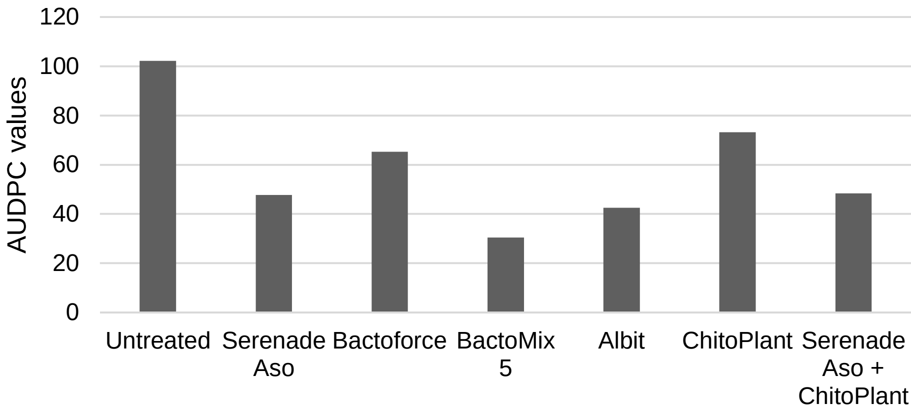

Figure 4. The development of yellow rust depending on biological control variants in 2018.

The effectiveness of biological products fluctuated depending on application scheme: from –28.9% to 11.8% in 2017, and from 35.5% to 70.04% in 2018 (Table 5). Reiss & Jørgensen (2017) concluded that for optimal yellow rust control, timing is significant – treatments at the day of inoculation or one day later promoted the best control. This could be the reason why the effectiveness of biological products in 2017 was low. In 2017, the treatments might have been carried out too early; biofungicide application on inoculation day would have increased the efficacy of biological products. Also, Li et al. (2013) concluded that *B. subtilis* is preventive and has curative properties in the early stages of the development of yellow rust.

Table 5. Efficacy % of biological products in 2017 and 2018

Biological products	Efficacy, %	
	2017	2018
Untreated	–	–
Serenade ASO	–3.4	53.13
Bactoforce	–0.77	35.5
BactoMix 5	–28.91	70.04
Albit	11.17	57.25
ChitoPlant	–6.59	27.92
Serenade ASO + ChitoPlant	6.22	52.60

The vitality of *B. subtilis* is influenced by biotic factors such as humidity and air temperature. Rainfall can wash the bacterium from wheat leaves. Increased application timing and the dosage of biological products in 2018 (Table 1) might have shown a better effect for yellow rust control.

Disease pressure influences the efficacy of biofungicides. In 2017, disease pressure was moderate (Fig. 1), with the effectiveness of products from –28.9% to 11.8%; whereas in 2018, when disease pressure was low (Fig. 2), product effectiveness varied from 35.5% to 70.0%.

Reiss & Jørgensen (2017) concluded that ‘Serenade ASO’ reduced the severity of yellow rust to 30% under high disease pressure and up to 60% under moderate pressure, compared to control.

The evaluation of yield, thousand kernel weight, and protein content in 2017 and 2018 showed no significant differences ($p > 0.05$) between treated variants and untreated ones. Data are not shown in this article. Reiss & Jørgensen (2017) obtained similar results – they found that the yield in treated plots was not signifficantly different from untreated although the treatments with Serenade ASO increased the yield to 1–7%.

This was the first research regarding the biocontrol of yellow rust under field conditions in Latvia. More and extended investigations are required to obtain long-term information about the biocontrol of yellow rust.

CONCLUSIONS

1. The severity of yellow rust in the untreated plots differed between the years of investigation.
2. The application of biological plant protection products did not significantly reduce the severity of yellow rust in 2017 and 2018.

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Controlled traffic farming delivers better crop yield of winter bean as a result of improved root development

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Abstract. This paper reports on the continuation of a long–term experiment on the effects of alternative field traffic systems (STP–random traffic with standard tyre inflation pressure, LTP–random traffic with low tyre inflation pressure and CTF–controlled traffic farming) on soil conditions and crop development as influenced by different tillage depths (DEEP–250 mm, SHALLOW–100 mm and ZERO–tillage), in a randomised 3 x 3 factorial design in 4 replicates launched by Harper Adams University in Edgmond, UK, in 2011. The results from season 2017–2018 revealed that CTF delivered 8% higher crop yield of winter field bean (*Vicia faba*) cv. *Tundra* comparing to STP ($p = 0.005$), i.e. 4.13 vs 3.82 tonnes ha^{-1} respectively (at 14% moisture content). The ZERO–tillage plots featured significantly lower plant establishment percentage comparing to shallow and deep tillage: 79% vs 83% and 83% respectively ($p = 0.012$). The research showed that roots traits differed significantly between contrasting traffic at depths greater than 50mm with $p < 0.05$ of: tap root biomass, number of lateral roots, biomass of lateral roots as well as total root biomass (tap+lateral roots), delivering significantly greater values of those before mentioned parameters on CTF comparing to STP. Tap root length significantly differed between traffic systems ($p < 0.001$) giving significantly greater results on CTF comparing to LTP and STP (17.7, 13.4 and 12.6 mm respectively). Significant differences in tap root diameter were found only at the depth of 100 mm ($p < 0.001$) where again CTF delivered significantly higher root diameter than the remaining 2 traffic systems.
In the shallow layer of soil (0–50 mm) a significant difference was found only for tap root biomass, for interactions, where STP ZERO gave significantly higher results than STP SHALLOW and CTF SHALLOW (1.430, 0.733 and 0.716 g respectively).

Key words: Soil compaction, random and controlled traffic farming (CTF), standard and low tyre inflation pressure, *Vicia faba*, root morphology.

INTRODUCTION

The demand of high crop yields due to increasing world population has resulted in agricultural intensification, which has been accompanied by an increase in machinery size and weight, thus soil has been subject to increasing degrees of compaction (Chamen et al., 2011).

The physical structure and functional properties of trafficked soil can be significantly different when compared to untrafficked soil as a result of increased soil compaction inhibiting root development, water availability, nutrient uptake and yields (Raghavan et al., 1979; Czyz, 2004; Chamen et al., 2011).

There are many causes of soil compaction identified by researchers, but most significant compaction is a result from farming vehicles traffic imposed via wheels pressure, since compaction is a result of stress upon the soil, and is related to load, tyre pressure and contact area (Soane & van Ouwerkerk, 1994; Raper et al., 1995).

Increased tyre inflation pressure increases contact pressure as a result of the reduced contact area. This was confirmed by Raper et al. (1995), who reported that rut depth increased with an increase of tyre inflation pressure, confirming the relationship between high inflation pressure traffic and greater vertical impact on the soil profile. Further works by Antille et al., (2013) confirmed that the least change in soil bulk density and vertical soil displacement was found for larger tyres with lower inflation pressure. Under inflating tyres, however is not the solution for compaction problems as tyres operated with inflation pressures below those specified by the manufacturers can be dangerous, have higher rates of wear and suffer an increased risk of failure (Smith, 2017). Raper et al. (1995) reported that the load is moved towards the edge of the tyre in case of under–inflated tyres, and as a consequence increases rolling resistance and manoeuvring in the field and on the road is more difficult.

The results of many studies on the effects of tyres pressure on soil degradation triggered the development of low ground pressure tyres and tracks (Alakukku et al., 2003). Since additional tyres mounted on the tractor caused problems with external width of a vehicle moving on a highway, tyres of larger volume but the same external diameter as the standard equivalent became an option (Michelin, 2018). Moreover, Michelin has developed a range of improved flexion tyres (IF) and of very high flexion tyres (VF) that are suitable for many agricultural machines. According to the manufacturer, these tyres feature even load distribution thanks to a wider footprint of the tractor wheel, which in turn offers increased soil protection and improves longevity and fuel and time efficiency (Michelin, 2018) and operate at lower inflation pressures.

Depending on crop and agronomy measures, the trafficked area i.e. the area covered by wheel marks, might reach up to 90% (Soane et al., 1980). Further surveys where global positioning system–tracking devices were applied revealed that random traffic farming practices, with conventional tyre inflation pressures, for wheat production covered some 86%, 65% and 45% of the field with at least 1 wheel–pass for conventional (plough based) tillage, minimum tillage and direct drilling/zero–till respectively (Kroulik et al., 2009).

Soil compaction results in the reduction of macro–porosity and in turn may limit root development (Rab et al., 2014), resulting in the reduction of crop yield (Czyz, 2004) The system of pores within the soil is essential for the transport of air, water and nutrients necessary for the growing plant (Eden et al., 2011). The analysis of soil pores structure (size and distribution) using X–ray Computer Tomography technique showed that soil percentage porosity is higher in untrafficked treatments. The porosity decreased with depth where the soil had been tilled to 250mm, and smaller soil pores were more frequent (Millington et al., 2018). The author reveals that shallow tillage treatments (100 mm) increased the percentage porosity with depth whilst providing the lowest soil penetration resistance.

The roots depth and their distribution are important features upon which water and nutrients uptake depend, particularly in areas of low rain (Manschadi et al., 1998) which could apply to this experiment in 2018 when the total rainfall in 3 months preceding harvest (May–July) was 72 mm, compared to a long–term average of 216 mm (Harper Adams University weather data for 2007–2017). During period with water insufficiency, the capacity of water uptake is related to the depths and the uniformity of roots system (Dardanelli et al., 1997). To avoid water stress in dry soil it is the root length density (mm root/ml soil) that plays a vital role (Tron et al., 2015).

Soil compaction as a result of farming traffic has been suggested as the main reason for crop yield penalty by many researchers (Raghavan et al., 1979; Horn et al., 2003; Chamen, 2011). The yield reduction on trafficked soil is related to restricted root growth and lower access to nutrients as a result of increased bulk density and reduced pore size in trafficked areas (Rab et al. 2014, Aguilera Esteban et al., 2019). This suggests that much could be gained from controlled traffic farming practices (CTF) where field operations are focused on predetermined wheel ways and equipment widths and wheel track spacing are matched (Tullberg et al., 2007). Thanks to the global positioning satellite guidance and auto–steer systems with real time kinetic (RTK) controlled traffic farming (CTF) has become practical and adopted by many farmers. CTF due to the reduction in number of wheel ways reduces soil compaction, consequently its potential advantages are: improved crop yields, improved soil conditions and infiltration of rainfall/irrigation water, reduced tillage and crop establishment draught forces/energy (Godwin et al., 2015). The experiment at Harper Adams University focused on traffic contrasted with 3 tillage systems revealed that CTF delivered higher crop yield than STP (Smith, 2017). This is in agreement with other research: Chamen et al. (2011) reported yield improvements between 7% and 35% for CTF, while Godwin et al. (2015) reported yield increases of between 7.3 –10% when controlled traffic farming was applied.

CTF however requires much investment in equipment mounted on a tractor necessary for precise guiding on permanent wheel ways. Godwin et al., (2017) concluded that the required breakeven area was 312 ha for 30% trafficked area and 168 ha in case of 15% of trafficked area.

Previously reported studies have focused on the farming traffic with one depth of tillage. To fill the gap in knowledge, a long–term experiment was established in 2011 on a uniform sandy loam field by Smith (2017) to determine the effects of farming traffic subject to three tillage depths. Since the launch of the experiment, the same vehicular traffic and tillage depth have been applied each year to the given treatment plot to ensure the long–term effects of contrasting systems might be studied. This paper reports on a continuation of that research and focuses on the effects of 3 traffic systems, namely random traffic with standard tyre inflation pressure (STP), random traffic with low tyre inflation pressure (LTP) and controlled traffic farming (CTF) contrasted with 3 different tillage depths (250 mm, 100 mm and zero tillage) on plant establishment, root morphology and crop yield of winter bean (*Vicia faba*) cv. Tundra. The crop was established in November 2017, samples were taken and analysed in spring and summer 2018.

MATERIALS AND METHODS

Location and site description

The experimental site is located on a field called Large Marsh, within the Harper Adams University campus in Newport, TF 10 8NB, Shropshire, United Kingdom. Its geo references are: 52°46'58.0"N 2°25'43.9"W. The total area of the field is 3.12 ha, which consists of the area of the experimental plots and the surrounding headlands.

The field lies at about 63 metres above mean sea level. The predominant soil type was identified as Claverley (Cvy), a very slightly stony sandy loam, with small areas of Olerton and Salwick series soils (Beard, 1988).

Before launching the experiment, the field had previously been managed with conventional soil and agronomic practices, with a cropping history of barley in 2009 and 2008 and grass in 2010. A sub–surface gravel back-fill land drainage system at 13 m intervals was installed in September 2011 and subsoiled to a depth of 0.45–0.5 m.

To ensure uniformity across the study, soil properties were examined in scope of bulk density, penetration resistance, electro conductivity, surface and sub-surface soil moisture as well as crop yield from the uniformity year. Once the site uniformity was confirmed, the 4–m wide plots were established in a randomised block design with an 8–furrow mouldboard plough and drilled with combination rotary harrow/drill. Crop spaying and fertilising takes place at 90 degrees to plots at 24 m spacing, creating permanent tramlines.

The crop rotation in this study was chosen to represent the range of crops grown in arable farming in UK with cereal as the main crop. As a break crop with oil seed rape was not feasible in this experiment, the winter barley in 2015 was followed by cover crop.

The crop rotation since the first harvest in 2012 is presented below, the year indicates the year of harvest:

2012 Winter wheat (uniformity year); 2013 Winter wheat; 2014 Winter barley; 2015 Winter barley, followed by a cover crop TerraLife-N-Fixx (DSV United Kingdom Ltd, 2015); 2016 Spring oat; 2017 Spring wheat; 2018 Winter bean.

The experimental field has been subject to many analysis focused on soil properties and most important findings are presented below to describe the field soil conditions.

Soil bulk density was measured in 2012, 2013, and 2015 in the permanent wheelways and between the wheelways by Smith (2017) and Millington (2019). The results from both studies suggested that soil bulk density significantly differed between traffic systems – and it was significantly lower on CTF in comparison to STP and LTP in the overall analysed 0–250 mm depth ($p < 0.001$). LTP didn't differ significantly from STP. Both researchers also suggested that the soil bulk density increased with depth ($p < 0.001$). Millington (2019) found that the BD on CTF increased from 1.2 mg m^{-3} in the top layer of soil (0–50mm) to 1.4 mg m^{-3} at the depth of 200–250 mm. On STP and LTP the value of BD ranged from 1.3 mg m^{-3} at the 0–50 mm depth to the maximum around 1.5 mg m^{-3} (for STP) and 1.53 (for LTP) at the 100–150 mm depth. It slightly decreased at the depth of 150–200 mm and again increased at the depth of 200–250 mm. Smith (2017) suggested that deep tillage featured significantly lower BD than shallow and zero tillage (1.57 mg m^{-3}, 1.66 mg m^{-3} 1.65 mg m^{-3} respectively ($p = 0.042$). Zero tillage had a significantly ($p = 0.007$) higher BD in comparison to deep and shallow tillage, but only at 100 mm depth (Smith, 2017). It was confirmed by Millington (2019) who revealed that zero tillage featured the highest BD in the shallow stratum (0–100 mm), nevertheless the results of BD between tillage systems didn't differ significantly. He also suggested that shallow tillage produced a tillage pan at 100–150 mm depth just below the depth of cultivation of 100 mm.

Soil organic matter content (SOM) in the soil profile 0–200 mm (loss on ignition method used) was measured by Wookey (2016) and Crawford (2019). Both studies suggested that traffic did not have a significant effect on SOM, however significant differences were found between contrasting tillage systems ($p = 0.005$). Wookey (2016) found that deep tillage featured significantly lower SOM content than shallow and zero tillage: 4.44%, 4.82% and 4.95% respectively. In agreement, Crawford (2019) reported significantly lower SOM on deep tillage comparing to zero (3.5% and 3.9% respectively), and shallow tillage with its 3.7% of SOM did not differ significantly from the remaining two systems.

The field saturated hydraulic conductivity analysis was conducted in 2016 and showed deep tillage was significantly higher than zero tillage ($K_{fs} = 2.42\ 10^{-5}$ and $7.13\ 10^{-6}$ respectively); shallow tillage with the result of $K_{fs} = 1.6\ 10^{-5}$ did not differ significantly from either of tillage systems (Abell, 2016). The same study found that hydraulic conductivity also differed significantly between traffic systems. CTF featured significantly higher result than STP ($2.64\ 10^{-5}$ and $5.52\ 10^{-6}$ respectively). LTP result ($1.55\ 10^{-5}$) was not found significantly different from CTF or STP.

Infiltration rate analysis showed significant differences between traffic ($p < 0.001$) and tillage ($p < 0.001$) systems (Abell, 2016). Mean infiltration rate on deep tillage was 14.15 mm h^{-1}, on shallow – 8.25 mm h^{-1} and on zero tillage – 4.61 mm h^{-1}. All three means were found significantly different. CTF featured significantly greater infiltration rate than trafficked wheelways (13.9 mm h^{-1} and 4.1 mm h^{-1} respectively).

Design replications and statistics

The experimental design is a 3 x 3 factorial in 4 complete randomized blocks (3 traffic x 3 tillage systems). Nominally the plots in block 1–3 are 4 m wide by 84 m long and in block 4–82 m long, however for operational reasons, the last plot in block 4 (plot 36) is only 78.2 m long.

Data was analysed by factorial analysis of variance ANOVA. Post–hoc test for significant differences of means was carried out with Tukey's test with 95% confidence (unless otherwise stated). All the statistical analysis was conducted with Genstat 18th Edition Software.

Crop and variety

The crop in season 2017–2018 was winter bean variety Tundra, sown on 10 November 2017. Thousand Grain Weight (TGW) = 720, seed rate 160 kg ha^{-1} with a 25% increase for the zero tillage plots. The seed placement depth was approximately 80 mm (after Millington, 2019).

Farm equipment and tyres

For the main farming tasks: tillage and drilling treatments and applying the effects of compaction caused by other field traffic events, a 290 hp Massey Fergusson 8480 tractor was used. The track width was 2.1 metres. The tractor was fitted with increased flexion AxioBib tyres (IF 600/70 R30 159D TL at the front, and IF 650/85 R38 179D, TL on the rear axle).

Tyres pressure were checked using a calibrated Newbow Ltd © tyre pressure gauge (NB604).

For the compaction treatment the tractor was fitted with additional load – 540 kg front weight and 1,400 kg on the rear linkage. The STP plots were driven with the tractor on standard pressured tyres, i.e. front tyres – 1.1 bar, rear tyres – 0.9 bar. On both – the CTF and LTP plots the tractor was operated with tyre pressures of 0.8 bar for both front and rear axles (Michelin, 2013).

Tyres for tillage operation were inflated to 1bar both – front and rear for STP plots, while for CTF and LTP to 0.7 bar on the front axle and 0.8 bar on the rear axle. For the tillage operation, only the front ballast of 540 kg was applied, as part of the cultivator's weight was applied to the rear axle.

The tyre pressures were reflecting the common farming practice for this type of increased flexion tyres applied in farming. Low tyre pressure for CTF and LTP plots was adjusted to be the lowest tyre inflation pressure possible whilst maintaining traction and protecting tyre performance (Michelin, 2013).

The tillage operations were conducted with a multipurpose Vaderstad, Top-Down cultivator, which can be adjusted for both shallow and deep tillage.

The navigation of the tractor was provided by an in-vehicle auto-steer system Trimble FmX connected to a Trimble EZ-Steer steering system.

Vaderstad Spirit pneumatic seed drill has been used for drilling the crop. For ZERO tillage plots the tines and discs were lifted to avoid additional soil disturbance.

For harvest a Claas Dominator combine was used with a 4–m header, matching the plots size (after Smith, 2017 and Millington, 2019). To assess the grain weight/plot, an external hopper was hung on a load cell carried by a JCB tele handler.

Compaction treatment

This experiment was designed to apply additional traffic to obtain the trafficked area reported by Kroulik et al. (2009), who determined the percentage of total wheeled area depending on tillage practice. To mimic those values, additional traffic was precisely applied on each plot with Trimble RTK satellite navigation system. The compaction protocol included offsets of the vehicle from the centre of each plot (600 and 1,200 mm) to apply the additional traffic passes. Since the launch of the experiment the vehicular traffic on the plots have been applied in the same patern. As a result of comparatively narrow plots and constant wheeling width, as well as limitation with offset to avoid extra traffic applied on adjacent plots, the area repeatedly trafficked did not exactly achieve the figures from the work of Kroulík (2009).

Following the protocol established by Millington, (2019), the compaction treatment was split to 3 sequences which allowed to achieve the trafficked area of approximately:

75% on STP and LTP plots with DEEP tillage;

60% on STP and LTP plots with SHALLOW tillage;

45% on ZERO tillage plots;

30% on CTF plots- as a consequence of permanent wheelways for tillage and seeding operations. No additional compaction treatment was applied on CTF plots.

Tillage

Tillage was applied with the implement set for 250 mm for deep and 100 mm for shallow tillage plots. The tillage depth was checked with a ruler in the tine slot. Tyres pressures were set accordingly as described above.

Drilling

To facilitate combine navigation and to prevent harvesting the crop from the adjacent plot the 2 outermost coulters of the 24–coulter drill were blocked to ensure easily identified gaps between the plots. The row spacing is 167 mm. Wheel mark eradicator tines were lifted on zero tillage plots, while on the remaining plots they were in use. Tyres inflation pressures were set accordingly.

Plant establishment

For the plant count a transect 5 m wide was established across all plots, at a distance about 0.5 m from the third tramline to the north, apart from plot 36 which was scrutinised towards the south due to unexpected weed patch at the end of the plot. The plant count was conducted on 26 March 2018, in such a way that for each plot several high resolution (9.6 Megapixels) photographs were taken, from above the centreline to the right, and to the left, always keeping the centreline label as well as the corner labels visible. The plant count was then undertaken using the photographs.

Root collection and analysis

The roots sampling took place on 29th May 2018. The bean was in the stage of full flowering (stage 66 BBCH) to ensure fully developed roots. Beforhand, a preliminary trial was conducted on the headland to determine the depth of rooting. The samples were excavated from the ground using a spade and a fork according to the bean shovelomics methods (Bean shovelomics, 2018). The tools were dug into the soil perpendicular to the surface ensuring enough distance from the sample of at least 25 cm from the stem in each direction. If there was another plant growing within the distance to avoid damaging the root system of a chosen plant, the adjacent plant was collected together with the chosen sample and soaked in water. Once the soil was soft enough the additional plant was discarded. One plant (sample) was collected from each plot at a distance of approximately 1 m to the north of the first sprayer line, which ran perpendicular to the direction of the plots. Samples from the LTP and STP traffic plots, were taken from the primary wheelways; while samples from plots representing CTF traffic were taken from the middle of a plot (between the wheelways) representing un–compacted soil.

The roots were washed, measured and counted in two depths: 0–50 mm and > 50 mm, the tap root diameter was measured at the soil surface and the depth of 100 mm. Once all measurements were conducted, the roots were placed in perforated plastic bags in an oven set to 80 °C to determine the dry biomass (Jones, 2001). The analysis was split into lateral roots and tap root at the above–mentioned depths. The overall analysis of total root dry biomass was also carried out.

The diameter and length of roots was measured with electronic callipers and a ruler respectively. The number of lateral roots was taken as a result of cutting off all lateral roots (from a given depth of tap root) with scissors and counting them manually.

The roots were analysed in terms of tap root diameter, length, biomass, and for lateral roots: number and biomass.

Combine harvest

Combine harvesting took place on 10th August 2018. The combine harvester's header matched the width of the plots (4 m). It operated in the same direction for all plots and the grain yield was weighed; subsequently a sample for hectolitre weight was taken.

Further sample were taken from each plot for moisture content analysis and placed in airtight containers.

RESULTS

Plant establishment percentage

Table 1 shows the plant establishment percentage which was found significantly different for tillage ($p = 0.029$) and interactions ($p = 0.012$, $CV = 5.6\%$) while for traffic significant differences were visible with reduced confidence level ($p = 0.061$).

Accepting this lower confidence level, CTF resulted in significantly higher plant establishment percentage than STP. For tillage, ZERO tillage plots featured significantly lower plant establishment percentage than SHALLOW and DEEP. For interactions ZERO STP featured the lowest establishment percentage while SHALLOW STP and DEEP CTF– the highest; the remaining interactions did not differ significantly one from another.

Table 1. Plant establishment percentage (number of plants established as a percentage of seeds sown) of winter bean for 3 tillage and 3 traffic systems as well as for interaction between tillage and traffic system. Significant differences between means are represented by different letters

Plant establishment percentage		
Tillage (93% confidence intervals)	Mean	
ZERO	79%	a
DEEP	83%	b
SHALLOW	83%	b
Traffic (94% confidence intervals)	Mean	
STP	80%	a
LTP	81%	ab
CTF	84%	b
Interactions Tillage.Traffic (95% confidence intervals)	Mean	
ZERO STP	73%	a
DEEP LTP	79%	ab
ZERO LTP	81%	ab
DEEP STP	81%	ab
SHALLOW CTF	82%	ab
ZERO CTF	82%	ab
SHALLOW LTP	83%	ab
SHALLOW STP	86%	b
DEEP CTF	89%	b

Root analysis

Statistical analysis revealed that significant differences (with $p \leq 0.05$) of roots characteristics were found for contrasting traffic systems as well as for interaction between traffic and tillage. There was no significant difference found of any root characteristics for contrasting tillage systems *with* $p \leq 0.05$.

Most of the roots characteristics revealed significant differences in the deeper layer of soil (> 50 mm) only. In the shallow stratum (0–50 mm) as well as total across both depths, only tap root biomass featured significant differences for interactions between traffic and tillage ($p < 0.015$; $CV = 27\%$): ZERO STP delivered almost 100% greater result than SHALLOW CTF and SHALLOW STP, Table 2.

Table 3 presents that across both depths (0–50 mm and > 50 mm), tap root biomass delivered significantly different results for interactions ($p = 0.016$, $CV = 29\%$). Tukey's test with confidence at 93% revealed that DEEP CTF featured significantly greater (over twice) tap root biomass, than SHALOW STP.

Table 2. Average tap root biomass (g) of winter bean at 0–50 mm stratum for interactions between 3 traffic and 3 tillage systems. Significant differences between means are represented by different letters

Tap root biomass at 0–50mm stratum		
Interactions Tillage. Traffic (95% confidence intervals)	Mean	
SHALLOW CTF	0.72	a
SHALLOW STP	0.73	a
DEEP STP	0.98	ab
DEEP LTP	0.99	ab
ZERO CTF	1.01	ab
ZERO LTP	1.04	ab
DEEP CTF	1.20	ab
SHALLOW LTP	1.24	ab
ZERO STP	1.43	b

Table 3. Average total tap root biomass (g) of winter bean across both depths: 0–50 mm and > 50 mm for interactions between 3 traffic and 3 tillage systems. Significant differences between means are represented by different letters

Total tap root biomass (across both depth)		
Interactions Tillage.Traffic (93% confidence intervals)	Mean	
SHALLOW STP	0.89	a
SHALLOW CTF	1.10	ab
DEEP STP	1.13	ab
DEEP LTP	1.20	ab
ZERO LTP	1.49	ab
ZERO CTF	1.61	ab
ZERO STP	1.71	ab
SHALLOW LTP	1.76	ab
DEEP CTF	1.86	b

At the depth > 50 mm, significant differences between contrasting traffic systems were found for: biomass of tap root (*p = 0.002, CV55%),* biomass of lateral roots (*p = 0.005*, *CV = 57%*), total (tap + lateral) root biomass (*p = 0.002*, *CV = 52%*) as well as number of lateral roots (*p = 0.03, CV = 36%*), giving significantly higher results for CTF than STP, delivering the below described results.

Table 4 shows that at the depth > 50 mm, tap root biomass was over two times greater on CTF than STP and LTP did not differ significantly from the two other traffic systems.

The results given in Table 5 show that the CTF treatments resulted in over 100% greater lateral root biomass than STP and over 67% greater than LTP. The LTP did not differ significantly from STP.

Table 4. Mean tap root biomass (g) of winter bean at the depth > 50 mm for contrasting 3 traffic systems. Significant differences between means are represented by different letters

Tap root biomass at the depths > 50 mm		
Traffic (95% confidence intervals)	Mean	
STP	0.19	a
LTP	0.39	ab
CTF	0.55	b

Table 5. Means of lateral roots biomass (g) of winter bean at the depth > 50 mm for contrasting 3 traffic systems. Significant differences between means are represented by different letters

Lateral roots biomass at the depth > 50 mm		
Traffic (95% confidence intervals)	Mean	
STP	0.23	a
LTP	0.31	a
CTF	0.52	b

Table 6 shows that the total roots biomass (tap+lateral) from the CTF treatment was more than twice of that from the STP, and LTP's result was not significantly different from the two other traffic systems.

Table 7 shows that CTF treatments resulted in 53% greater number of lateral roots, in comparison to STP. LTP didn't differ significantly from two remaining traffic systems. Number of lateral roots also significantly differed for interactions: ZERO STP gave significantly smaller result than DEEP CTF, while the remaining interactions didn't differ significantly one from another.

Significant differences between tap root diameter for contrasting traffic treatments were revealed only at the depth of 100 mm with $p < 0.001$, $CV = 49.9\%$. Tillage or interactions did not have significant effect on this feature. The results in Table 8 show that CTF resulted in significantly greater tap root diameter over the remaining 2 other traffic systems; LTP and STP didn't differ significantly one from another.

Tap root length differed significantly between traffic systems with $p < 0.001$, CV 20.7%. Table 9 shows that CTF treatments featured the greatest tap root length which differed significantly from STP and LTP and was over 40% and 35% longer. LTP and STP didn't differ significantly one from another.

Table 6. Means of total roots biomass (g) of winter bean, at the depth > 50 mm for contrasting 3 traffic systems. Significant differences between means are represented by different letters

Total (tap+lateral) roots biomass at the depth > 50 mm		
Traffic (95% confidence intervals)	Mean	
STP	0.42	a
LTP	0.71	ab
CTF	1.07	b

Table 7. Average number of lateral roots of winter bean at the depth > 50 mm for contrasting 3 traffic systems and interactions between 3 traffic and 3 tillage systems. Significant differences between means are represented by different letters

Number of lateral roots at the depth > 50 mm		
Traffic (95% confidence intervals)	Mean	
STP	26.3	a
LTP	32.6	ab
CTF	40.3	b
Interactions Tillage. Traffic (95% confidence intervals)	Mean	
ZERO STP	19.5	a
DEEP LTP	23.3	ab
DEEP STP	24.5	ab
SHALLOW CTF	29.0	ab
ZERO LTP	33.3	ab
SHALLOW STP	34.8	ab
SHALLOW LTP	41.3	ab
ZERO CTF	42.8	ab
DEEP CTF	49.0	b

Table 8. Mean tap root diameter (mm) of winter bean at 100 mm depth for contrasting 3 traffic systems. Significant differences between means are represented by different letters

Tap root diameter (mm)		
Traffic (95% confidence intervals)	Mean	
STP	1.4	a
LTP	1.7	a
CTF	3.4	b

Table 9. Mean tap root length (mm) of winter bean for contrasting 3 traffic systems. Significant differences between means are represented by different letters

Tap root diameter (mm)		
Traffic (95% confidence intervals)	Mean	
STP	1.4	a
LTP	1.7	a
CTF	3.4	b

Combine harvest data

The yield of winter bean significantly differed between contrasting traffic systems (*p = 0.005*, *CV = 5.3%)*, with no significant differences between tillage or interactions. Fig. 1 shows that the CTF treatment produced 8% higher yield than STP. The LTP did not differ significantly from the remaining two systems.

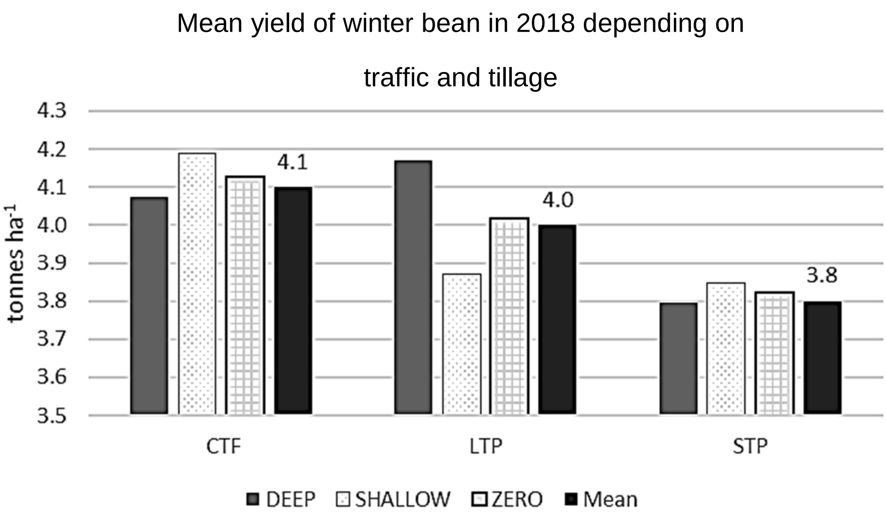

Figure 1. The mean yield of winter bean cv. Tundra in 2018 depending on 3 traffic and 3 tillage systems. The number above the black bar indicates the mean yield from each traffic system.

Discussion

There are many factors that can affect plant establishment and root growth, such as soil bulk density, oxygen and nutrients availability (Soane and van Ouwerkerk, 1994; Fan Jian Ling et al., 2016). The results from this work confirm that soil compaction as a result of field traffic affects root growth, plant establishment percentage and yield, and is in agreement with results from many studies. The winter bean crop is vulnerable to compaction thus the significant differences are visible between different traffic treatments, and is in agreement with Arvidsson and Håkansson (2014) who concluded that dicotyledons are more sensitive to compaction than monocotyledons. The lowest plant establishment percentage on ZERO tillage plots might be a result of water logging and oxygen deficit as concluded by Boone (Soane & van Ouwerkerk, 1994).

It is important to highlight that while the overall growing season was dry which possibly reduced the overall yield of the crop, the total precipitation from crop establishment (November 2017) until the root sampling (end of May 2018) was slightly higher than the average for preceding 10 years for the same period (397 mm vs 388 mm long-term average) which suggests that the root growth would not be subject to any greater water stress than normal.

The observed largest tap root diameter at the depth of 100 mm were found in the least compacted soil i.e. CTF. On average CTF tap root diameter at 100 mm below the soil surface is almost twice that of the LTP treatment and almost two and a half times larger in diameter than the STP traffic system. This characteristic is highly correlated with the tap root length, as a number of samples from STP and LTP failed to reach that depth, thus their diameter was zero. Shortening of roots in highly compacted soil is in agreement with Głąb (2008) who found out that tractor traffic resulted in shortening of roots of lucerne (*Madicago sativa*), as well as in agreement with Chen et al., (2014) who observed that the root system of narrow-leafed lupin on compacted soil in Australia was characterised by a short and thickened taproot.

Among 6 roots characteristics analysed, only tap root biomass at the shallow stratum (0–50 mm) delivered significantly different results. The remaining features showed differences in the deeper stratum only (> 50mm). This is in agreement with Głąb, (2013) who showed that significant differences between roots traits of grass and clover mixture as a result of soil compaction and fertilization were only found at depths greater than 50 mm.

ZERO STP delivered highest tap root biomass, what is in agreement with Materechera et al. (1991) who found out that in strong soil elongation of roots is reduced, however the diameter increases. Muñoz-Romero et al. (2011) concluded that no-till featured significantly greater results of length and diameter of *Faba bean* than conventional ploughing. Hettiaratchi (1990) suggested that thickening of roots in strong soil is a result of a mechanism of overcoming limiting axial stress by loosening the soil at the root tip.

CTF featured significantly greater roots biomass for both tap and lateral roots as well as for number of lateral roots at the depth greater than 50 mm, in agreement with Głąb (2013) who reported highest root biomass from uncompacted soil but contradicts another study of the same author (Głąb, 2008) who found out that Lucerne's roots biomass increased with an increase in soil density. The higher root biomass found within CTF resulted from better root penetration in uncompacted soil and possibly better oxygen availability as suggested by Czyz (2004).

The significantly higher yield of winter bean delivered on CTF plots was 8% higher than on STP which agrees with other studies that report yield increases of between 7.3–10% when controlled traffic farming was applied (Lamers et al., 1986; Li et al., 2007; Chamen et al., 2011; Godwin et al., 2015; Godwin et al., 2017). Soil compaction as a result of field traffic has been suggested as the main reason for crop yield penalties by many researchers (Raghavan et al., 1979; Horn et al., 2003; Kroulik et al., 2009; Chamen et al., 2011; Chyba, 2012). The yield reduction on trafficked soil is related to restricted root growth and lower access to nutrients as a result of increased bulk density and reduced pore size in trafficked areas. Results from the same experiment collected by Smith (2017) and Millington (2019) confirmed that across 5 years of observations, CTF has delivered higher yield than STP, however the differences between the means were statistically significant for 2 seasons/crops: winter wheat in 2013 with $p = 0.073$ and for spring oat in 2016 with $p = 0.057$ (Millington, 2019).

The highest yield from CTF plots may have resulted from a greater number and length of roots which allowed the plants to uptake more water in comparatively dry months (May–July) preceding harvest (August). The total precipitation in these 3 months was m, compared to a long-term average of 216 mm (Harper Adams University weather data for 2007–2017). Bond et al. (1994) found that *Faba bean* is very sensitive to water stress particularly when filling pods. This could explain why the CTF benefited the most from the well-developed roots and why ZERO tillage despite comparatively high number of plants at the beginning of the season, delivered lower yield. For logistical reasons, following the early harvest, due to the dry summer any soil moisture analysis was delayed until 3rd October 2018 after 132 mm of rain. This analysis revealed that the ZERO tillage plots had a significanly lower (*p = 0.005)* gravimetric soil moisture content compared to SHALLOW and DEEP tillage (15.2%, 16.7% and 17.1% respectively). These correspond to soil water potentials in the range of -20 kPa to -10 kPa, for typical sandy loam soils in the UK (Hall et al., 1977) where the field capacity soil water potential is considered to be -5 kPa.

LTP resulted in greater crop yield by 5% comparing to STP (4.020 t ha^{-1} and 3.821 t ha^{-1} respectively), albeit the result was not found to be significantly different. The result is in line with the results from previous years from Large Marsh and Illinois experiments (Shaheb et al., 2018), where LTP delivered higher yields than STP. The Large Marsh 2013–2017 results revealed that LTP gave greater yields than STP, however the means of yields were not significantly different (with $p < 0.05$) from STP or CTF. The experiment in Illinois focused on different tyres pressures (Shaheb et al., 2018) and revealed significantly greater yields of corn in 2017 by 4.31% ($p = 0.005$) and in 2018 by 2.8% ($p = 0.019$) and of soybean in 2018 by 3.7% ($p = 0.021$) when comparing LTP to STP.

The reason for lack of significant differences between LTP and STP might be high soil moisture on the date of soil compaction treatment (3rd October 2017) before the crop was drilled causing the soil susceptible to compaction. The precipitation in the preceding month (total for Sept. 69 mm) was much higher than the average in previous 4 years (2013–2016 average for Sept. was 28 mm) (Harper Adams weather data). Moist soil is more vulnerable for soil compaction (Sohne, 1958) so the soil was posed to the stress that exceeded its strength, regardless the low tyre inflation pressure. On the other hand, LTP did not differ significantly from CTF, therefore leading to a conclusion that LTP might be a simple practical mitigation measure for soil compaction, agreeing with Godwin et al. (2015), who suggested that 'low ground pressure systems for wheel loads up to a maximum of around 5 t can offer farmers an alternative to controlled traffic.'

CONCLUSIONS

1. Controlled traffic farming resulted in significantly better plant establishment percentage, improved root development and greater yield of winter bean, in comparison to random traffic farming with standard tyre presures.

2. The type of tillage system and its interactions with the traffic system had no significant effect on the crop yield.

3. The significant differences between roots traits were observed mainly at depths greater than 50 mm. The total root biomass, tap root biomass, number of lateral roots, and biomass of lateral roots deeper than 50 mm of the winter bean crop, were significantly higher for the controlled traffic farming, in comparison to random traffic with standard tyre pressures.

4. Tillage systems did not result in significant differences between roots characteristics, only traffic and interactions between traffic and tillage. The tap root biomass in the shallow stratum of soil (0–50 mm) was significantly greater for zero tillage together with random traffic and standard tyre pressures in comparison to shallow

tillage contrasted with random traffic with standard tyre pressures as well as with controlled traffic farming.

5. Controlled traffic farming subject to deep tillage gave significantly greater tap root biomass at both depths (0–50 mm and > 50 mm) than random traffic farming with standard tyre pressures.

6. Plant establishment percentage, root development and crop yield of the low tyre pressure treatments was greater but not significantly different from the standard tyre presures treatments.

7. Zero tillage delivered significantly lower plant establishment percentage in comparison to deep and shallow tillage.

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Conversion of an industrial cutaway peatland to a *Betulacea* family tree species plantation

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Abstract. To evaluate the potential of establishing a deciduous tree plantation on an industrial cutaway peatland over an 8 ha large experimental site was established in the central part of Latvia and silver birch (*Betula pendula* Roth) and black alder (*Alnus glutionsa* (L.) Gaertn.) tree species were planted. As it is a harsh and unfavorable environment wood ash, otherwise a waste product, was used as a fertiliser and liming material in three applications (5, 10 and 15 t ha^{-1}). In comparison with control, fertilised soils had higher Ca, Mg, P amounts, whilst the most substantial difference was seen in the amount of K. Application of wood ash also considerably increased soil pH from 3.5 (Control) to 5.9 (15 t ha^{-1}). Even though showing reduced growth in unfertilised soil both alder and birch seedling survival rate was higher than 80%. The highest survival rate for birch was under wood ash treatment, while alder under 10 t ha^{-1} wood ash fertiliser treatment showed the lowest survival rate i.e. 81%. In total, more than 60 naturally occurring vegetation species were observed in the first and the second year of sites establishment after fertilisation. Species as *Betula pendula*, *Betula pubescens*, *Populus tremula*, *Pinus sylvestris*, *Salix* spp. often occurred from natural vegetation regeneration. Already after one year of vegetation succession increase in tree and shrub species cover was observed, suggesting perhaps such areas can be naturally afforested thus creating a more heterogeneous forest stand. In such a way sustaining economic use of land resources after peat extraction while providing other ecosystem services.

Key words: afforestation, drained peatland, wood ash fertilization.

INTRODUCTION

Peatlands are estimated to cover 2.84% of total land area, yet they are important part of carbons cycle storing about one third of world's total soil carbon (Yu et al., 2010; Xu et al., 2018). In many countries peat is also an important resource extracted for fuel or horticulture (Karofeld et al., 2017). Peat extraction process greatly changes the ecosystem. Prior the extraction hydrological conditions in the peatland are altered by drainage and melioration system establishment that can further result in leaching of nutrients (Laiho & Laine, 1995; Leupold 2004). Extraction process itself causes major changes, from removing the existing vegetation, that in turn causes increase in greenhouse gas emissions, elevated fire risks, erosion and degradation of biodiversity, to increased peat density due to the pressure of heavy machinery, that further changes regulatory functions of the peatland (Wichtmann et al., 2016; Leifeld & Menichetti

2018). In Latvia, after the extraction it is required by law to mitigate the inflicted and prevent further environmental damage by undertaking some form of restoration or reclamation measures (Karofeld et al., 2017). Restoring the cutaway area to a peatland is the most suitable option for maintaining biotope diversity. Due to technical or economic limitations it is not always possible to restore the field to similar conditions prior the peat extraction, mainly due to ongoing peat extraction (Joosten et al., 2015). In such cases an alternative can be to extend the use of the peatland for economical purposes by growing plants, simultaneously providing ecosystem services and increasing carbon sink. Afforestation is one of the economically and environmentally justified recultivation options (Laasasenaho et al., 2017). We evaluate the possibility to utilize cutaway peatlands to grow deciduous tree species. Silver birch and black alder were selected as typical economically important deciduous tree species for Latvia that are tolerant to fluctuating hydrological conditions (Bebre & Lazdiņa, 2017). Silver birch is naturally occurring in peatlands and black alder is water demanding species that is adapted to anaerobic soil conditions, thus showing potential to successfully grow in peatland soils (Claessens et al., 2010). Due to nitrogen fixing properties of black alder, it is also suited to serve as nurse plant for other tree species (Mangalis, 2004).

There are challenges that need to be addressed in order to successfully afforest a cutaway peatland. Low pH and limited mineral element availability is characteristic to peatlands (Lazdiņa et al., 2011). This in turn leads to nutrient deficiency and reduced biomass production of planted trees. It can become apparent shortly after planting or in long term, when trees have depleted the reserves that were originally present in peat (Black et al., 2017). To ameliorate these harsh conditions, wood ash can be used as liming material and fertiliser (Demeyer et al., 2001; Jacobson, et al., 2004; Augusto et al., 2008; Libiete et al., 2016). Woody biomass is important source of energy in most Northern countries, including Latvia. Wood chip use has been increasing in Latvia, thus providing waste product – wood ash in large quantities as potential resource (CSB, 2018). Wood ash has positive effect on mineralization processes in organic soil and contains bioavailable macro and micro nutrients crucial for tree development that are often lacking in peatland soil, such as K, P, Ca, Mn and Mg. However, N evaporates during incineration process and it might be necessary to add it as additional fertiliser, since it is often not present in adequate amount in bioavailable form in peat soil (Saarsalmi et al., 2012; Brais et al., 2015). Studies have shown positive effect of wood ash on tree growth in especially unfavorable conditions (Huotari et al., 2008; Moilanen et al., 2013; Lazdina et al. 2017; Ots et al. 2017), yet some studies find only short-term positive effect (Brais et al., 2015). In this study we look at impact of wood ash in different application dosages on early growth and survival of silver birch and black alder saplings as well as treatment effect on natural afforestation process. Natural afforestation and regrowth of vegetation is relatively slow in most cutaway peatland sites, but can be promoted by fertilising. Vegetation cover plays an important role in mitigating erosion and leaching of nutrients (Huotari et al., 2011). Often overlooked is the fact, that vegetation can store more C than young trees (Huotari et al., 2009). We looked at species composition of naturally occurring vegetation, especially trees and shrubs, in first and second vegetation season after site establishment and fertilisation.

The objective of this study was to evaluate survival and growth of birch and alder tree species and natural vegetation regeneration in a cutaway peatland, as well as to determine whether fertilising such area with wood ash is beneficial.

MATERIALS AND METHODS

Study site

Study site is located in central Latvia (N 56°.43'.41.35'' E 23°.34'.39.61'') in a cutaway peatland where active peat extraction is still happening in other parts of the peatland. Total study site area is 8 ha and it can be considered as marginal land due to unfavorable soil structure. Peat layer after extraction was left 50 cm or thicker.

Prior the establishment of the plantations, study site was cleaned of covering vegetation, mostly trees and reeds. To stabilize hydrological conditions, contour ditches were cleaned and the peat acquired in the process was dispersed across study site. Reeds had to be cut each year, due to competitiveness with planted trees.

Study design

Wood ash was wetted, dispersed and mixed in to the top layer of peat. Based on other study results three doses of wood ash (5, 10 and 15 t ha^{-1}) were chosen and applied in three repetitions (blocks) (Ernfors et al., 2010; Huatori et al., 2011; Lazdiņa et al., 2013; Huatori et al., 2015; Ots et al., 2017). Three repetitions with no treatment was set as control (Fig. 1). Wood ash on a dry mass basis consisted of 24.7 potassium (K), 18.2 magnesium (Mg), 120.4 calcium (Ca), 6.6 phosphorus (P) g kg^{-1}.

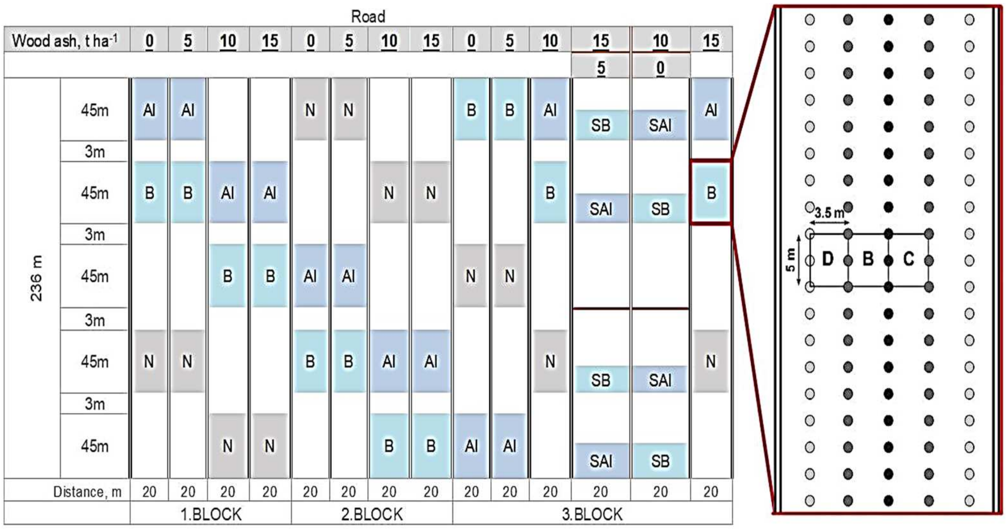

Figure 1. Design of the study site (left) and design of plot (right) with sub-plots (D – near contour ditch, B – in between, C – in the centre of the plot). Al – black alder; B – silver birch; N – natural regeneration; SAl – sown black alder; SB – sown silver birch. 0, 5, 10 and 15 – dosage of wood ash applied (t ha^{-1}). Dots represent individual trees and double lines represent contour ditches.

In spring of 2017 silver birch and black alder (288 per plot or if drainage system is not accounted for 1,142 trees per ha) containerized seedlings were planted in 40 x 45 m large plots between the contour ditches. A distance of 2.5 m was left from the ditch and trees were planted in 5 rows with 3.5 m distance between the rows and 2.5 m between the trees. In addition, twelve plots were left unplanted for natural regeneration.

To estimate the viability of regeneration by sowing, in the spring of 2018 black alder and silver birch were sown in 4 plots each. Three unchilled seeds per planting spot were chosen for black alder and five seeds for silver birch and manually sown in the top 1 cm of the soil.

Soil analysis and chemical properties

To better describe the conditions in the experimental field and to be able to draw broader conclusions from the results, soil samples were collected at the beginning of the second growing season. Three soil samples per wood ash treatment were collected from the centre of the plot from the top 10 cm soil layer. Samples were analysed according to Bardule and co-workers (2013) described methodology.

Data collection

Survival and height of planted trees was measured at the end of 2017 and 2018 year in each plot and each row from 6th to 14th tree (in total 1,080 trees were surveyed).

Vegetation cover was evaluated at the end of the summer of 2017 and 2018. Vegetation composition was determined within each plot in three sub-plots 5 x 3.5 m each, 108 sub-plots in total (Fig. 1). Naturally occurring herbaceous, moss and woody species were noted as present or absent, since relative cover per species (with occasional exceptions) was below 10 percent of the sub-plot area. In each plot one sub-plot was located near contour ditch (D), one in between (B) and one in the centre of the plot (C). Species affiliation to perennials, annuals or biennials as well as weeds, woody species and monocotyledon was noted. Due to unfavorable growing conditions, some plants were lacking the typical characteristics for the species and were identified only to subspecies level.

Data analysis

R version 3.5.1 (R Core Team, 2018) was used for statistical analyses. Generalized linear models (binomial and Poisson) were used to evaluate species richness and planted tree survival difference between treatments and control and species richness differences depending on sub-plot location in relation to contour ditch.

For the *analysis of variance (ANOVA)* height was set as the numeric variable and tree species, wood ash dose and location was used as factors. Afterwards package 'car' (Fox & Weisberg, 2011) function Anova with type 'III' was used to account for the unbalanced design. Tukey's HSD test used for pairwise comparison. Damaged trees were not included in the analysis.

RESULTS AND DISCUSSION

Soil chemical properties

Fertilisation with wood ash impacted pH and the amount of all of the measured nutrients (see Table 1). After wood ash application on a cutaway peatland similar changes in soil pH (Moilanen et al. 2012) and K concentration (Kikamägi et al., 2013), Ca an Mg concentration (Mandre et al., 2010) and in the top layer have been observed.

Table 1. Chemical properties and available nutrients of soil with a different dose of wood ash, ± standard deviation

Wood ash dose, t ha^{-1}	pH_{CaCl2}	C_{total}, g kg^{-1}	N_{total}, g kg^{-1}	P, g kg^{-1}	HNO^3 method of extraction		
					K, g kg^{-1}	Mg, g kg^{-1}	Ca, $g^{-1}g$
0	3.52 ± 0.02	554.6 ± 10.7	16.2 ± 2.2	0.24 ± 0.01	0.07 ± 0.01	1.0 ± 0.18	11.1 ± 0.3
5	4.15 ± 0.06	530.4 ± 8.3	13.4 ± 0.7	0.26 ± 0.01	0.33 ± 0.01	1.45 ± 0.04	13.5 ± 0.4
10	4.83 ± 0.06	529.8 ± 8.7	13.7 ± 2.0	0.45 ± 0.10	0.69 ± 0.13	2.07 ± 0.18	18.7 ± 2.0
15	5.87 ± 0.07	483.0 ± 8.4	12.1 ± 0.4	0.79 ±0.07	1.70 ± 0.20	2.81 ± 0.13	24.9 ±1.2

Tree survival

Germination of sown birch or alder seeds was not observed. Perhaps due to the high temperature and severe drought during the summer.

The average survival for both planted tree species in all of the experimental plots was above 74% (see Table 2). It would seem that in general birch seedlings survived better, but it did not gain enough statistical significance in the binomial regression model to be proven. Nevertheless, the survival of both species was high. No clear pattern for both species and wood ash fertiliser dose or location was observed. Only for birch seedlings the survival on average was higher in fertilised soil. While alder seedlings had on average higher survival rate in the plots located in the centre of the plot.

Table 2. Planted tree survival depending on wood ash treatment (0, 5, 10 and 15 t ha^{-1}) and location (D – near contour ditch; B – in between; C – in the centre of the plot)

Wood ash dose, ha^{-1}	0			5			10			15		
Location	D	B	C	D	B	C	D	B	C	D	B	C
alder	88.9	86.8	92.9	77.8	79.6	92.6	79.6	77.8	85.2	85.2	87	85.2
average		89.5			83.3			80.9*			85.8	
birch	87	88.9	74.1	94.4	100	96.3	94.4	98.1	96.3	96.3	96.3	96.3
average		83.3			96.9*			96.3*			96.3*	

* – result significantly differ from the control plots (0 t ha^{-1} dose of wood ash).

Planed tree height

As can be seen in Fig. 2 after two growing seasons both black alder and silver birch seedling had higher growth rate when wood ash was used as fertiliser in a drained and cutaway peatland. The significant effect of wood ash application can already be seen after the first growing season (see 2017 season in Table 3). However, the overall trend is not identical for both species. *Tukey's HSD test* confirmed that birch tree seedlings have significantly higher average height with increased wood ash dose after second growing season. Interestingly it has been previously stated that the pH does not impact the total amount of produced biomass for birch on a cut away peat soil (Hytönen, 2005). While no significant difference between height of alder tree seedlings in plots with 5, 10 and 15 t ha^{-1} dose of fertiliser was found. Thus suggesting to avoid increased fertilisation in alder plantations on cutaway peatlands to reduce the amount of leached nutrients at least for the first growing seasons (Piirainen et al., 2013; Maresca et al., 2019).

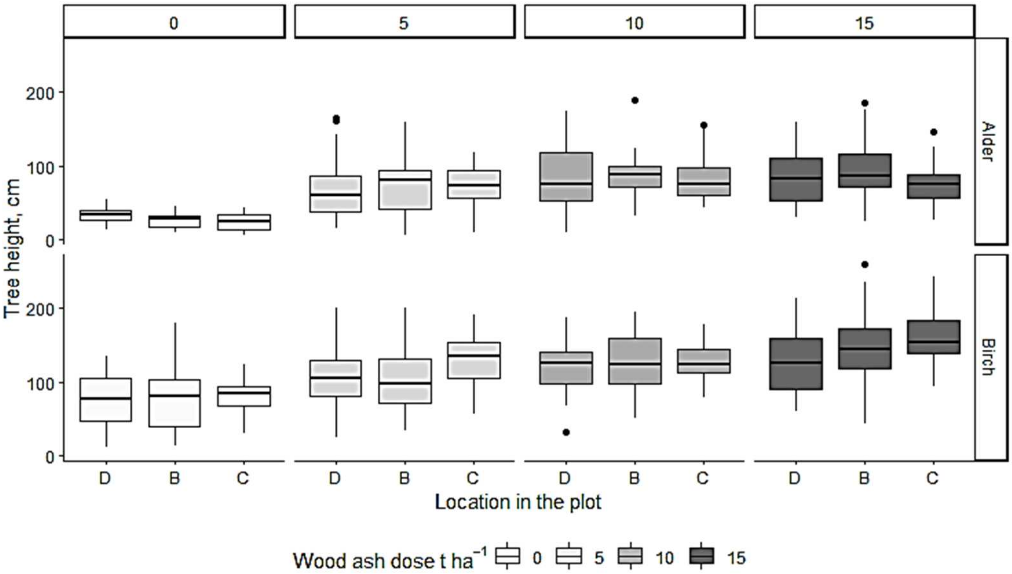

Figure 2. Boxplot graphs showing the tree height after second vegetation season of alder (*Alnus glutinosa*) and birch (*Betula pendula*) tree species located near contour ditch (D), in between (B) and in the centre of the plot (C) with different dose of wood ash fertiliser in the soil (0, 5, 10 and 15 ha^{-1}). Points show outliers, vertical lines – either the minimum or maximum x value plus 1.5*interquartile range (upper) or minus 1.5*interquartile range (lower), lover hinge – 25% quantile, upper hinge – 75% quantile, vertical line in the middle – median.

Containerized seedlings from a nursery have a small amount of substrate around their root system. Thus, when planted, some nutrients are provided. Perhaps due to nutrient availability from the container and soil mineralization process, larger impact of wood ash fertilisation is seen after the second year of establishment. When nutrients of the container have been used up and seedlings have formed greater root systems. Furthermore, it has to been observed that in some cases after few years the effect of fertilisation may diminish and due to lack of nutrients cause tree species dieback (Black et al., 2017). In such cases re-fertilization may be useful.

Table 3. Analysis of variance of tree height for two tree species grown in plots with four wood ash doses in three locations after first growing season of year 2017 and the second (year 2018)

Source of variation	df	SS		F		P	
Year		2017	2018	2017	2018	2017	2018
tree species	1	65,458	95,394	253.5	77.12	***	***
wood ash dose	3	4,849	222,902	6.3	**60.07**	***	***
location	2	134	6,915	0.3	**2.80**	0.7	0.06
tree species by wood ash dose interaction	3	2,749	14,669	3.54	3.95	*	**

*** – $P \leq 0.001$; ** – $P \leq 0.01$; * – $P \leq 0.05$; df – degrees of freedom; SS – sum of squares.

Vegetation cover

Total of 62 species of plants were present at the study site sub-plots (Annex 1). Species distribution and richness was not dependent on planted tree species (birch, alder or none), therefore plot species were excluded from the model. However, planted tree species, birch and alder, could have effect in long-term, due to characteristics of leaf litter, foliage and the shading effect on understory vegetation (Augusto et al., 2003).

Perennial weeds, especially weeds common after disturbances, were the most prevalent plants in both of the study years. Such weed species can also be found in peatlands, that have been used as agricultural land prior restoration (Hausman et al., 2007). The change in species composition in two years is rather small and decrease in annual and biannual species can be expected in later years (Salonen, 1990). However, most species have spread across more sub-plots, especially tree and shrub species and weeds. Monocotyledons showed decrease in species richness, but not in overall presence in sub-plots. The biggest decrease of presence in sub-plots was observed for species such as *Arabidopsis thaliana*, *Juncus articulatus*, *Chamaenerion angustifoliu*m and the biggest increase in presence was observed for *Salix caprea*, *Populus tremula*, *Calamagrostis spp.*, *Erigeron canadensi*s and *Pinus sylvestris*. Compared to control, all treatments had a significant ($P < 0.05$) positive effect on species richness already in the first year after application (Table 4). This shows the potential use of wood ash not just as a fertiliser and liming material for target species, but as an amendment to accelerate natural regeneration as well. Natural vegetation regeneration is particularly important in the first years of establishment to avoid nutrient leaching from fertilized peat soil since part of them are taken up by plants (Huotari et al., 2011). In the second year, interaction between treatment and location in relation to contour ditch become significant, possibly due to extreme weather conditions (hot and dry) of particular summer. Vegetation sub-plots located closer to contour ditches showed higher species richness than the sub-plots located closer to centre of the plots. Such association was present already in the first year of the study and was slightly less prominent in second year. This finding could be connected to hydrological conditions as well as other factors – micro-patterns of dispersion of wood ash, seed dispersal ways and plant propagation mechanisms.

Table 4. Species present in sub-plots depending on sub-plot location (D – near contour ditch, B – in between, C – in the centre of the plot) and treatment (0, 5, 10 and 15 t ha^{-1})

Wood ash dose, t ha^{-1}	0			5			10			15		
Location	D	B	C	D	B	C	D	B	C	D	B	C
2018	27	17	13	27	28	26	33	30	25	29	28	24
total species		28			31*			38*			33*	
2017	19	8	11	27	23	20	26	22	23	31	25	25
total species		24			32*			32*			34*	

* – result significantly differ from the control plots (0 t ha^{-1} dose of wood ash).

Seven tree and shrub species were observed to naturally regenerate in cutaway peatland within two years. These species are *Pinus sylvestris*, *Populus tremula*, *Salix caprea* and other *Salix spp.*, *Betula pendula*, *B. pubescens* and in separate cases individual *Picea abies* sprouts. In plots treated with wood ash *Populus tremul*a and *Salix* species showed significantly ($P < 0.05$) better regeneration than in control plots. Other woody species did not show significant association between treatment and presence.

From species present in the study site, *Typha latifolia* and *T. angustifolia*, *Silene vulgaris*, *Juncus effusus*, *J. articulatus*, *Equisetum arvense*, *Cirsium arvense* as well as *Pinus sylvestris* and some *Salix* species are plants known to be used in phytoremediation (Valujeva et al., 2015). Given the wood ash fertiliser, these plants (*Salix* species, *Typha latifolia* and *Silene vulgaris* in particular) with some management could be used to mitigate the environmental impact of heavy metals present in ash (Augusto et al., 2008; Huotari et al., 2011; Ingerslev et al., 2014).

Species typical to *Sphagnosa*, *Caricoso-phragmitosa*, *Dryopteriosa-caricosa*, *Filipendulosa* as well as *oxalidosa turf. mel*., *Myrtillosa turf. mel*., *Vacciniosa turf. mel*. and *Callunosa turf. mel*. forest types can be found in the study site (forest types according to Bušs, 1976). But there is no prevalence of species typical to any specific forest type in either of the years. Only small portion of the species present two years after disturbance are typical peatland plants, probably not only because of changes in hydrological and soil properties, but also due to loss of large portion of seed bank caused by the removal of top-soil (Hedberg, et al., 2014).

CONCLUSIONS

Fertilisation with wood ash improved both the survival and the growth of birch tree seedlings in the first two growing seasons, but with increased dose only the growth rate improved. In comparison alder seedlings exhibited a different pattern, where the application of fertiliser improved the growth rate, but the survival rate was decreased. Suggesting that other factors as location (thus possibly hydrological conditions or physical peat properties) could be of more importance.

No added benefit of applying larger doses than 5 t ha^{-1} wood ash in alder plantation was detected thus for environmental concerns it may be suggested to limit fertilization at least in the first growing seasons.

Regeneration of vegetation was more rapid in plots treated with wood ash. However, the difference between treatment dosages was rather small, suggesting, that 5 to 10 t ha^{-1} application of wood ash is sufficient to promote natural regeneration in first two years after disturbance.

Wood ash treatment had a significant positive effect on natural regeneration of *Populus tremula* and *Salix* pioneer tree species, but did not have an effect on tree species more typical to peatlands (birch and pine).

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Annex 1. Species present in study site (x – presence) in 2017 and 2018 at 0, 5, 10 and 15 t ha^{-1} wood ash. *P* – perennial; A – annual; B – biannual; W – weed species; m – monocotyledons; WS – woody species

Wood ash dose, t ha^{-1}	**0**		**5**		10		15					
Growing season	1.	2.	1.	2	1.	2.	1.	2.	Type	*W*	*M*	*WS*
Agrostis tenuis	x		x		x		x		P	*x*	*x*	
Arabidopsis thaliana	x		x		x	x	x		A	*x*		
Arctium spp.							x		B	*x*		
Arctium tomentosum				x					B	*x*		
Betula pendula	x	x	x	x	x	x	x	x	P			*x*
Betula pubescens	x	x	x	x	x	x	x	x	P			*x*
Bidens tripartita			x	x		x			A	*x*		
Brassica spp.	x		x	x	x	x	x	x				
Calamagrostis spp.	x	x	x	x	x	x	x	x	P	*x*	*x*	
Carex cespitosa					x				P		*x*	
Carex spp.	x	x	x	x	x	x	x	x	P		*x*	
Cerastium holosteoides					x				P	*x*		
Chamaenerion angustifolium	x		x		x	x	x	x	P	*x*		
Chenopodium spp.							x			*x*		
Cirsium arvense	x	x	x	x	x	x	x	x	P	*x*		
Crepis spp.		x					x					
Echinochloa crusgalli						x	x	x	A	*x*		
Epilobium spp.	x	x	x	x	x	x	x	x	P	*x*		
Equisetum arvense	x		x						P			
Equisetum sylvaticum		x							P			
Erigeron canadensis				x	x	x		x	A	*x*		
Eriophorum vaginatum			x					x	P			
Eupatorium cannabinum		x	x	x	x	x	x	x	P			
Fragaria vesca					x	x			P			
Hieracium spp.					x		x		P	*x*		
Hieracium x floribundum		x		x					P	*x*		
Juncus articulatus	x	x	x	x	x	x	x	x	P	*x*	*x*	
Juncus effusus		x	x	x		x	x	x	P	*x*	*x*	
Juncus tenuis	x		x	x	x	x	x		P	*x*	*x*	
Lamium spp.			x			x		x		*x*		
Linaria vulgaris						x			P	*x*		
Lycopus europaeus	x	x		x		x			P	*x*		
Matricaria perforata			x	x					A	*x*		
Mycelis muralis					x		x		A			
Phragmites australis	x	x	x	x	x	x	x	x	P		*x*	
Picea abies					x	x			P			*x*
Picris hieracioides	x		x		x	x	x	x	B/P	*x*		
Pinus sylvestris	x	x	x	x	x	x	x	x	P			*x*
Plantago lanceolata								x	P	*x*		
Plantago major			x				x	x	P	*x*		
Polygonum persicaria	x	x	x	x	x	x	x	x	A	*x*		
Polygonum spp.							x			*x*		
Polytrichum spp.	x		x		x				P			
Populus tremula	x	x	x	x	x	x	x	x	P			*x*
Rubus idaeus	x	x	x	x	x	x			P			*x*
Rumex acetosella				x		x			P	*x*		
Salix caprea		x	x	x		x		x	P			*x*

Salix spp.	x	x	x	x	x	x	x	x	P			*x*
Scirpus sylvaticus			x		x		x		P	*x*	*x*	
Senecio vulgaris		x		x		x		x	A/B	*x*		
Silene vulgaris			x						P	*x*		
Solidago canadensis						x		x	P	*x*		
Solidago spp.							x		P	*x*		
Sonchus arvensis		x		x		x		x	P	*x*		
Sonchus asper					x				A	*x*		
Stellaria spp.		x		x		x	x	x				
Taraxacum officinale	x	x	x	x	x	x	x	x	P	*x*		
Tussilago farfara	x	x	x	x	x	x	x	x	P	*x*		
Typha angustifolia					x				P		*x*	
Typha latifolia		x				x			P		*x*	
Urtica dioica							x	x	P	*x*		
Viola arvensis					x				A	*x*		

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Surface water runoff of different tillage technologies for maize

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Abstract. The present paper is focused on the evaluation of efficiency of soil-conservation technologies to reduce surface water runoff in Central Bohemia Region. In the last years, there has been an increase in maize planting on hillslope plots due to the construction of many biogas plants in conditions of Czech Republic. It enhances the risk of water erosion because the occurrence of sloping lands in the Czech Republic is high. To evaluate the technologies of stand establishment a field trial was laid out with four treatments of maize planting. The trial was laid out on a plot with light soil and slope of around 12%. It was a multi-year trial. To measure erosion parameters a rainfall simulator was used (measurement of surface runoff). The values obtained in two seasons show a positive effect of the soil surface cover by organic matter when reduced soil tillage was used. Soil loss also decreased at the same time compared to treatments with conventional soil tillage. It was found up to six-fold reduction in surface runoff by appropriate soil tillage technology during two seasons of measurement.

Key words: water erosion, soil tillage, organic matter on surface.

INTRODUCTION

In the Czech Republic approximately 50% of the arable land area is vulnerable to water erosion of soil. A crucial problem is excess surface runoff during intensive rainfalls connected with topsoil washing away (Janeček et al., 2005). At the same time, there is a negative effect of the reduced soil ability to transfer the highest water amount possible from precipitation to the soil profile. An increase in soil water retention is a desirable contribution to the soil moisture budget with respect to grown crops. Reduced water infiltration into soil is usually a consequence of undesirable soil compaction. Baumhard & Jones (2002) described inappropriate soil cultivation that can contribute to the formation of compacted layers in the soil profile (in location North American Great Plains). Titi et al. (2002) confirmed a reduction in soil permeability for water as a result of the formation of homogeneous soil layer when conventional soil tillage is used in the long term. In agricultural operations, the impacts of axle load traffic on soil are the most frequent cause of soil compaction (Chyba et al., 2014).

To express the exposure of agricultural land to erosion and to assess the effectiveness of soil-conservation measures a universal equation for the computation of long-term soil loss due to erosion (universal soil loss equation) is used (Wischmeier &

Smith, 1978). An assessment of particular factors applied in this equation reveals the importance of sufficient water infiltration into soil. The model was adapted for conditions in the Czech Republic by Janeček et al. (2005). For rainfall erosivity factor (Czech conditions) the annual value of this factor is computed from long-term precipitation data while total rainfall amounts lower than 12.5 mm and rainfalls when at least 6.25 mm did not fall within 15 minutes are not included (Janeček et al., 2012).

To measure the infiltration rate of water into soil and water surface runoff rainfall simulators are used. Advantages of artificial rain generated with a rainfall simulator are the regulation of water amount falling on soil in the form of drops and the setting of rain duration. The infiltration rate is determined from defined intensity of artificial rain and surface runoff of water from the measuring surface. The weight of intercepted water from surface runoff is recorded at a regular time interval during the entire measurement time. The beginning of water runoff from the measuring surface shows the time of the origin of overland flow (Hůla & Kovaříček, 2010). The measurement time is terminated after the infiltration rate has stabilized. The origin of overland flow and stabilized infiltration rate are typical and mutually comparable parameters for defined soil properties at the measuring site (Kovaříček et al., 2008).

Sufficient water infiltration into soil and limitation of surface runoff during intensive rainfalls are very important in fields with maize and other wide-row crops. Truman, Shaw & Reeves (2005) studied the importance of soil-conservation technologies for these crops. The authors reported twice lower surface runoff and five times lower soil loss after zero tillage compared to conventional soil cultivation during rainfall simulation for 60 minutes. Leij et al. (2002) described a frequent situation: the soil can be in an unstable condition after ploughing, soil porosity and other physical properties can quickly change in time. Schillinger (2001) highlighted a risk of water erosion as a consequence of insufficient infiltration of water into soil during snow melting when the surface layer of soil has thawed but there is frozen water in soil pores at deeper layers. Particularly vulnerable are lands on long hillslopes, without vegetation cover or plant residues on the soil surface. Most studies have focused on comparing individual crops. Effect of tillage method is then assessed much less frequently. The aim was to evaluate the impact of technology tillage (maize stand establishment) to the values of surface runoff.

MATERIALS AND METHODS

For the purposes of measurements a field trial with different treatments of maize planting was laid out in location Nesperská Lhota in Central Bohemia Region. Measurements were done in two seasons, always in June. The evaluated indicators were the speed of surface runoff and infiltration rate of water into soil under intensive rainfall simulation.

The plot was on a hillslope with an average slope of 12.2%. The trial was laid out on a light soil at the altitude of 420 m. A rainfall simulator (own construction CULS in Prague) was used to measure water infiltration into soil, surface runoff of water and soil washing away (4 repeats).

The simulation of rainfalls is generated with a full cone nozzle installed above the centre of the measuring surface. Sites suitable for measurements were chosen on the plot. The square measuring surface of 0.5 m^2 in size was bounded by metal strips along the entire circumference. On the bottom side of the measuring surface there is a collector that directs running water and washed away soil into a pipe and then into a graduated vessel. The surface runoff collected in the vessel is weighed on an automated balance and the values are recorded in a portable computer. The nozzle is fed with water conducted by a hose from the pump with a pressure adjusting valve. Rainfall intensity (90 mm for these measurements, calibration was performed in laboratories CULS in Prague) and kinetic energy of rain drops are controlled through a change in spraying pressure (Kovaříček, 2008). To measure the soil surface roughness downslope a chain method was used (Klick, 2002). Soil moisture before sprinkling was measured in disturbed soil samples taken in the proximity of the measuring surface with a gouge moisture sensor and determined by a gravimetric method (Valla et al., 2008). Kopecky cylinders with the volume of 100 cm^3 were taken to determine the basic physical properties of soil (each variation: 12 pieces). Soil sampling was performed prior to measurement (15.6.2017, 20.6.2018).

Measurements were performed in four treatments of the field trial that differed in the method of soil tillage for maize.

Experimental treatments

Treatment 1 – In autumn skimming was performed by a disk harrow. Plant residues and emerged shattered seeds of triticale were left to cover the soil surface over the winter season. The emerged shattered seeds were killed with a nonselective herbicide in spring. Before maize planting the soil tillage was done by a tine cultivator to a depth of 0.08 m and after this operation maize was planted.

Treatment 2 – In autumn skimming was performed by a tine cultivator to a depth of 0.15 m. Winterkilled catch crop (white mustard) was sown at the same time. Over the winter season the catch crop cover was left on the soil surface. The emerged shattered seeds were killed with a nonselective herbicide in spring. The soil was left untreated in spring, only maize was planted.

Treatment 3 – In autumn 2009 a part of the plot was ploughed to a medium depth (0.20 – 0.22 m) when contour ploughing was used. The soil surface was left in rough condition over winter. In spring the seedbed preparation was done (by field drag and spike-tooth harrow) and maize was planted. The soil surface cover by organic matter was almost zero at the time of planting.

Treatment 4 – The soil was also ploughed to a medium depth in autumn 2009. The soil surface was left in rough condition over winter. A week before maize planting the seedbed preparation was done (like in Treatment 2) and subsequently a cover under planted crop was sown in the space between rows (grain crop sown in spring before maize planting). Maize planting followed.

RESULTS AND DISCUSSION

Table 1 shows the results of the measurement of physical properties of soil. In general, the values are very similar. Differences between treatments are smaller than expected. From the values, it is obvious that the effect of ploughing (significant soil loosening) at the time of measurement has already faded. Slightly more favourable values of physical properties of soil have treatments with reduced soil tillage. However, the difference is below the threshold of statistical significance. Measurement in 2018 was strongly influenced by the dry course of spring.

Table 1. Soil bulk density and total porosity

Treatment	Depth, m	Porosity, %		Bulk density, g cm^{-3}	
		2017	2018	2017	2018
1	0.05–0.1	44.87	37.04	1.57	1.46
	0.1–0.15	41.10	38.51	1.47	1.48
	0.15–0.2	39.40	42.41	1.61	1.56
2	0.05–0.1	43.45	39.58	1.53	1.44
	0.1–0.15	42.05	43.45	1.44	1.48
	0.15–0.2	42.25	42.05	1.48	1.44
3	0.05–0.1	40.99	39.90	1.53	1.59
	0.1–0.15	37.90	41.99	1.48	1.58
	0.15–0.2	40.86	43.44	1.44	1.51
4	0.05–0.1	38.63	38.63	1.54	1.54
	0.1–0.15	41.23	41.23	1.48	1.48
	0.15–0.2	40.97	40.97	1.52	1.52

The results (see Fig. 2) of the 2017 season measurement demonstrate the need to use appropriate maize growing technologies. The results clearly demonstrate the beneficial effect of reduced technologies on surface runoff (Treatment 2 especially). The results are shown in the graph in Fig. 1. Here are the cumulative runoff values of the individual treatments during simulating rainfall. Curves can be successfully supplemented with linear dependencies. It can be seen from the graph that conventionaltreatments exhibit greater cumulative runoff values. There is a difference between conventional treatments. The grain crop between rows significantly protects the soil. Interrow crop reduced surface runoff by half. Conversely, the conventional treatment has shown minimal ability to infiltrate water. More than 80 percent of the water from the applied dose flowed in the form of a surface effluent. This was undoubtedly affected by the soil crust. The crust prevented infiltration and the water flowed freely throughout the simulation. The crust was not disturbed in the interrow space by any growth as in Treatment 3.

Figure 1. Field experiment (a), rainfall simulator developed on CULS in Prague (b).

Minor differences were noted for reduced treatments. The first half hour was better infiltrated treatment 1. After saturation, however, the surface runoff rate increased Treatment 2 then utilized the beneficial effect caused by the root system of white mustard. The root system has the effect of longer simulation when it significantly improves the infiltration of water to greater depths. Generally, each soil cover with organic matter has a beneficial effect on infiltration conditions. At the same time, the risk of damaging surface by water erosion is reduced. Treatment 2 during this season has shown the most beneficial effect on surface runoff reduction. The differences between the treatments this season were far more intense than in the next year.

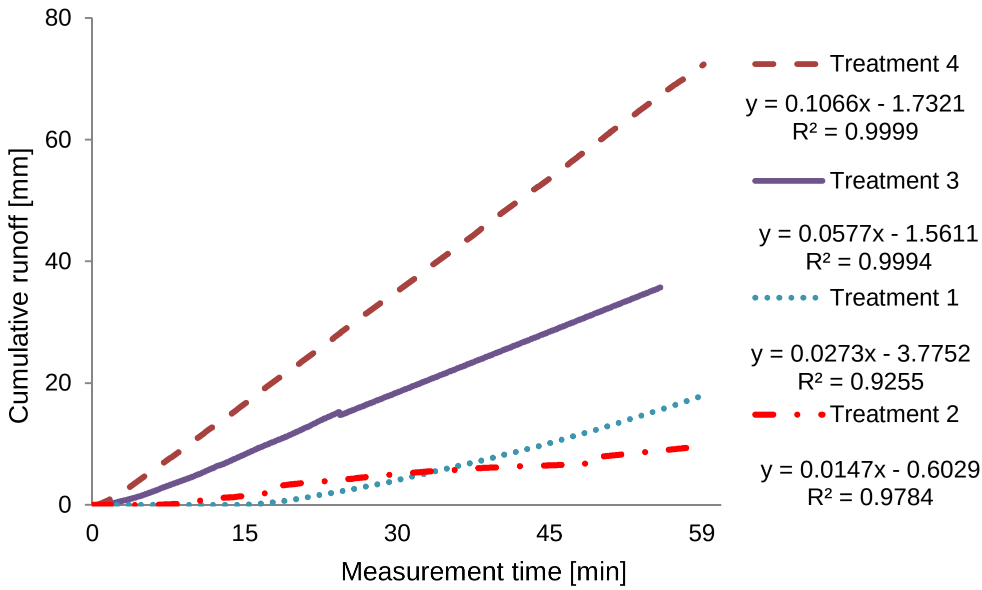

Figure 2. Cumulative runoff in June 2017.

The measurement results throughout the 2018 season reaffirm the beneficial effect of reduction technology (Treatment 2 especially) on surface runoff (see Fig. 3). It is also necessary to mention the influence of extreme temperatures and droughts throughout the spring and summer that affected the whole measurement season. Differences between treatments were far less than in the previous year due to drought. Still, the trend has remained unchanged. Very similar results of treatments 2 and 3 are very interesting. The worst results are again achieved by treatment 4. Nevertheless, in the 2018 season, it has shown a much higher infiltration capacity. All treatments after saturation, the ability to infiltrate decreased rapidly. Treatment 2 could be even worse affected by mustard vegetation where plant roots did not reach such proportions.

The input hypotheses consisted in the assumed reduction in surface water runoff using reduced soil tillage technology. These hypotheses have largely been met in evaluating the field experiment. Long-term attempts of this type have been dealt with by many other authors.

A decrease in surface runoff in non-redeveloping treatments has been found, which utilizes the covering of the soil surface with organic matter. This is confirmed by a number of authors. Moreno et al. (1997) on six plots (14 x 22 m in size) with light sandy alluvial soil comparing ploughing soil with protective soil treatment, represented only by shallow loosening and tillage of soil with a disc harrows. After 3 years of systematic soil tillage, the infiltration of the soil layer was higher at the soil protection tillage (124 mm h^{-1}) than in conventional soil treatment (66 mm h^{-1}).

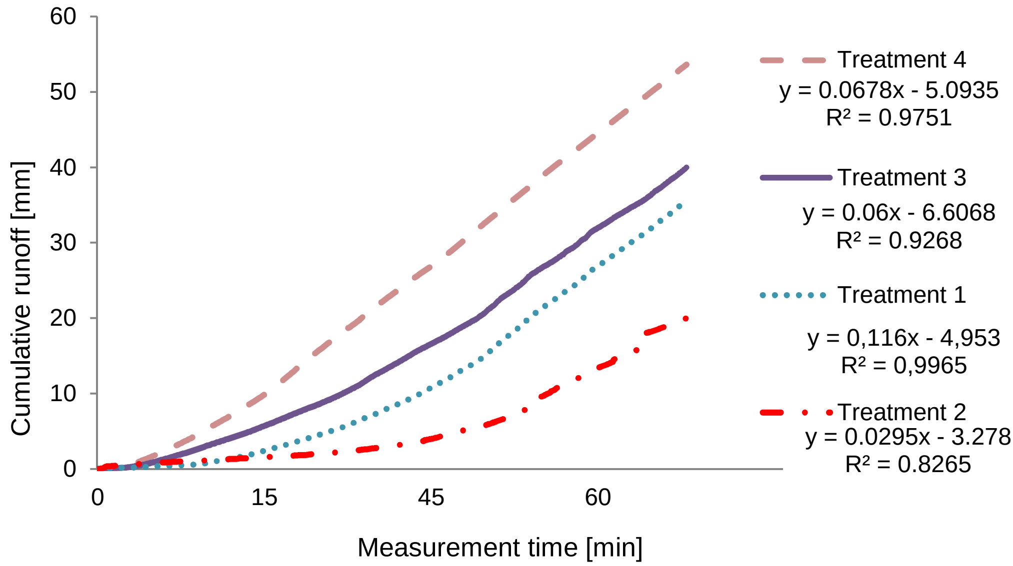

Figure 3. Cumulative runoff in June 2018.

Tebrügge & Düring (1999) carried out experiments on soils that have long been managed in a different way - ploughing and reduction tillage. After several years of repetition, they found 1.2–2.6 times higher infiltration rates of reduction tillage methods than conventional soil tillage. In analogy with infiltration, the surface runoff in conventional treatments was 1.2–2.6 times higher than in the reduced ones. Measurements were mostly performed during simulated intensity of 40 mm h^{-1}.

The rain simulator to measure surface runoff was also used by Zhang et al. (2014), who selected an area of 1 m^2 on the surface of each treatment. The irrigation intensity (90 mm h^{-1}) was the same as for measurements in this work. The authors also confirm the reduction of surface effluent in the no-flood-based technologies of planting versus plowing and emphasize the influence of organic matter on the surface.

The observed trend is confirmed by the measurements made by Baumhard & Jones (2002) or by Anken et al. (2004). They emphasize that plant residues in the surface layer of soil reduce the surface drainage of rainwater. The results of these experiments correspond very well to the results measured during the field experiment in this work. Novák et al. (2011), in their previous study, found different behaviour of soil types and less influence of soil tillage technology under the same simulation conditions. On the other hand, Hůla & Kovaříček (2010) found even greater dependence on tillage technology in Southern Bohemia (sandy soils). In their study they used an older model of rainfall simulator.

CONCLUSIONS

Our measurements showed different values of surface runoff and water infiltration into soil in the period of an increased risk of the occurrence of torrential rains and subsequent potential origin of erosion event. Treatment 2 (conventional tillage of soil with ploughing) was the most vulnerable to excess surface runoff when erosion risks of growing maize on a hillslope and light soil without soil-conservation technologies were confirmed.

The measurements proved a positive effect of the soil cover by organic matter. The infiltration rate of water into soil also influences water supply to plants. Fast infiltration also facilitates water retention in landscape, which is important with respect to the risk of local floods.

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Effects of drip irrigation on the yield of strawberry plants grown under arable conditions

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Abstract. The study investigated the effects of drip irrigation on the yield of 'Honeoye' strawberry plants for commercial purposes grown under arable conditions throughout the harvest season. The plants were irrigated at irregular intervals depending on natural precipitation. Crop yields and fruit parameters (diameter, length, individual weight, count per plant) were compared on several harvest dates. Statistical analysis has shown that irrigation has a significant impact on yield and fruit parameters. The irrigated plants yielded more strawberries, which also had a larger diameter, length, and individual weight.

Key words: strawberry, drip irrigation, fruit crop.

INTRODUCTION

To obtain a high yield of high quality strawberries, it is necessary to provide the plants with an adequate water supply when it is most needed. Thus, a good knowledge of the critical stages in the development of strawberry plants and their water requirements is essential for ensuring optimum irrigation effects. The plants need the most water when rapidly increasing weight by absorbing large quantities of nutrients. Indeed, providing appropriate irrigation levels at the right time is a prerequisite for high yields and good fruit quality (Krüger, 2002; Gaworski & Nowakowski, 2009; Nowakowski, 2009a; Nowakowski, 2009b; Rumasz-Rudnicka, 2009). Strawberry plants naturally tend to develop a large number of leaves. Importantly, the more leaves they have, the more buds turn into lateral crowns with more flower clusters (Żurawicz & Masny, 2010). Strawberries are highly sensitive to water deficits, especially from the beginning of April to the end of the harvest season as well as following the August harvest, which is associated with a large surface area of the leaves, high water content, as well as a shallow and rather compact root system (Treder, 2003; Klamkowski et al., 2013).

Unfortunately, one of the main features of Poland's climate is large variability in precipitation throughout the agricultural season. The total amount of rainfall, its intensity, and moisture distribution in the soil strongly affect plant growth and development, leading to variation in the yield and quantity of crops (Kaniszewski, 2005; Vilde et al., 2009; Barwicki et al., 2012; Treder et al., 2014; Chyba et al., 2015; Kroulik et al., 2016; Namaghi et al., 2018). Thus, strawberries cultivated on sandy soils must be irrigated to maintain high productivity of the plantation in the event of long periods without precipitation (Rolbiecki & Rzekanowski, 1997). The installation of an adequate irrigation system on a farm helps increase crop yield and mitigate water deficits during critical periods of increased plant susceptibility (Nowakowski & Strużyk, 2006, Gaworski & Nowakowski, 2009). Of great importance is also water quality and availability for irrigation (Rolbiecki & Rzekanowski, 1997).

The objective of the study was to evaluate changes in crop yield throughout the agricultural season brought about by the drip irrigation of 'Honeoye' strawberries under arable conditions.

MATERIALS AND METHODS

Strawberry plantation

The experiment was conducted on a 2-year plantation of 'Honeoye' strawberries, an early high-yield cultivar widely grown across Europe. The cultivar is characterized by juicy medium-sized fruit with a shiny red skin and a satisfying taste (Hancock et al., 2008). The plants are rather cold-hardy and resistant to leaf diseases, but with a vulnerable root system. This plant prefers sunny positions, sheltered from the wind. Only then the fruit will be tasty, aromatic, sweet and with high aesthetic qualities. It grows best on lighter, aerated soils with good water conditions. It is sensitive to drought, so there is need to maintain sufficient soil moisture content.

The research was conducted in the strawberry production field on the commercial farm in the village of Nowe Przybojewo, Mazovian Province, Poland. It was conducted on a 0.6 ha strawberry plantation with plant rows oriented in the east-west direction, with the terrain slightly inclined to the east. The strawberries were planted on class V poor and light soil (Żurawicz & Masny, 2010).

The study plantation was established in the autumn 2015. The preceding crop was triticale, for which the soil had been limed the year before. Immediately after harvesting the grain and collecting the straw, manure was applied at 40 t ha^{-1}. The propagation material consisted of fresh nursing stock, which was planted in double rows, with an inter-row distance of 62 × 90 cm. Young plants, both, immediately after planting and in the first year, were irrigated using the reel irrigator by Irtec company. After the first year, the strawberries were covered with a floating perforated row cover for the winter in order to advance crop production in the subsequent season. The crop cover was removed in the second half of April 2016, at a time when approx. 20% of the blooms were shown. Following mechanical weeding, the plants were sprayed with several fungicides to prevent mildew, leaf spot, and gray mold, as well as treated with calcium fertilizers. Towards the end of the flowering period, during early fruit development, the plantation was mulched with rye straw. The last agricultural procedure prior to the harvest season was the installation of drip tubing along strawberry rows. The plants produced the first crop in the summer of 2017, which was the second year since planting.

Study conditions

Throughout the study period, the experimental strawberry plants were irrigated exclusively using a drip irrigation system. The dates of irrigation treatments mostly depended on the occurrence of natural rainfall, and were designed to maintain optimum soil moisture for strawberry cultivation with a view to obtaining good fruit size and weight, and preventing plant wilting or growth failure.

During the study period, the weather conditions varied, with most days being sunny and dry. The experiment lasted for a total of 27 days (from the installation of the drip tubing to the last harvest), with 5 rainy days (Table 1). Rainfall varied in terms of intensity and amount, which was measured using a rain gauge with a millimeter resolution placed in the vicinity of the experimental plot.

Strawberries are particularly vulnerable to spring ground frost, especially directly after the removal of floating row cover and exposure of the emerging flowers and fruit to low temperatures. In the spring of 2017 Poland saw two major ground frost events, which caused substantial damage not only to strawberries, but also to other kinds of horticultural plantations, and delayed the first crops (www.gismeteo.pl/weather-nowe-przybojewo-265829/).

Table 1. Occurrence of night ground frosts and rain during research

No.	Weather events	Date	Temperature/ Rainfall amount
1	Ground frost	April 16/17, 2017	-3 °C
2	Ground frost	May 09/10, 2017	-7 °C
3	Rainfall	May 24, 2017	3.5 mm
4	Rainfall	June 04, 2017	8.0 mm
5	Rainfall	June 06, 2017	12.0 mm
6	Rainfall	June 12, 2017	7.0 mm
7	Rainfall	June 16, 2017	3.0 mm

www.gismeteo.pl/weather-nowe-przybojewo-265829/

Irrigation system

The irrigation system consisted of T-TAPE Rivulis 508-20-500 drip tubing characterized by:

– tube wall thickness: 0.2 mm,
– emitter spacing: every 20 cm,
– water flow rate: 5.00 $dm^3\ h^{-1}$ per 1 m of tubing, or 1.00 $dm^3\ h^{-1}$ per emitter.

Eight irrigation treatments were performed during the study at varying intervals (1 to 5 days, depending on natural rainfall) and with varying duration (2 to 4 h). Water for irrigation was drawn from a drilled well. The applied working pressure was 0.11–0.12 MPa. The schedule of irrigation treatments, including their duration and water flow rate, is given in Table 2.

Table 2. Schedule of irrigation treatments performed during the study

No.	Date	Duration, h	Water flow rate per 1 m of tubing, $dm^3\ h^{-1}$
1	May 20, 2017	2.0	5
2	May 21, 2017	3.0	5
3	May 26, 2017	4.0	5
4	May 28, 2017	2.0	5
5	May 31, 2017	2.5	5
6	June 03, 2017	3.5	5
7	June 08, 2017	2.0	5
8	June 11, 2017	2.5	5

The experiment encompassed a total of four strawberry rows with a length of 100 m each (Fig. 1). To compare yields and assess the influence of irrigation, two of them (3, 4 rows), similarly to the rest of the plantation, were drip-irrigated. On the other hand, the two control rows (1, 2 rows) were deprived of access to additional water. For that purpose, drip tubing supplying four neighboring rows was removed ("X" marks). The fruit harvested from this segment of strawberry plantation was used in measurements.

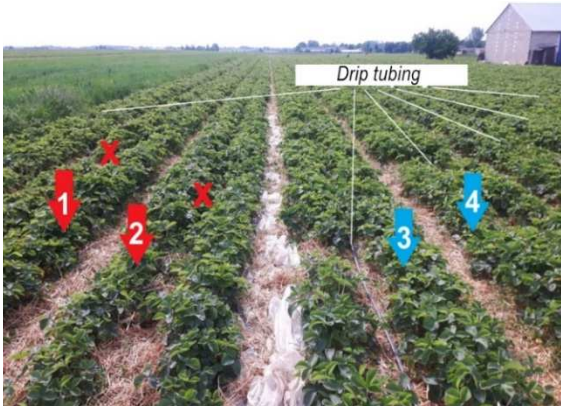

Figure 1. The location of irrigated (3, 4) and non-irrigated (1, 2) rows on the plantation

Yield measurement

The first harvest measurement was made on May 25, 2017, with subsequent ones following at intervals of several days, depending on the degree of fruit ripening. Each time, strawberries were collected from the same segments of the same rows (1, 2, 3, 4). The fruit was harvested seven times. In the first measurement, strawberries were collected from 100 m rows, while in the second measurement crops collected from 3 m long segments were used to compare counts of ripe fruit on the plants. Data on the weight of strawberries collected on the various harvest dates were used to calculate the percentage increase in the yield of irrigated (Ir) vs. non-irrigated (NIr) strawberries, from the formula below:

$$Q_p = \frac{m_{Ir} - m_{NIr}}{m_{NIr}} \cdot 100 \qquad (1)$$

where Q_p – increase in yield, %; m_{Ir} – weight of the collected irrigated strawberries, kg; m_{NIr} – weight of the collected non-irrigated strawberries, kg.

Measurements were made for each harvesting, individual fruit characteristics were examined by analyzing the content of two full punnets (one for each cultivation method) in terms of strawberry diameter, length, and weight. The mass measurements were made using an electronic scales Radwag WLT 6/X/2 with an accuracy of 0.1 g. The dimensions were determined using a caliper with an accuracy of 0.05 mm. The measurements of fruit number were made for all collected fruit from a measuring section with a length of 3 m.

The obtained results were developed using statistical analysis methods using the Statistica v.13.1 program, using the ANOVA variance analysis. Statistical differences between groups were estimated using the Duncan test. Statistical tests were assessed at the significance level $p < 0.05$.

RESULTS AND DISCUSSION

The obtained results were subjected to statistical analysis. In order to verify the significance of variation in strawberry yield, in individual measuring systems, analysis of variance in a two-factor system was carried out. Analysis of variance showed a statistically significant variation in yield, at the level of $\alpha = 0.05$, for the studied factors: harvest time and cultivation system (irrigated and non-irrigated plants) (Table 3).

Table 3. Analysis of variance for strawberry yield

Source	Sum of Squares	DF	Mean Square	F-ratio	P-Value
Harvest dates	28,938,434	6	4,823,072	129.08	< 0.0001
System (Ir, NIr)	427,530	1	427,530	11.04	0.0148
Residual	224,182	6	37,364		

Ir – irrigated; NIr – non-irrigated.

The yield of strawberries depended on irrigation and differed between the various harvest dates. At the beginning of the season, the yield of both non-irrigated and irrigated plants was low, but increased with each successive harvest as more strawberries ripened. Similarly, the amount of harvested strawberries declined towards the end of the season. The smallest yield was recorded on the first day of harvest (May 25) at 0.97 kg and 1.24 kg for non-irrigated and irrigated strawberries, respectively, while the greatest yield was obtained on the fifth date. (June 9), at 69.36 kg and 75.66 kg, respectively. In both cases, as well as on the other harvest dates, the weight of strawberries collected from the irrigated rows was greater than that from the non-irrigated ones (but to varying degrees).

Based on the data gathered from the experimental plantation, it was also possible to calculate the overall yield per hectare (for all harvest dates taken together), which would amount to 10,732 kg for the non-irrigated strawberries and 13,178 kg for the irrigated ones. For non-irrigated strawberries, the changes in yield for harvest terms were varied from 64 kg ha^{-1} to 4,563 kg ha^{-1} and for irrigated strawberries from 81 kg ha^{-1} to 4,978 kg ha^{-1} (Fig. 2). Thus, the overall seasonal yield of irrigated plants would be greater by approx. 2,446 kg (Q_p = 22.79%) as compared to plants utilizing exclusively rainwater. The highest increase in strawberries yield, caused by irrigation, was in the second harvest term (May 27) and was Q_p = 162.8%. In next harvest term sit was varied from Q_p = 66.7% (May 30) to Q_p = 9.1% (June 09). The overall yield should be deemed rather low in light of the paper by Żurawicz et al. (2005). In that study, encompassing 18 cultivars of drip-irrigated strawberries, yields ranged from 8,800 kg to 35,806 kg, with an average of 24,720 kg ha^{-1}.

The presented findings also show the significance of weather conditions to strawberry cultivation. The much lower yields, obtained in the present study, were largely attributable to the spring ground frosts. The ground frosts that occurred in the spring considerably damaged the plantation, inhibiting growth and delaying fruit formation, thus substantially decreasing the overall yield.

At each harvesting term, on the individual irrigated plants, there were more fruit than on non-irrigated plants (Fig. 3). This was confirmed by the analysis of variance, which also showed that the number of fruit varied statistically depending on the harvest term (Table 4). On average, throughout the whole season, from individual non-irrigated plants were collected 11.9 strawberries, while from irrigated once it was 14.3 strawberries. Ochmian et al. (2009) for strawberries of the 'Aga' cultivar were collected 36 fruit per plant.

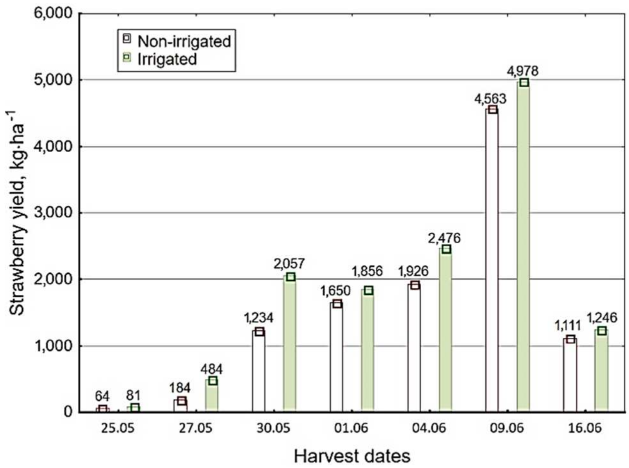

Figure. 2. Strawberry yield converted to kilogram per hectare vs. harvest date for irrigated and non-irrigated plants.

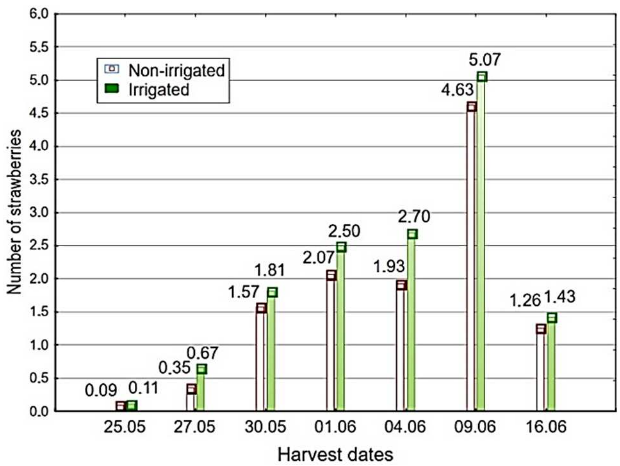

Figure 3. Number of fruit on individual strawberry plant: irrigated and non-irrigated.

Table 4. Variance analysis of fruit number on individual plant

Source	Sum of Squares	DF	Mean Square	F-ratio	P-Value
Harvest dates	29.10028	6	4.85005	164.496	< 0.0001
System (Ir, NIr)	0.40763	1	0.40763	13.825	0.0098
Residual	0.17691	6	0.02948		

Ir – irrigated; NIr – non-irrigated.

The three basic parameters of individual strawberries were: diameter, length, and weight (although the studied fruit also differed in terms of appearance, shape, and degree of ripeness). In order to check the significance of variation in the diameter, length and weight of fruit, an analysis of variance was carried out. The analysis showed statistically significant variation in the fruit parameters tested at the level of $\alpha = 0.05$ depending on the harvest term and cultivation system (irrigated and non-irrigated plants) (Table 5).

Table 5. Analysis of variance for parameters of strawberry fruit size (diameter, length, weight)

Source	Sum of Squares	DF	Mean Square	F-ratio	P-Value
Diameter					
Harvest dates	24,084	6	4,014	227.81	<0.0001
System (Ir, NIr)	382	1	382	21.71	<0.0001
Residual	30,236	1,716	18		
Length					
Harvest dates	5,905	6	984	46.40	<0.0001
System (Ir, NIr)	701	1	701	33.03	<0.0001
Residual	36,395	1,716	21		
Weight					
Harvest dates	16,864.8	6	2,810.8	180.38	<0.0001
System (Ir, NIr)	220.8	1	220.8	14.17	0.0002
Residual	26,739.2	1,716	15.6		

Ir – irrigated; NIr – non-irrigated.

The irrigated strawberries exhibited slightly larger values for all of these three characteristics. On the basis of Duncan's test (Table 6) it can be concluded that the fruit differed in diameter, length and weight depending on the harvest term and formed separate homogeneous groups. The exception was the fruit diameter and weight in the last two harvest terms (June 09 and June 16), and length in the last three harvest terms (June 04, June 09 and June 16), which created a single homogeneous groups.

The fruit of the largest size and weight were obtained at the beginning of the harvest season.

The differences were up to 2 mm in terms of diameter and length, and 1.9 g in terms of weight (Table 7).

All the measured characteristics gradually decreased with each subsequent harvest for both types of strawberries. The weight of individual fruit collected from non-irrigated plants ranged from 3.0 g to 29.0 g, with a mean of 13.7 g, while that for fruit from irrigated plants ranged from 2.0 g to 32.0 g, with a mean of 14.5 g.

Table 6. Homogenous groups for diameter, length and weight of fruit on the basis of Duncan`s test depending on harvest term

Harvest terms	Average	Homogenous group					
		1	2	3	4	5	
Diameter							
May 25	40.23						×
May 27	37.87					×	
May 30	34.85				×		
June 01	31.99			×			
June 04	29.86		×				
June 09	28.69	×					
June 16	28.41	×					
Length							
May 25	34.42					×	
May 27	33.46				×		
May 30	32.19			×			
June 01	30.54		×				
June 04	29.31	×					
June 09	29.05	×					
June 16	28.67	×					
Weight							
May 25	19.23						×
May 27	17.82					×	
May 30	15.29				×		
June 01	12.67			×			
June 04	10.80		×				
June 09	10.01	×					
June 16	9.84	×					

Table 7. Measures of individual non-irrigated (NIr) and irrigated (Ir) strawberries harvested on five dates

Harvest time	Function	Diameter, mm		Length, mm		Weight, g	
		NIr	Ir	NIr	Ir	NIr	Ir
May 25	Mean	39.3	41.2	33.4	35.4	18.3	20.2
	Median	39.0	41.0	33.0	35.0	17.0	20.0
	Min	29.0	32.0	23.0	25.0	8.0	11.0
	Max	48.0	51.0	43.0	44.0	28.0	30.0
	SD	5.2	4.3	5.0	4.1	5.3	4.4
	CV%	13.2	10.5	14.9	11.6	29.0	21.9
May 27	Mean	37.7	38.0	32.9	34.0	17.7	17.9
	Median	38.0	37.0	32.0	34.0	18.0	17.0
	Min	22.0	28.0	19.0	22.0	5.0	8.0
	Max	50.0	52.0	49.0	47.0	29.0	32.0
	SD	5.2	4.9	4.8	4.9	4.6	5.2
	CV%	13.8	13.0	14.5	14.3	26.2	28.9
May 30	Mean	34.6	35.1	31.4	33.0	15.0	15.6
	Median	34.0	35.0	31.0	33.0	14.0	15.0
	Min	24.0	30.0	21.0	26.0	5.0	10.0
	Max	46.0	41.0	49.0	40.0	26.0	22.0
	SD	5.2	2.9	4.9	3.6	4.8	3.0
	CV%	15.2	8.4	15.9	11.0	34.0	20.1
June 01	Mean	31.8	32.2	30.1	31.0	12.5	12.9
	Median	31.0	32.0	30.0	31.0	12.0	12.0
	Min	22.0	25.0	21.0	19.0	5.0	6.0
	Max	47.0	42.0	42.0	42.0	27.0	25.0
	SD	4.2	3.7	4.7	4.4	4.2	3.7
	CV%	13.3	11.5	15.6	14.1	33.2	28.9
June 04	Mean	29.0	30.8	28.3	30.3	10.4	11.2
	Median	29.0	31.0	28.0	30.0	10.0	11.0
	Min	19.0	24.0	20.0	20.0	3.0	6.0
	Max	39.0	42.0	41.0	43.0	20.0	22.0
	SD	3.8	3.1	4.2	4.0	3.3	3.0
	CV%	13.0	10.1	14.8	13.1	31.7	26.6
June 09	Mean	28.3	29.1	28.6	29.5	9.6	10.4
	Median	28.0	29.0	28.0	29.0	9.0	10.0
	Min	21.0	22.0	18.0	20.0	4.0	2.0
	Max	41.0	44.0	43.0	44.0	21.0	23.0
	SD	3.9	3.9	4.7	4.9	3.5	3.8
	CV%	13.9	13.5	16.4	16.6	36.6	36.2
June 16	Mean	27.9	28.9	28.4	28.9	9.3	10.4
	Median	25.0	29.0	26.0	28.0	7.0	10.0
	Min	22.0	21.0	20.0	22.0	5.0	5.0
	Max	45.0	41.0	47.0	38.0	18.0	22.0
	SD	5.9	4.0	6.4	4.3	4.3	3.9
	CV%	21.3	13.8	22.5	14.9	46.6	37.4

SD – standard deviation, CV – coefficient of variation.

The analysis of the results allows to conclude that the increase in yield due to the irrigation is associated with increasing number of fruit on individual plants, their diameter and length, and hence the weight of a single fruit. In their two-year study on ‘Honeoye’ strawberries Boček et al. (2011) reported a mean weight of 11.2 g per fruit in 2009, and 14.8 g the following year. In turn, Masny & Żurawicz (2007) obtained an average fruit weight of 8.59 g to 13.77 g, with a mean of 11.44 g. Much lower values were reported by Rolbiecki & Rzekanowski (1997): 7.97 g for ‘Senga Sengana’ strawberries grown on drip-irrigated experimental plots and 5.81 g for the same cultivar grown on non-irrigated control plots.

CONCLUSIONS

The statistical analysis showed that the use of irrigation in the field cultivation of strawberries 'Honeoye' not only significantly increased the yield, but also allowed to obtain fruit of a larger diameter, length and weight, what is improved by the F statistic and the critical significance level ($p < 0.05$).

Analysis of the results shows that the yield potential of strawberries was largely dependent on irrigation and varied across harvest dates. Drip irrigation led to a considerable increase in yield as compared to the non-irrigated plants (by 22.79% in all measurements of harvest terms. The magnitude of the difference was probably mitigated by the occurrence of natural rainfall during the study period and the water holding capacity of the soil. The observed increase in yield primarily resulted from the higher fruit count per plant as well as greater individual fruit weight (on average by approx. 6%). While strawberries from the irrigated and non-irrigated rows did not differ visually, significant differences were found in terms of their size and weight.

Most scientific papers on the yield of strawberries are obtained on experimental plantations. Therefore, yields obtained from real commercial plantation allow to compare them with yield potential obtained from experimental studies.

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Bioenergy in agricultural companies: financial performance assessment

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Abstract. The target of increasing the use of renewable energy in rural areas has initiated the investments in bioenergy. The purpose of this paper is to assess the financial performance of Estonian agricultural companies that have invested in bioenergy solutions. An investment in bioenergy is attractive to the company if the results obtained by it enable benefits to the investors. In the context of the study of financial performance of agricultural companies that have undertaken bioenergy investments, the key performance indicators based on DuPont identity are analysed from the perspective of formulating and implementing a company's financial decisions. The data of financial statements of the analysed companies are from Estonian Agricultural Registers and Information Board (ARIB) and Commercial Register. The study reports the financial performance results of Estonian agricultural companies using renewable resources and producing bioenergy: whether they achieved higher efficiency and profitability or change in financial structure. The Estonian agricultural companies that have invested in bioenergy solutions may need to control their financial performance by improving profitability and controlling financial leverage.

Key words: agricultural companies' performance, bioenergy investment, DuPont identity, renewable energy.

INTRODUCTION

Bioenergy investments to agricultural companies contribute to the renewable energy target, objectives of rural development and Europe 2020 strategy for smart, sustainable and inclusive growth. The EU Renewable Energy Directive (2009/28/EC) requires Member States to develop plans to achieve the renewable energy target (Renewable Energy Directive (2009/28/EC). The National Renewable Energy Action Plan show a large commitment to biomass. The input of biomass in the EU planned by the Member States for 2020 bases mainly on wood and crops. National Development Plan of the Energy Sector until 2030 states that by 2030 the share of renewable energy accounts for 50% of final consumption of domestic electricity and 80% of the heat generated in Estonia (National Development Plan of the Energy Sector until 2030, 2017).

Wind and biomass are the most important resources of renewables in Estonia (Republic of Estonia, 2017).

According to the EU regulation No 1305/2013 Article 5 on support for rural development by the European Agricultural Fund for Rural Development defines the EU priorities for rural development. The objectives of rural development, which contribute to the Europe 2020 strategy for smart, sustainable and inclusive growth, will be achievable through the priorities for rural development. These priorities reflect the relevant thematic objectives: promoting resource efficiency and supporting the shift towards a low carbon and climate resilient economy in agriculture, food and forestry sectors. The focus is on efficiency in water use in agriculture; efficiency in energy use in agriculture and food processing; the supply and use of renewable sources of energy, by-products, wastes and residues and of other non-food raw material for the purposes of the bio-economy. The tasks include reducing greenhouse gases and ammonia emissions from agriculture and fostering carbon conservation and sequestration in agriculture and forestry (Regulation (EU) No 1305/2013).

The increasing efficiency of energy use in agriculture and food processing is achievable by promoting bioenergy investments in agricultural companies. Agricultural companies in Estonia have the supported possibility to invest in biomass production equipment, and bioenergy production facilities. A major part of the investments was financed according to The Estonian Rural Development Plan (ERDP) 2007—2013 Measure 3.1.3. – Investments into the production of bioenergy national resources (Estonian Rural Development Plan 2007–2013. 2008). Bioenergy investments are mostly capital-intensive, but implementation of these sustainable environmental investments in company level facilitates the supply and use of renewable sources of energy for the purposes of the bio-economy and will lead agricultural companies to greater social benefits and increased efficiency to in the longer period. The question by incorporating sustainable bio-based solutions in company level is whether it improves its financial performance.

The relationship between responsible behaviour of companies, environmental responsibility and financial performance has been widely debated subject in recent years. The environmental responsibility improves reputation and corporate image in the long run and will influence financial performance. (Adams, 2002; Oh et al., 2017). Bioenergy investments pursue environmental objectives in addition to profitability.

The financial performance of agricultural companies, which have invested in bioenergy solutions, is under the consideration in this paper. The purpose is to find out what change has occurred in the efficiency, the profitability, and the financial structure of Estonian agricultural companies that have invested in biomass production equipment, and bioenergy production facilities in 2009–2015, having used financing from the ERDP 2007–2013 Measure 3.1.3. The financial ratios are a valuable tool in understanding financial performance. The DuPont analysis is used to determine how the key performance indicators have changed after the implementation of bioenergy investments. According to the model, financial profitability ratio is decomposed into three separate components: efficiency, profitability, and leverage ratios (Grashuis, 2018).

The motivation for examining the financial performance of agricultural companies that have invested in biomass production equipment and bioenergy production facilities arise from the fact that the economic performance of agricultural companies, which contribute to achievement of the goals of EU to the renewable energy have not been systematically examined in Estonia. Several international studies have examined problems close to overall performance of agricultural companies (Ahrendsen & Katchova, 2012; Zorn et al., 2018), effect of corporate social responsibility on financial performance (Lassala et al., 2017), financial issues of bioenergy production (Hall & Howe, 2012; Bikar et al., 2018), whether the adoption of sustainable energy systems improves corporate financial performance and efficiency (Abulfotuh, 2007; Martí-Ballester, 2017).

As such, the agricultural companies that have invested in biomass production equipment and bioenergy production facilities have impact leading to greater environmental stability. Financially well-performed companies that are environmentally responsible should have a possibility at least to maintain their current competitive position. Even though being capital-intensive, bioenergy investments should enable agricultural companies through the increased financial performance to increment financial resources in the long run.

MATERIALS AND METHODS

The bioenergy investments, financing decisions and profitability: literature review

Bioenergy investments have increased due to new investment support policy in the EU. Bioenergy production as a part of bio-based business is a commercial activity that uses renewable biological resources and technologies to replace fossil fuels (Schmidt et al., 2012). The option to develop a sustainable bio-based economy is with the support the development of technologies, facilities and infrastructure for the biomass production. Bioenergy usage helps to improve agricultural productivity, reduce losses in agriculture and food wastage. Bioenergy production technology enables to use the remaining agricultural residues and refuses for energy purposes, and leads technically and economically to the use of all parts of the crop.

Bioenergy as a renewable energy option has been progressive as a promising option well suited to the food supply chain given the biological nature of its products (Hall & Howe, 2012; Jensen & Govindan 2014). Bioenergy production using biomass converting technologies may use various types of biomass: agricultural residues, forest residues, bio-energy crops on degraded land, especially perennial crops, aquatic biomass. Bioenergy is obtainable by combusting solid, liquid or gas fuels made from biomass, which may or may not have undergone some form of conversion process (Fig. 1). The technologies used for converting biomass to biofuels and bioenergy, especially biomass production equipment and bioenergy production facilities, are developing rapidly.

The cost of biomass is the most important cost element of all forms of bioenergy use. In order to remain competitive in energy markets, the food and agricultural prices cannot rise faster than energy prices for agriculture. Barring massive subsidies for bioenergy, the need to maintain competitiveness should create an endogenous brake on food prices (Schmidhuber, 2006). The fluctuations in biomass and fuel prices complicate the financial evaluation of the implementation of bioenergy technology for using biomass resources to substitute fossil fuels (Jensen & Govindan, 2014). Financial and environmental assessment of bioenergy application has indicated that it is possible to realize financial benefits in terms of additional profits and cost savings, but that challenging conditions can be problematic from a company perspective and provide challenges for the promotion of bioenergy investments. (Jensen & Govindan 2014). The analyses of whether the adoption of sustainable energy systems, which use renewable energy sources, improves corporate financial performance have shown that the adoption of sustainable energy systems help to improve short-term corporate financial performance (return on assets) due to the level of implementation of sustainable energy management system (Marti-Ballester, 2017).

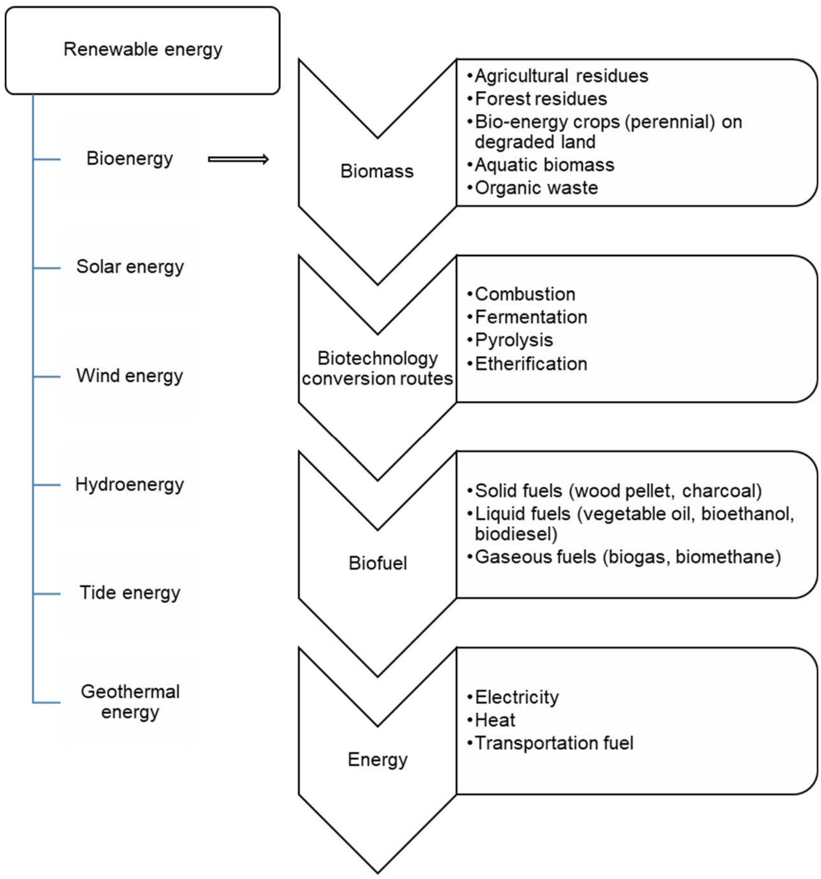

Figure 1. Bioenergy production process.
Source: Authors' compilation.

Financial issues act as both drivers and barriers in bioenergy production. They include high initial capital costs, available arrangements to buying and selling energy to a national grid, fluctuations in fuel prices (Hall & Howe, 2012). In spite of financial barriers, it has been found, that those heating companies which used renewable resources, performed remarkably better (Bikar et al., 2018). The use of renewable technologies may increase profits in the long and short-term (Hart & Ahuja, 1996). Also, the integration of sustainable energy strategies and systems may facilitate the improvement of financial performance (Lopez-Gamero et al 2009; Endrikat et.al, 2014), more precisely increasing the profitability in the long term (Schaumann, 2007).

Investments in bioenergy technology enable to realize financial benefits in terms of additional profits and cost savings, but require significant capital expenditures. Depending on current financial structure, these investments involve a significant amount of debt financing. Therefore, it is necessary to evaluate the relationship between financing decisions, and profitability in order to control the financial performance of the agricultural company.

Data and method of analysis

This analysis bases on the financial statement information of all Estonian agricultural companies, which have invested in biomass production equipment or bioenergy production facilities in 2009–2015, having used financing from the ERDP 2007–2013 Measure 3.1.3. These were micro-entrepreneurs, engaged in agricultural production, which employed at least 10 people and which sales revenue and/or total annual assets did not exceed 2 million euros. According to the measure the objective of the investment was the diversification of the activities of agricultural company with non-agricultural production; the production of biomass, biofuels, bio-electricity and bio-heat from biomass. Altogether, there were 123 farms in Estonia which made supported investments in biomass production equipment or bioenergy production facilities. Of these, 49 were agricultural sole proprietors and 74 agricultural companies.

The data of financial statements of the analysed companies were obtained from Estonian Agricultural Registers and Information Board (ARIB) and Estonian Commercial Register. The financial statements of agricultural sole proprietors are not included in the database of Estonian Commercial Register. The final sample consists of 74 agricultural companies. Of these 34 have invested in biomass production equipment, and 38 in bioenergy production facilities. 2 companies were invested both in biomass production equipment, and bioenergy production facilities. The types of investment objects were determined according to the information obtained from ARIB. The scope scale of biomass investments was calculated according to the type of investment by year.

The information found in companies' financial reports was the starting point of the analysis, providing information and data about their financial position and performance, including profitability. The observations exist every year. The steps that followed in analysis according to the set purpose and context of the analysis included collection of input data; processing of data, and interpretation of the processed data; development and communication of conclusions and recommendations. Carrying out descriptive statistics, companies' financial performance and trends in that performance were examined. Major considerations in analysis was the ability to maintain sufficient profitability after the implementation of the investments. The financial ratios for the agricultural companies for each pre-and post- investment year were calculated. The guide used in assessment of the financial performance of Estonian agricultural companies that have invested in biomass production equipment, and bioenergy production facilities was DuPont identity. DuPont analysis, a common technique that bases on the interrelationships between performance measures, is commonly used in the context of agricultural finance to analyse the components and linkages of a business (Escalante et al., 2009; Mishra et al., 2012). Financial performance is measurable by financial ratios, typically the ratio of return on equity in quantitative assessments of the financial performance at the company level. The ratios are inter-related and treatable as a system, and assessment of a company's efficiency, profitability, and leverage in combination provides a concrete information about financial performance for decision-makers in agriculture (Isberg, 1998; Latruffe et al., 2016).

DuPont identity decomposes the ratio of return on equity on three separate components: the net profit margin ratio, the asset turnover ratio, and the equity multiplier ratio. The formula is:

$$ROE = \frac{NI}{S} \cdot \frac{S}{A} \cdot \frac{A}{E} \tag{1}$$

where NI – net profit; S – sales revenue; A – total assets; E – equity. Specifically, the three indicators are NI/S – net profit margin ratio, S/A – asset turnover ratio, and A/E – equity multiplier. Financial performance analysis of the agricultural companies in pre- and post- investment years included these components as it enables to assess the financial situation of a company in detail. The data allows the analysis of a time series of diverse agricultural companies, but due to the small number of agricultural companies, the regression analysis cannot be performed. Since the data is not normally distributed, the non-parametric testing for comparison of the average indicators of the two differently financially structured groups is added. The comparison of different companies was done by using financial ratios instead of absolute values.

RESULTS AND DISCUSSION

The results of the study indicate that the bioenergy investments of Estonian agricultural companies, which were intended to facilitate the supply and use of renewable sources of energy were diverse. The equipment for biomass production included wood chips devices, biomass loaders, collectors of scrub and logging waste, woodpecker machines, logging waste loaders, energy brush harvesters. The bioenergy production facilities' investments included various types of heaters, biogas pipelines, boiler house heat pipes, mobile dry ovens, wood based bioenergy chimneys, renovation of bioenergy production complex, boiler plant equipment, biogas sediment pools, pellet stoves, wood chip warehouses, biomass storages etc. More than 73% of the bioenergy investments, in total amount of 21,911,187 euros, were made by agricultural companies (Table 1).

Table 1. Number and amount of investments of Estonian agricultural companies that were supported from the ERDP 2007–2013 Measure 3.1.3. – Investments into the production of bioenergy national resources (2009–2015)

	Total agricultural entities supported (number)	Total investment amount (€)	Agricultural companies supported (number)	Investment amount of the ag. companies (€)
Biomass production equipment	49	12,293,627	35	11,018,442
Bioenergy production facilities	74	17,404,798	39	10,892,745
TOTAL	**123**	**29,698,425**	**74**	**21,911,187**

Source: Authors' calculations.

During the period of 2009–2015 nearly 22 million of these investments, measured in euros, were made either in biomass production equipment or bioenergy production facilities. Half of the investments, i.e. more than 11 million euros, were allocated in biomass production equipment, and another half in bioenergy production facilities. Most of the investments were completed between 2013 and 2015 as can be seen from Table 2.

Table 2. The number of agricultural companies and amount in euros invested in biomass production equipment or bioenergy production facilities (2009–2015)

Year	Biomass production equipment		Bioenergy production facilities	
	Agricultural companies (number)	Investment amount (€)	Agricultural companies (number)	Investment amount (€)
2009	3	298,744	4	301,861
2010	3	679,796	0	-
2011	4	1,487,983	0	-
2012	5	1,823,026	5	898,762
2013	6	1,355,814	10	2,926,964
2014	10	3,906,051	7	814,888
2015	4	1,467,029	13	5,950,270
TOTAL	**35**	**11,018,442**	**39**	**10,892,745**

Source: Authors' calculations.

The summary statistics of financial indicators in investment year is shown in Table 3. Comparing to another group, these companies which invested in bioenergy production facilities, had higher sales revenues, and slightly lower net profits. The financial indicators were estimated for the groups according to investment type.

Table 3. Mean group comparisons of financial indicators in investment year (t)

Biomass production equipment, *n=35*				
Indicator (€)	mean	min	max	SD
Sales revenue (S)	470,503	2,766	2,384,297	463,035
Net profit (NI)	59,849	-427,598	625,919	135,476
Total assets (A)	1,254,769	11,147	11,340,197	1,643,438
Equity (E)	625 187	-189 404	6 874 054	940 722
Bioenergy production facilities, *n=39*				
Indicator (€)	mean	min	max	SD
Sales revenue (S)	796,865	0	10,717,000	1,340,644
Net profit (NI)	33,708	-2,414,411	985,278	257,621
Total assets (A)	1,486,519	3,389	10,524,000	1,525,748
Equity (E)	731,484	-223,772	4,173,000	899,933

Source: Authors' calculations.

The key financial indicators of companies have been changed year-by-year. The amount of sales revenue, net profit, total assets, total equity, and the ratio of investments-to-assets can be seen in Table 4, where the financial indicators for the year of the investment, for the years prior to investments (t-2), (t-1), and after the investment (t+1)…(t+4) are shown. During the observable period, the sales revenue was increasing, and the net profit was decreasing. Thus, implementation of the new technology have mostly increased the costs of agricultural companies. Thus, sales revenue and costs move in diverging directions, accounting for trends in profits and margins.

Table 4. Annual average financial indicators of Estonian agricultural companies, supported from the ERDP 2007–2013 Measure 3.1.3. – Investments into the production of bioenergy national resources (2009–2015)

\Year Indicator\	t-2	t-1	t	t+1	t+2	t+3	t+4
S	474,652	534,693	533,685	587,950	714,364	883,976	1,033,767
NI	86,765	99,439	44,473	37,279	-2,961	21,744	21,396
A	956,992	1,160,956	1,356,143	1,453,158	1,578,038	1,618,982	1,719,339
E	541,187	623 482	655,777	710,155	796,759	756,476	698,000
I/A	0.113	0.181	0.101	0.032	0.009	0.021	0.027

Source: Authors' calculations.

Financial performance analysis of the agricultural companies in pre- and post-investment years according to the DuPont model for financial statements evaluating the ability to earn a return on the capital, measured by financial ratios such as asset turnover ratio, net profit margin ratio and equity multiplier, is in Table 5. Profitability ratios show that companies were able to generate profit not in all years. The financial performance, measured by return on equity (ROE) has been higher before the years of the investment. The profitability ratio (NI/S) reveals low profitability of agricultural companies' after the investment has been implemented (t … t+4). In general, the higher the ratio, the better – this applies throughout the profitability ratios (Zorn et al., 2018). If costs are growing in faster rate than the sales revenue, profits will decrease. The decline of profits reflect company's weaker competitiveness in markets.

Table 5. Financial ratios of agricultural companies which invested in biomass production equipment or bioenergy production facilities (2010–2017)

Ratio \ Year	t-2	t-1	t	t+1	t+2	t+3	t+4
NI/S	0.183	0.186	0.083	0.063	-0.004	0.025	0.021
S/A	0.447	0.407	0.372	0.397	0.433	0.545	0.580
A/E	1.963	2.108	2.185	2.087	2.069	2.145	2.552
ROE	0.161	0.159	0.0067	0.0052	-0.004	0.029	0.031

Source: Authors' calculations.

The asset use efficiency has improved as asset turnover ratio (S/A) shows a slight increase in post-investment years. Compared to pre-investment period, the ratio is higher on the second year after investment, and growing. Asset management control seems to be not a potential weakness of companies. The more detailed assessment of indicators that comprise in asset turnover and profitability ratios indicate that the weaker financial performance is not as much the result of weaker generation of income as it is the problem of cost control. Both operating and financial costs have been grown in agricultural companies during the observable period.

The financial leverage, measured by asset-to-equity ratio (A/E) has been increased, precisely at the end of the period indicating that financial risk has been increased as the use of loan capital has increased interest expenses. The loan repayment capacity has decreased with the extensive use of leverage. Lack of sufficient equity capital is a problem of many smaller agricultural companies.

Several companies ended the second year after the implementation of bioenergy investment (t+2) with a loss. According to the micro-level data the declining return on equity, which is considered as negative change, was reported by 51 companies. Of 74 companies, 23 experienced an increase in return on equity. Since the number of analysed companies is small and the data are not normally distributed, the non-parametric test was used for evaluation. First, the significance of the return on equity change with the paired samples Wilcoxon test (difference between two years (t-1 and t+2)) was tested, and comparison of the average indicators of the two groups was done. The results on the Fig. 2 show that the *p-value* of the paired-samples test is 0.010 and average-samples test 0.049, which is less than the significance level alpha = 0.05. Of this the conclusion can be made that the median weight of the return on equity before treatment differs significantly from the median weight after treatment with a *p-value*, but the change of indicator value is negative.

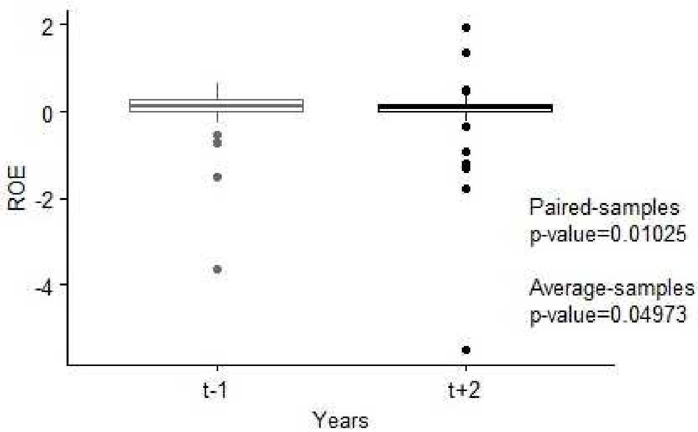

Figure 2. Return on equity before and after implementation of the bioenergy investment.

The fact that net profit was negative in many agricultural companies at that period, leaded to the situation where nearly 23% of the companies' equity was negative at the end of the period. The negative profitability for multiple years requires financing of these losses from retained earnings or additional external sources. These results are explainable as a result of various factors. The financial performance depends both on management decisions made inside a company, and on external factors. Plans for bioenergy investments have developed on estimates and assumptions in light of company's experience and perception of historical trends, current conditions and expected future developments. The future developments were predicted according to the management's expectations regarding the company's financial performance. In reality, the non-coincidence of the expectations and reality may occur. The factors that could cause the company's actual financial results, performance or achievements of future developments may differ from initial expectations. These factors could be the impact of adverse economic conditions, unfavourable weather conditions, seasonal sales, high levels of indebtedness, unavailability of additional capital, dependence on financing sources or strategic partners. Sometimes, unreasonable investments are also motivated by the thoughtless use of support measures. Therefore, recommendations for improving the financial performance relate to controlling costs, profitability and financial leverage constantly. Although results of many previous studies by Hart & Ahuja, 1996; Schaumann, 2007; Lopez-Gamero et al 2009; Endrikat et al., 2014; Marti-Ballester, 2017; Bikar et al., 2018 etc. are encouraging, showing positive return from investments in sustainable renewable energy facilities, some obstacles may occur in achieving high performance if specific control is neglected.

The current study captured 100% of Estonian agricultural companies that invested in biomass production equipment, and bioenergy production facilities in 2009–2015, having used financing from the ERDP 2007–2013 Measure 3.1.3., enabling to make conclusions about all of the companies. Still, the limitations remain in this study that could be taken into account in the future research. The dataset included relatively small number of agricultural companies. The further analysis would benefit from a larger sample.

CONCLUSIONS

In this article, the financial performance of Estonian agricultural companies in 2009–2017 was assessed. The purpose, to find what change has occurred in the efficiency, profitability, and financial structure of Estonian agricultural companies that have invested in biomass production equipment, and bioenergy production facilities in 2009–2015, having used financing from the ERDP 2007–2013 Measure 3.1.3., was estimated using the DuPont analysis. A comprehensive analysis of the financial indicators captured three components: asset turnover ratio, net profit margin ratio and equity multiplier.

The results of the descriptive statistics analysis confirm mainly that there is no improvement in the financial performance in the short run. Return on equity has generally been higher in years' before the investment. The profitability ratios indicate a low performance of agricultural companies' after the investment has been implemented. Although the asset use efficiency has improved, the weaker financial performance in post-investment years is not as much the result of weaker generation of income as it is the problem of cost control. Implementation of investments in biomass production equipment, and bioenergy production facilities may reduce environmental impact, but it does not necessarily improve financial performance. The results indicated that many of the agricultural companies that invested in biomass production equipment, and bioenergy production facilities did not show remarkable improvement of financial performance. The lack of equity capital is a problem of many agricultural companies. This reveals to the necessity of improvement of the company's control over profitability, costs and financial leverage.

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Geostatistics applied to evaluation of thermal conditions and noise in compost dairy barns with different ventilation systems

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Abstract. The objective of this work was to evaluate the spatial distribution of thermal conditions and bed variables in compost dairy barns with different ventilation systems, through the technique of geostatistics. The experiment was conducted in April 2017, in farms located in Madre de Deus, Minas Gerais, Brazil. Three facilities were evaluated with different ventilation systems: natural (NV); mechanical of low volume and high speed (LVHS); and mechanical of high volume and low speed (HVLS). The interior of the premises was divided into 40 meshes equidistant points, in which air temperature, relative humidity and air speed were manually collected. Geostatistics technique was used to assess the spatial dependence of the variables. The results showed the occurrence of dependence and spatial variability of the variables evaluated. Based on thermal comfort indexes, it was concluded that dairy cows were under stress conditions during the hottest hours of the day in the three animal facilities evaluated. The results obtained allow us to understand that the thermal environment is more influenced by the ventilation system adopted.

Key words: animal welfare, dairy cattle, compost barns, geostatistics.

INTRODUCTION

The dairy industry is one of the most important for Brazilian agribusiness, especially for the importance of milk and its derivatives in the composition of the human diet (Sabbag & Costa, 2015). In 2017, the national production increased +4.02%, with a total of 24.07 million tons of milk (Carvalho et al., 2018).

Thus, in order to achieve satisfactory results in their activity, more dedication and investments are demanded by the milk producers. Every day, they face several challenges, since factors such as building structure, thermal cow environment, management, among others, have direct implications on the productivity of the herd. Especially the building structure is of great importance for the success of the activity, since well-sized facilities provide better comfort conditions for the animals, thus improving wellbeing and thereby contributing to increased productivity (Costa & Silva, 2014).

Among the systems of confined production of dairy cattle, the compost barn (CBP, Compost Bedded Pack) appears as a viable alternative to the conventional systems used in milk production. According to Barberg et al. (2007), the system consists of the confinement of the animals in a large common area, covered by bed in comfortable material that under appropriate conditions of temperature and humidity undergoes the composting process over time. The advantages of the system are the improvement in the comfort and well-being of the herd, the gains in productivity and sanity, the reduction of production costs, as well as the correct destination of the organic wastes, through the composting process of the wastes produced by the animals (Black et al., 2013).

The construction of CBP should consider several factors, especially the ventilation system employed, which is responsible for maintaining a comfortable environment for the animals, for the removal of gases and heat, and for drying the bed material (Janni et al., 2007; Lobeck et al., 2011; Angrecka & Herbut, 2014, Lendelova et al., 2017). In some CBP where it is not possible to naturally achieve the volume of air necessary to promote animal comfort and bed drying, mechanical ventilation is the preferred solution. The main types of fans used in the facilities are the high volume and low rotation – HVLS and low volume and high rotation - LVHS (Leso et al., 2018).

Some milk producers and researchers have been looking for the assistance of innovative methods, computational tools for evaluation and decision support to control the welfare of confined animals for better evaluation of the animal production (Borges et al., 2010; Herbut & Angrecka, 2015). Among the methods used, we highlight the evaluation of the spatial distribution through geostatistics, which allows the interpretation of the results from the natural structuring of the data, based on spatial dependence in the sampling interval considered (Cambardella et al., 1994; Vieira, et al., 2000). Thus, the variability of the attributes of interest and their influence on the environment can be understand (Silva Neto et al., 2012).

The objective of this work was to evaluate the spatial distribution of thermal conditions and bed variables in compost dairy barns with different ventilation systems, through the technique of geostatistics.

MATERIALS AND METHODS

Characterization of animal facilities

The study was carried out during April 2017 in two milk farms located in the Madre de Deus de Minas, Minas Gerais state, Brazil (latitude 21° 29' 2" S, longitude 44° 19' 58" W, and altitude 985 m). The climate of the region, according to Köppen climatic classification, is classified as Cwa - temperate humid, with dry winter and rainy summer, subtropical, with dry winter and warmest month temperature higher than 22°C (Sá Júnior et al., 2012).

In this study, three compost dairy barns (CBP) were evaluated in two milk farms close to each other (about 2.0 km away). Two CBP facilities were located on the same milk farm and had the same constructive characteristics, such as: 17.0 m wide and 33.2 m length, 4.6 m eave height, roof pitch of 16°, and cover with metallic tiles (thickness of 0.50 mm), with orientation in the northeast-southwest direction (Fig. 1, a). In the first CBP, the ridge opening was closed and the ventilation system was LVHS: four box fans, 4.5 m of height and slope of 45° (Mamute®, diameter of 2.0 m, number of propellers 5, rotation 1,750 rpm, power of 2.2 kW or 3.0 hp, flow of 120.000 m³ h^{-1}).

The second CBP had an elevated ridge opening and natural ventilation (VN), without the use of mechanical ventilators. In both CBP, the feed alley had a line of sprinklers, which were operated for 1.0 min and disconnected for 5 min. The sprinkler system was manually switched on whenever the temperature was found to be above the suitable temperature for the animals (23.0 °C).

In the third CBP evaluated, the constructive characteristics were based on: 17.5 m wide and 48.6 m length, 4.2 m eave height, roof pitch of 16° and overshot ridge opening, with metallic structure, coverage in metal tiles (thickness of 0.40 mm), and orientation in the east-west direction (Fig. 1, b). It was equipped with a HVLS ventilation system: two fans allocated at 3.8 m (BigFan®, diameter 7.5 m, power of 2.2 kW and air flow of 650.000 $m^3 h^{-1}$).

In all CBP, the bedding material was wood shaving, and the depth of the bed was approximately 0.40 m. The bed aeration of bed in the first and second CBP was done only once per day, using a rototiller. In the third CBP, the aeration of bed was performed twice daily during the milking period using a field cultivators adapted to the property.

In the CBP with LVHS, 79 Holstein dairy cows were kept, with a mean milk production of 30 kg $animal^{-1}$ day^{-1}. Furthermore, 105 Holstein dairy cows were housed in the CBP with natural ventilation, average milk production of 28 kg $animal^{-1}$ day^{-1}. In the CBP with HVLS ventilation system, 126 Holstein dairy cows were housed, with an average milk production of 30 kg $animal^{-1}$ day^{-1}.

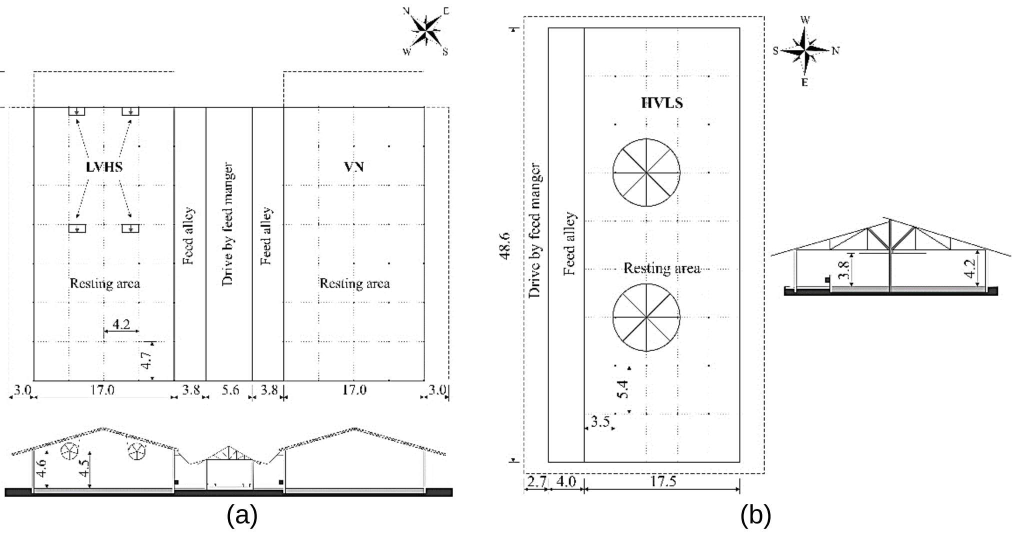

Figure 1. Schematic representation of CBP with different ventilation systems: a) LVHS and VN; b) HVLS. Dimensions in meters (m).

Instrumentation and data collection

For the collection of data, the interiors of the CBP facilities were divided through meshes points composed of 40 equidistant points, such divisions being made according to the constructive characteristics of the CBP facilities. All data collections were carried out during 12:00 to 16:00 hours. The schematic representations of the CBP facilities with meshes points used to measure the data is illustrated in Fig. 1.

The environmental variables were collected near the geometric centres of the animals (1.5 m height above the ground, simulating the height of the dorsum of the animal). A portable digital thermo-higro-decibel-lux meter was used to collect air temperature (t_{db}), relative humidity (RH) and noise level (Instrutherm®, model THDL-400, with accuracy of ± 3.5%). The air velocity was measured by means of a hot wire anemometer (Instrutherm®, model TAFR-190, with accuracy of ± 0.1 m s^{-1}).

For the evaluation of the thermal comfort inside the CBP, the Temperature and Humidity Index (THI) was used, according to the equation proposed by Buffington et al. (1983):

$$THI = 0.8 \cdot t_{bs} + RH \cdot \left(\frac{t_{bs} - 14.3}{100} \right) + 46.3 \quad (1)$$

where t_{db} is dry-bulb air temperature (°C); and RH is the relative humidity (%).

For dairy cattle, the limits of THI that characterize a situation of comfort or discomfort are not fully shared among the scientific community. In general, the limits proposed by Thom (1959) and Hubbard et al. (1999), for dairy cattle are: THI < 74 - thermal comfort condition; $74 \leq \text{THI} < 79$ - an alert condition for producers; $79 \leq \text{THI} < 84$ - a hazard condition, and safety measures must be taken to prevent disastrous losses, especially for confined herds; and, THI > 84 - emergency situation, and urgent steps must be taken to avoid loss of staff. However, THI values above 72 represent a stressor condition for Holsteins cows, which may lead to reduced productivity (Johnson, 1980; Herbut et al., 2015).

Statistical and geostatistics analysis

Statistical analyses of variance were performed using the data collected to verify the influence of the different types of ventilation on the analysed variables and the results of the analyses were all significant. Thus, we analysed the differences between means, which were compared by Tukey's test ($p < 0.05$), using statistical software R (Development Core Team, 2016).

In order to verify the spatial behaviour of the variables within the CBP facilities, as well as to predict their levels in non-sampled locations and the occurrence of spatial dependence, the geostatistical technique was used. The analyses were performed using the R (Development Core Team, 2016) software, through the geoR library (Ribeiro Junior & Diggle, 2001). The evaluation of the spatial dependence of the variables inside the CBP facilities was made through semivariogram adjustments. For the estimation of the semivariogram we used the estimator of Matheron (1962):

$$\hat{\gamma}(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} \left[Z(X_i) - Z(X_i + h) \right]^2 \quad (2)$$

where $N(h)$ corresponds to the number of experimental pairs of observations $Z(X_i)$ and $Z(X_i + h)$, separated by a distance h.

The coefficients of the theoretical model for semivariogram, called nugget effect – C_0, plateau – $C_0 + C_1$, and reach – a, were obtained from a mathematical model for the calculated values of Bachmaier & Backers (2008).

The degree of spatial dependence (GDE) was determined by the ratio between the nugget effect (C_0) and the threshold ($C_0 + C_1$), multiplying by 100. Dependency analysis was performed using Cambardella et al. (1994). According to this classification, it is considered as a strong spatial dependence the semivariograms that have nugget effect of less than 25% of the plateau, moderate spatial dependence that have a nugget effect between 25% and 75% of the plateau and weak spatial dependence of the semivariograms that present nugget effect greater than 75% of the plateau.

Due to the small grouping of data, the Restricted Maximum Likelihood Estimation (REML) method was used, as suggested by Marchant & Lark (2007). The model tested for the adjustment of the experimental semivariogram was the Spherical, a model widely used in geostatistics and that returns good results.

In order to make maps of the spatial distribution of the levels of variables within the CBP facilities, the ordinary data kriging technique was used. From the interpolated data, response surface maps were generated, using the ArqGIS® software, version 10.1.

The descriptive statistics were used to determine the fraction of area occupied by the intervals of each of the analysed variables and to better characterize the spatial distribution of the variables inside the CBP facilities.

RESULTS AND DISCUSSION

The mean values of t_{db}, RH, THI, V_{air}, and noise within the CBP facilities are listed in Table 1. There was a statistically significant difference between the means of all variables analysed, at the level of 5% probability using the Tukey test. In relation to the t_{db}, RH, THI attributes, the highest mean values were verified for the CBP with VN, while the lowest values were found inside the CBP with HVLS ventilation system. According to the classification suggested by Warrick & Nielsen (1980), the variability of these variables and index was low (CV < 12%). The average THI values inside the CBP facilities were higher to Holsteins cows, which is 72 (Johnson, 1980).

Table 1. Mean values of dry-bulb air temperature (t_{db}, °C), relative humidity (RH, %), temperature and humidity index (THI), air velocity (V_{air}, m s^{-1}), and noise (dB)

Ventilation	t_{db} (°C)		RH (%)	THI		V_{air} (m·s^{-1})		Noise (dB)	
VN	28.8 (±0,5)	a	53.0 (±2)	77.0 (±1)	a	0.3 (±0.1)	c	49.9 (±1.3)	c
LVHS	28.1 (±0,4)	b	46.0 (±2)	75.0 (±1)	b	1.0 (±0.5)	a	72.2 (±2.3)	a
HVLS	27.0 (±0,4)	c	43.0 (±1)	74.0 (±1)	c	0.8 (±0.6)	b	53,9 (±1.8)	b
CV (%)	1.57		3.49	0.65		62.66		3.19	

* Means followed by the same letter do not differ statistically at the 5% level of significance, by the Tukey test; VN – natural ventilation; LVHS – mechanical ventilation of low volume and high rotation; HVLS – mechanical ventilation of high volume and low rotation; CV – coefficient of variation.

Regarding V_{air} and noise level, there was a significant increase of their levels with the use of forced ventilation, being greater when using LVHS ventilation. Considering the classification suggested by Warrick & Nielsen (1980), the variation of the noise level was low (CV < 12%). On the other hand, for the V_{air}, a high variability condition (CV > 60%) was observed. Since it is an attribute with high spatial and temporal variability, which can change its magnitude and direction abruptly (Faria et al., 2008), the heterogeneity of the data is a common occurrence.

In countries of tropical and subtropical climate, such as Brazil, the reduction of heat stress is necessary, so that the thermal comfort required by the animals can be assured. The solution most commonly employed by the producers is the use of environmental conditioning systems, which reduces the heat load on the animals to ensure adequate environmental welfare. Lack of homeostasis results in animal physiological reactions such as an increase in rectal temperature and respiratory rate (Frazzi et al., 1998; Godyn et al., 2019). The analysis of the results presented in Table 1 allows us to understand that the use of mechanical ventilation alone (LVHS and HVLS) provided a better thermal comfort condition within CBP facilities evaluated by increasing the velocity of the air around the animals and thus increasing the convection exchange, but it is not sufficient to promote adequate thermal comfort to animals. It is also observed that the use of ventilators caused an increase in sound pressure levels.

As a way to better evaluate the variables and index studied in a quantitative and qualitative way, the techniques of descriptive statistics and geostatistics were used, which provide important information regarding the area occupied by each class of the attribute, as well as to understand its variability and influence on the environment. In this way, the models and parameters of the experimental semivariograms adjusted for the variables and index of the thermal and acoustic environment in the three facilities are presented in Table 2. For these attributes, semivariograms conformed to the spherical model, which, according to Isaaks & Srivastana (1989), is considered transitive since it has a threshold.

Table 2. Estimated models and parameters of the experimental semivariograms adjusted for the attributes of the thermal and acoustic environment

Variable	Ventilation	Method	Model	C_0	C_1	$C_0 + C_1$	*a*	GDE
t_{db}	VN	REML	Spherical	0.00	0.15	0.15	14.88	0.00
	LVHS			0.00	0.18	0.18	4.39	0.00
	HVLS			0.00	0.13	0.13	4.48	0.00
RH	VN	REML	Spherical	0.00	5.25	5.25	12.10	0.00
	LVHS			1.50	2.01	3.52	17.80	42.73
	HVLS			0.00	1.63	1.63	29.72	0.00
THI	VN	REML	Spherical	0.00	0.39	0.39	11.93	0.00
	LVHS			0.00	0.32	0.32	17.30	0.00
	HVLS			0.00	0.05	0.05	33.49	0.00
V_{air}	VN	REML	Spherical	0.05	0.01	0.06	24.94	77.08
	LVHS			0.32	0.25	0.57	28.96	55.80
	HVLS			0.11	0.16	0.27	16.16	39.57
Noise	VN	REML	Spherical	0.00	3.53	3.53	4.52	0.00
	LVHS			0.00	3.90	3.90	35.90	0.00
	HVLS			0.00	3.78	3.78	19.17	0.00

* VN – natural ventilation; LVHS – mechanical ventilation of low volume and high rotation; HVLS – mechanical ventilation of high volume and low rotation; C_0 – nugget effect; C_1 – contribution; $C_0 + C_1$ – threshold; a – reach; GDE – degree of spatial dependence; t_{db} – dry-bulb air temperature; RH – relative air humidity; THI – temperature and humidity index; and Vair – air velocity.

The nugget effect (C_0) is an important parameter of the semivariogram, since it indicates the unexplained variability. The importance of this parameter is related to the discontinuity check of the semivariograms for distances less than the shortest distance between the collection points, being this discontinuity caused by errors of analysis and during the collection, local variations, among others, being impossible to perform the quantification of each of these components (Ferraz et al., 2017a).

In relation to the evaluated attributes, the values of C_0 were mostly equal to zero (t_{db}, RH, THI and noise), indicating that, in general, such variables did not present unexplained variability, semivariograms did not have discontinuity and characterizing dependency condition spatial distribution according to the classification of Cambardella et al. (1994). The exceptions were the RH (only in the CBP with LVHS) and V_{air} (all CBP evaluated), which presented non-zero C_0 values. In the LVHS ventilation system, the unexplained spatial variability of the RH variable at the threshold was 42.73%, indicating that the spatial dependence of this variable for this installation is moderate (GDE = 42.73%). The same was observed for the variable V_{air}, which presented initial variability higher than 25% of the level in the three facilities, being greater than 75% in the CBP with VN. The V_{air} presents high variability, being able to change of magnitude and direction abruptly and to present high variations in a small interval of time (Faria et al., 2008).

Since it is a very variable attribute in space and time, its measurement is difficult to perform, being subject to several sources of error, both related to its collection and to local variations. The occurrence of only moderate (25% < GDE $\leq$ 75%) and weak (GDE > 75%) spatial dependence, verified for V_{air} in mechanical ventilation and natural ventilation, respectively, is a function of the initial unexplained variability, common to such an attribute. For V_{air}, the lowest GDE was verified for the installation with HVLS mechanical ventilation (39.57%).

In relation to the acoustic environment, the contribution of C_0 in the level was equal to zero in the three installations, characterizing a condition of strong spatial dependence, in which there is no initial variability unexplained and there is no discontinuity in the semivariograms.

According to Ferraz et al. (2017a), which provides as information the distance that a variable is influenced by the space, making possible the determination of the spatial dependence limit. If the distance between sampling points is less than a, these points are correlated to each other, and interpolation techniques can be used to determine the levels of the variable in non-sampled locations. On the other hand, if the value of a is less than the shortest distance between collection points, the semivariogram is constant for any value, there is no spatial dependence and the geostatistical technique can not be applied (Vieira, 2000).

For all variables studied, the values of a were greater than the smaller distance between the points used in the CBP facilities. The lowest range values were verified for the variable t_{db} within the LVHS and HVLS ventilation installations (4.39 and 4.48 m, respectively), which were still higher than the smaller distance between sampling points (4.25 m). Since the values of a were different for each of the variables, it is inferred that it is possible to use different meshes for the sampling of the different attributes, being able to be used the same mesh in cases in which the variables present values of the next to each other. This makes it possible to reduce the number of collection points, since, in cases of occurrence of high values of a (as observed for the RH and V_{air} variables), meshes with a greater distance between collection points (> 10 m, for example).

From the knowledge of the existence of spatial variability, the geostatistical technique can be used to make maps of spatial distribution, through data interpolated through the ordinary kriging technique. These maps can be used to identify the areas with higher and lower value of the study variable, allowing the precise management of the necessary interventions in the areas where the technique is applied (Ferraz et al., 2017b).

In this way, the spatial distribution maps of the variables t_{db}, RH and THI for the CBP facilities equipped with different ventilation systems, as well as the graphs of cumulative frequency of the variables in each CBP facilities, facilitate the understanding of the data.

The variability of the t_{db} attribute was higher for the VN installation (Fig. 2, a), which presented a range of variation equal to 3.0 °C (27.0 to 30.0 °C). In such a CBP, the area with the highest temperature was observed in the northeast face, where the cut of a slope was made for the installation to be constructed. Due to its location close to the slope, natural ventilation on this face of the facility became reduced, reducing heat exchanges with the environment and making t_{db} higher. In the LVHS ventilation system, the t_{db} presented a lower amplitude of variation (2.0 °C), and the region with the highest temperature (28.0 to 29.0 °C) occurred near the southwest face, a region that received direct solar radiation in the afternoon absence of lateral closure. On the other hand, the HVLS mechanical ventilation system had milder temperatures (26.0 to 28.0 °C), and the region with the lowest t_{db} occurred near the west face, a region near the waiting and milking rooms, which operated as lateral closure, avoiding the incidence of direct solar radiation inside the CBP facilities.

According to Nääs (1989), the thermoneutrality zone for lactating cows is between 4.0 and 24.0 °C, and can be restricted to the range of 7.0 to 21.0 °C, according to the RH and incident solar radiation. For Holsteins cows, the temperature range characterized as thermoneutrality is between 4.0 and 26.0 °C (Huber, 1990). At the outside temperature of 35.0 °C the milk yield decreased by 33%, and at the temperature of 40.0 °C by 50% (West, 2003).

Inside of the three CBP facilities the t_{db} was above the upper recommended critical limit for lactating Holstein cows (26.0 °C), the most critical conditions being observed for the VN, which presented temperatures above 28.0 °C throughout the entire installation (99.9% of the bed area), a condition that may lead to a deterioration in welfare and thus reduced productivity of the animals (Fig. 2, b). Although the t_{db} were still above adequate, in the CBP facility provided with mechanical ventilation lower temperatures were observed, with the best results verified for installation with HVLS ventilation. In such an installation, the t_{db} was below 27.0 °C in 45.5% of the area, and at 28.0 °C in 54.5% of the bed area, being close but still above the upper critical temperature limit. In the LVHS ventilation system, in only 47.0% of the bed area, the temperature was below 28 °C, indicating that the ventilation system promoted the reduction of t_{db}, but it was not enough to reduce it to adequate levels.

Fig. 2, c shows the occurrence of higher RH and higher amplitude of variation in the VN installation, which presented regions with values between 45 and 60%. In such CBP facility, it can be inferred that the occurrence of higher values of humidity is due to the low capacity of removal of moisture provided by natural air currents. It is also worth noting that the region where the RH was highest is located near the feed alley, where the animals were cooled by wetting (sprinkling) during the hottest hours of the day. In the feed alley were also located drinkers, sources of elevation of the humidity of the environment. Also the water spill realized by the animals when they drink favours the increase of humidity, due to the evaporation of the water. On the other hand, in the installations provided with mechanical ventilation, RH was less than 50%, indicating that the ventilation systems used were effective in promoting the reduction of ambient humidity. The lowest RH values were verified in the LVHS ventilation installation, where the prevalence of RH was below 45%. As it is a system of ventilation with greater speed of rotation, it is possible to obtain a greater removal of humidity from the environment. In the installation with HVLS ventilation, the predominance of humidity values between 45 and 50%, with uniform distribution throughout the CBP facility, indicates that, despite the slower rotation speed, the use of fans of this type guarantees homogeneous RH conditions.

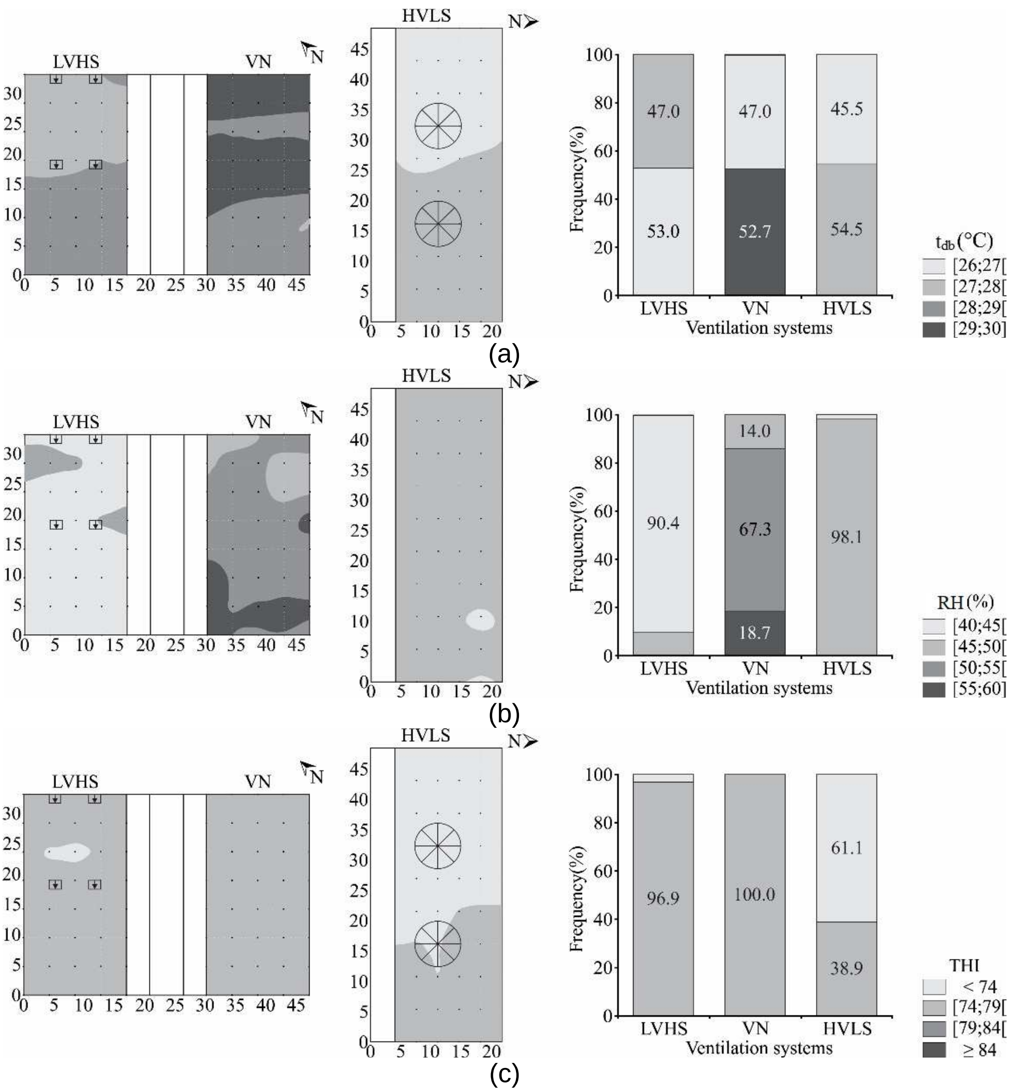

Figure 2. Spatial and frequency distribution of the variables: dry bulb air temperature – t_{db} (a), relative humidity – RH (b), and temperature and humidity index – THI (c) at the CBP facilities. * VN – natural ventilation; LVHS – mechanical ventilation of low volume and high rotation; HVLS – mechanical ventilation of high volume and low rotation. Dimensions in meters (m).

According to Fig. 2, b, in 86.0% of the area of the CBP facility with VN the RH was superior to the one observed in installations with mechanical ventilation (RH ≥ 50%). With a lower RH and a better uniformity for such attribute among the evaluated facilities, the HVLS mechanical ventilation system had 98.1% of its RH area between 45 and 50%. In the facility with LVHS ventilation the RH was less than 45% in 90.4% of the area.

The THI had a uniform distribution throughout the CBP facility, with the highest uniformity verified inside the CBP with VN (Fig. 2, c). On the other hand, within this whole installation, an alert condition was observed, due to the combination of high tdb_{bs} and RH, verified in the same. A similar condition was found for the LVHS facility, which despite having lower RH values, showed t_{db} values still relatively high (27.0 to 29.0 °C), making the THI above comfort condition (THI ≥ 74). Since both facilities were separated only by the feed alley, located close to machine sheds and placed in a region with low wind speed (near slope), it is inferred that their location may have impaired ventilation, reducing heat exchanges by convection, and causing high values of THI.

The spatial distribution of the THI in the HVLS mechanical ventilation system showed better thermal conditions, characterizing an adequate comfort condition from the west face (48 m) to the location of the ventilator (15 m). In such an installation, only the area located near its eastern side was found to be alert condition, being a function of the highest t_{db} observed at this site. This region, for the absence of lateral closure, was exposed to direct solar radiation in the morning The increase of t_{db}, due to this reason, remained throughout the day. It is inferred that the use of lateral closure or auxiliary cover may contribute to the reduction of THI in this region, since it avoids direct exposure to solar radiation.

Fig. 2, c, which shows the frequency distribution of the THI classes, shows that only in the HVLS mechanical ventilation the thermal conditions were characterized as adequate comfort, corresponding to 61.1% of the bed area.

In all CBP facilities evaluated, the V_{air} was lower than the recommended (Fig. 3, a). According to Black et al. (2013), in CBP facilities, the ventilation should be provided such that the V_{air} is close to 1.8 m s^{-1} throughout the entire CBP, so that it can dry the bed, remove gases and favour the heat exchanges between the animal and the environment.

The worst situation was verified for the CBP with VN, where this attribute was less than 1.0 m s^{-1} in 99.9% of the bed area. On the other hand, in CBP with presence of LVHS and HVLS ventilation, V_{air} was greater than 1.0 m s^{-1} in 58.4% and 42.1% of bed areas respectively, showing that the systems used promoted the increase of such an attribute to levels close to adequate in most of the facilities (Fig. 3, a). Since they have not been able to maintain the V_{air} throughout the entire CBP area, it can be understood that the quantity and arrangement of the fans in the barn is not adequate, in relation to the design of facility. The results also show that the use of mechanical ventilation in tropical conditions is necessary for the proper functioning of the system, since only the VN was not sufficient to promote V_{air} values according to the recommendation for CBP barns.

The noise level distribution within the facilities was uniform, with a variation of approximately 10 dB for the three CBP facilities (Fig. 3, b). The most significant values were observed inside the LVHS ventilation system, which had a noise level higher than 70 dB near and throughout the region of influence of the fans, being a function of the rotation of the blades. In the CBP with HVLS ventilation the observed noise levels were lower and closer to that verified for VN. For this CBP, the noise levels varied between 50 and 60 dB, and the areas with higher values (> 55 dB) occurred immediately below the area where the fans were located, and their occurrence could be attributed to equipment rotation and noise characteristic of the engines. According to the manufacturer's catalogue of specifications (AIRWAY BIGFAN, 2018), the noise levels emitted by the fans used are between 50 and 63 dB, characterizing them as low emission. Therefore, it can be verified that the results found are in accordance with the specifications of the equipment. The lowest values of sound pressure were observed in the shed with NV. The areas with the highest values were located in the central-peripheral region of the facility and were caused by the vocalization of the animals, the management operations and external sources. Eventually, it was also verified the contribution of noises coming from the walking of employees and the traffic of machines in the vicinity of the facility.The frequency of occurrence of noise in the facilities was very different in the three CBP. In the VN the 56.2% of the area presented a noise less than 50 dB, in the HVLS the noise was higher than 50 dB in 99.4% of the area, and in the LVHS the noise was higher than 70 dB in 83.2% of the area (Fig. 3, b).

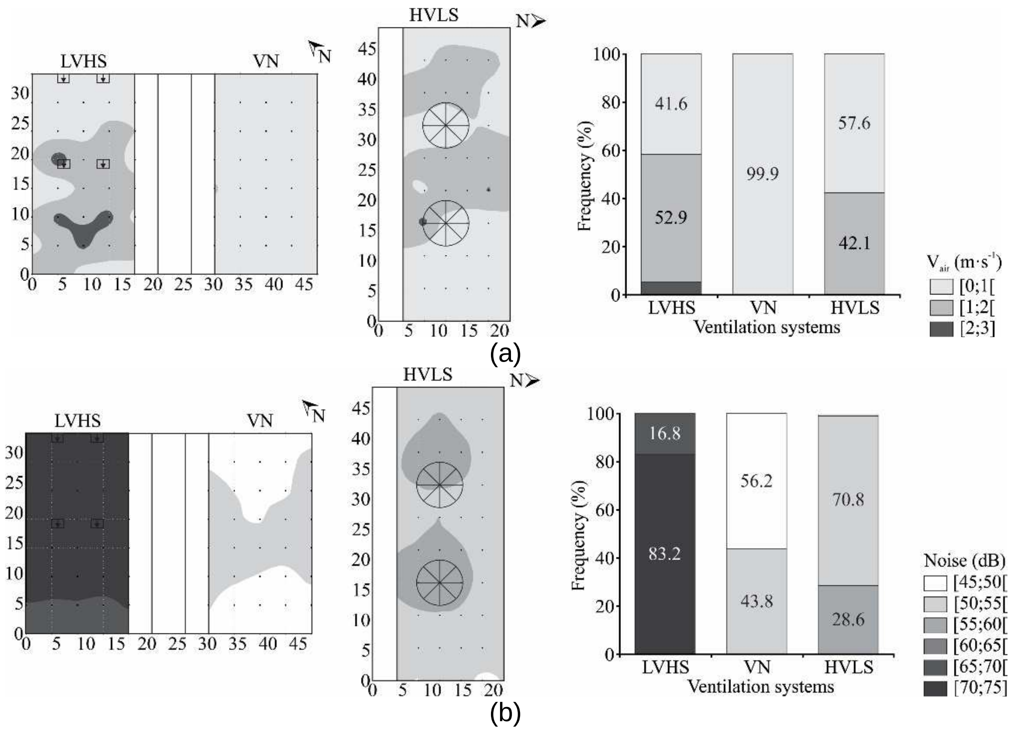

Figure 3. Spatial and frequency distribution of the variables: (a) air velocity and (b) noise level. * VN – natural ventilation; LVHS – mechanical ventilation of low volume and high rotation; HVLS – mechanical ventilation of high volume and low rotation; V_{air} – air velocity; Dimensions in meters (m).

With regard to the rearing of housed cattle, there is no applicable legislation laying down the minimum conditions of accommodation and, therefore, it is not possible to verify whether they meet the needs of the animals. In relation to work safety, the main norm related to the quantitative and qualitative evaluation of the noise to which the worker is exposed is Brazilian Regulatory Standards (Ministry of Labor and Employment, 1978), which establishes the limits of tolerance for continuous or intermittent noise to which he may be exposed without risk to his health. According to this standard, the maximum noise level at which the worker can be exposed during an 8-hour day's workload is 85 dB (A), and therefore normal animal handling activities at the facilities assessed do not pose a health risk of the professionals who carry them out.

CONCLUSIONS

The use of the geostatistics technique allowed to verify the occurrence of spatial dependence of the evaluated attributes, being predominantly strong for the variables of the thermal and acoustic environment.

The spatial distribution maps showed the occurrence of variability of the variables inside the facilities. Regarding the thermal environment, the best results were observed for the installation with high volume and low rotation ventilation (HVLS), which presented lower levels of dry bulb air temperature (t_{db}), relative humidity (RH), and temperature and humidity index (THI), as well as noise levels close to those found inside the facility with natural ventilation (NV).

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Most appropriate measures for reducing ammonia emissions in Latvia's pig and poultry housing

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Abstract. New goals of ammonia emissions reduction for each of EU Member State, including Latvia, were approved by the EU Directive 2016/2284/EU 'on the reduction of national emissions of certain atmospheric pollutants'. Agriculture sector, particularly livestock farming, is the main source of these emissions. Besides, the implementation of modern or intensive animal rearing/breeding technologies causes the increase of emissions in Latvia. Therefore, more effective ammonia abatement measures or techniques should be chosen for implementation in Latvia to reach the objectives. The description and benefits of such measures are provided in the guidelines and recommendations developed and approved by the United Nations Economic Commission for Europe (UNECE) and the European Commission. However, all of these recommendations are not applicable in Latvia. Therefore, the aim of research was to find most appropriate ammonia emissions abatement measures for pig and poultry farming in Latvia. The study was focused on the intensive pig and poultry farming, particularly animal housing. Evaluation or assessment of most appropriate ammonia emissions' reduction measures was conducted using an expert method. The results of the study indicate that it is possible to ensure reduction of ammonia emissions by comparatively simple and less expensive options that could be more or less easy implemented (e.g. ensuring cleanness in the livestock building, periodical removal of manure, covering of poultry litter or solid manure stockpiles with plastic sheeting, etc.). Even more effective reduction of ammonia emissions can be achieved by implementation of measures, which require significant investments, as well as additional operating costs.

Key words: ammonia, abatement measures, survey, housing.

INTRODUCTION

The environmental impact of modern or intensive farming, has led to a series of international protocols (e.g., Gothenburg Protocol), EU legislation, as well as national regulations. The new EU Directive 2016/2284 'on the reduction of national emissions of certain atmospheric pollutants' has adopted new ammonia emissions' reduction goals, which are based on the UN level agreement and the revised Gothenburg Protocol. Directive 2016/2284 sets out the commitments of each EU Member State to reduce emissions of five pollutants, including ammonia (NH_3) emissions (EC, 2016).

Two different timelines are considered: from 2020 to 2029, and from 2030 onwards; and the reduction goal is set by EU for each Member State as a percentage with 2005 emissions as its basis. For Latvia the reduction goal is equal for both periods: 1% for any year from 2020 to 2029; and 1% for any year from 2030 (EC, 2016), which is also approved on national level (Cabinet of Ministers, 2018).

It is recognised that agricultural sector has got the largest share of total amount NH_3 emissions in the world, Europe – 94%, as well as in Latvia – 86% (Frolova et al., 2017).

Moreover, many Member States reported the increase of emissions between 2014 and 2017 (Amann et al., 2017). In Latvia NH_3 emissions have increased substantially from 2005 until 2015 by 20.1%. The emissions from inorganic N fertilizer application have almost doubled (by 96.2%); from poultry (broilers) manure management, increased by 50%, and from livestock manure application grew by 19.2% (Melece, 2017). In 2015, 46% of Latvia's agricultural NH_3 emissions were generated from manure management (animal housing, grazing and manure storage), but 54% from other agricultural activities (i.e., application of manure and fertilizers) (Frolova et al., 2017).

The findings of our previous studies show (Frolova et al., 2017; Melece, 2017) that the implementation of modern or intensive agriculture, especially livestock rearing technologies and techniques, does not reduce, but increases the NH_3 emissions in Latvia. For instance, in the period from 2005 the NH_3 emissions rose by 80% in poultry farming. This is stressed by scientists that the adoption of proposed manure management technologies in practice is regionally diverse and still limited (Hou et al., 2018). Besides, it is outlined that the opinions of stakeholders are unknown and unexplored.

In terms of emission, including NH_3, control (i.e., monitor, reduce and mitigate) the EU has established regulations for large farms under the Directive 2010/75/EU, so called 'Industrial Emissions Directive'. For the intensive rearing of poultry or pigs, EU Decision 2017/302 of 15 February 2017 provided a recent update by establishing best available techniques (BAT) (EC, 2017). The Decision was supplemented by reviewed and updated BAT reference document (BREF) entitled 'Intensive Rearing of Poultry or Pigs' (Santonja et al., 2017). The BREF covers processes and activities in farms for the intensive rearing of poultry or pigs, as indicated in EU legislation: (a) with more than 40,000 places for poultry (b) with more than 2,000 places for production pigs (over 30 kg), or (c) with more than 750 places for sows.

Therefore, the aim of the research was to determine the most efficient and appropriate measures of ammonia emissions' reduction that could be implemented under Latvian circumstances in pig and poultry farming, particularly in housing.

MATERIALS AND METHODS

Preparation phase – review of ammonia emissions abatement measures

The literature review seeks to identify the main NH_3 emissions abatement (i.e., reduction) and mitigation measures or techniques for pig and poultry housing, which could be included in the questionnaire for further evaluation by experts or stakeholders. The principal materials used for literature review are as follows: different sources of literature, e.g., scholars' articles, research papers and the reports; as well as legislation, guidelines and recommendations of both international institutions (UN, UNECE) and EU (European Commission, EEA). The most promising NH_3 emissions' reduction measures for pig and poultry housing were indicated; and divided in three main groups:

(1) Measures that could be implemented in pig housing; (2) Measures that could be implemented in poultry housing; (3) Measures that could be implemented in the storage of pig and poultry manure.

Questionnaire and survey

For the evaluation of stakeholders' view the expert method was applied (Hand et al., 2001; Tan et al., 2006; Markovičs, 2009). For the evaluation of NH_3 emission abatement each technique or measure, the expert group of 10–15 stakeholders was created. The expert, who is well knowledgeable about the housing systems of particular livestock category, as well as manure management, was chosen. Therefore, in the each group of experts the following stakeholders were included: the leading specialists/experts of the Latvian Rural Advisory and Training Centre, the teachers and researchers from the Latvia University of Life Sciences and Technologies and specialists/managers from the largest livestock farms. Besides, there were an equal number of experts from each region of Latvia.

A pilot studies were carried out in order to clarify the questions and to increase knowledge and awareness of the experts about measure, issue and question. For this purpose, the introduction questionnaire was developed, in which not only the possible measures were mentioned, but there also additional information and characteristics of implementation of each abatement measure was given, as well as the NH_3 emissions' reduction potential was also presented. Besides, the experts were encouraged to add own proposals for improvement of the questionnaire. Hence, the thoughts or measures, which were dominant in the pilot, were also included in further study (development of the questionnaire).

The experts had to evaluate the necessity of implementation of every emission reduction measure using the following symbols: P – measures that need prior introduction, L – measures that can be implemented later, R – measures that can be rejected. Additionally, they had to mark the possible cost level and the necessity for the state support.

Accordingly the priority range of every emission reduction measure was determined and the measures that are suitable for the conditions of Latvia were stated. All emission reduction measures vary according to the character of their implementation possibilities in the livestock holdings. Therefore, they can be divided in three groups:

Group I - measures that do not require large capital investments, but it is mainly sufficient to improve the organisation of work;

Group II - measures the introduction of which requires reconstruction of the pig and poultry buildings, but the state support for it is not needed;

Group III - measures involving essential reconstruction of the pig and poultry housing facilities, and therefore the state financial support are needed.

Evaluation method of survey

Special methodology was developed for evaluation of the survey results and calculation of the possible reduction of emissions. For every answer of each question the number of positive answers was totalled and expressed as percents. After that the priority of each particular emissions reduction measure was calculated using following formula:

$$A = 1.0 \cdot N_P + 0.5 \cdot N_L \quad (1)$$

where A – evaluation of priority of implementation of the particular measure, in points; N_P – number of experts, expressed in %, who have evaluated the measure with P, %; N_L – number of experts, expressed in %, who have evaluated the measure as L, %; *1.0* and *0.5* – adopted or considered coefficients.

Applying such evaluation methods the obtained results can be from 0 to 100 points. If all experts evaluate a particular measure as prior, the total priority evaluation is 100 points. If, in turn, all experts consider that it is not necessary to implement a particular measure, the total evaluation is 0 points. Nevertheless, using this evaluation method in some cases, several measures have an equal number of points. Therefore, the additional information obtained from questionnaire, regarding the cost or investments for the measure's implementation, as well as the necessity of the state support was taken into account and was used as an additional factor, which was indicated by experts not in points but 'yes' or 'no'. Hence, unequivocal ranging can be obtained for all emissions' reduction measures.

Then the emission reduction coefficient was calculated for implementation of the particular measure (group of measures). For the calculation the following formula is used:

$$K_s = k_{s1} \cdot k_{s2} \cdots k_{sn} = \left(1 - \frac{S_1}{100}\right), \left(1 - \frac{S_2}{100}\right), \cdots \left(1 - \frac{S_n}{100}\right) \quad (2)$$

where K_s – emission reduction coefficient; $k_{s1}, k_{s2} \ldots k_{sn}$ – emission reduction coefficients for every emission reduction measure (Table 1 and Table 2); S_1, $S_2 \ldots S_n$ – amount of emission reduction for every particular measure at introduction, %.

RESULTS AND DISCUSSION

The results of the experts' questionnaire evaluation are summarised in the tables below. The NH_3 emission abatement measures are ranked according to received points. The results of reduction measure for pig housing are presented in Table 1.

Table 1. Emission reduction measures for pig farms

Abatement measure	NH_3 reduction, %**	Priority	
		Points	Group
Partly slatted floors (also improve animal welfare)	20–50%	89	I
Adding chemical or biological additives to slurry collected in canals and/or intermediate storages	up to 60%	87	I
Air scrubbing techniques	70–90%	83	III*
Dumping of liquid manure collection canals not less than 2 times per week	25%	83	I
Partly slatted floor and manure channel with slanted walls	up to 60%	78	II
Usage of vacuum (bath) system for collection of manure and transportation to the intermediate storage	up to 65%	66	II
Partly slatted floor and cooling manure surface	46–70%	66	III*
Replacement of reinforced grid for pen floors with metal grid or grid with plastic coating	15–20%	61	II
Reduction of indoor temperature in hot weather (also improve animal welfare)	up to 30%	55	I

* State support is needed to implement the measure; ** Bittman et al., 2014; UNECE, 2014; UNECE, 2015.

It can be seen that the experts not always have taken into account economic or investment costs of implementation of the measure. For instance, experts ranked as priority for pig housing (Table 1) the third most efficient measure 'Air scrubbing techniques', which is a more expensive measure (Table 4), not only for implementation expenses, but also operating costs are required. For example, the annualised investments for bioscrubbers in pig houses are around EUR 4–7 per animal place per year, and the annual operating costs vary between EUR 7.5 and EUR 9.5 per animal place per year. The system's lifetime is expected to be around 10 years (Santonja et al., 2017). Therefore, for Latvia this measure is included in priority Group III, as well as the necessity of state support is indicated.

Until now, the design of air scrubbers at pig and poultry housing facilities has mostly been based on the removal of NH_3. Optimising design and operation of air scrubbers should facilitate the simultaneous reduction of odour, nitrous oxide, methane and particulate matter in an efficient and cost-effective manner (Van der Heyden et al., 2015). Moreover, Dumont (2018) argues that in pig housing the chemical scrubber has no effect, whereas biological treatments can increase GHG emissions.

The research results regarding implementation priorities for the emission reduction measures in poultry housing are summarised in Table 2. Four emission reduction measures correspond to the priority Group I, but to Group II and Group III – one measure. It is important to outline that complying with the animal welfare regulations and implementation of comparatively simple measures, which does not require large financial investments, provides significant potential of emissions reduction.

Table 2. Emissions reduction measures in poultry housing

Abatement measure	NH_3 reduction, %**	Priority	
		Points	Group
Dry, well aerated house, the indoor temperature corresponds to animal welfare requirements	~70	100	I
Usage of nipple instead of bell drinkers	30%	100	I
Ventilated belts, manure removals more than two times a week	70%	71	II
In case of deep litter, usage of wood shavings and sawdust is advisable	~70%	67	I
Addition of aluminium sulphate (alum) to the litter, non-caged housing	70%	67	I
Drying of fresh manure on belts, removed 2–3 times a week, cage batteries	35–45%	57	III*

* State support is needed to implement the measure; ** Bittman et al., 2014; UNECE, 2014; UNECE, 2015.

The measures for reduction of NH_3 emissions that can be introduced in manure storage are summarized in Table 3. The content shows that in the storage of pig and poultry manure special attention should be paid to the covering of poultry litter or solid manure stockpiles with plastic sheeting or other covering material. Up to now, the special attention has not been paid to this measure in Latvia. Nevertheless, the experts have given 75 points for this measure. Besides, this measure is easy to be implemented and therefore it corresponds to the priority Group I. Appropriate reduction measure for storage of slurry or liquid manure in pig and poultry farms could be usage of chemical or biological additives, which has been highly ranked by experts. Nevertheless, implementation of this measure is problematic due to the following issues: (i) necessity of comparatively large investments, well trained personnel and safety issues of chemicals; (ii) the lack of investigations and results regarding the impact of manure with low pH application on quality of soil. Accordingly, in our opinion this measure possibly could be implemented in the future.

Table 3. Measures for reduction of emissions in pig and poultry manure storage in farm

Abatement measure	NH_3 reduction, %**	Priority	
		Points	Group
Covering of poultry litter or solid manure with plastic covering or other synthetic sheeting	up to 60%	75	I
Usage of chemical or biological additives for slurry	up to 68%	75	I
Installation of light construction roofs over tall open tanks	up to 80%	70	III*
Replacement of lagoon slurry storages with covered tank or tall open tanks	30–60%	66	III*
Reduction of slurry storage surface (mirror surface) in new built storages	up to 60%	55	III*
Increase of litter stockpile height	up to 30%	55	II

* State support is needed to implement the measure; ** Bittman et al., 2014; UNECE, 2014; UNECE, 2015.

Despite that the results of presented study are indicated as very useful by involved and informed stakeholders, the latest guidelines, especially updated BAT reference document (BREF) 'Intensive Rearing of Poultry or Pigs' provides the findings of the latest studies, which are devoted to assessment of the various NH_3 emissions reductions or abatement measures and techniques, as well as applicability potential or current implementation limitations. The techniques and its applicability limitations of some emissions reduction options for pig housing are presented in Table 4, and for poultry housing in Table 5.

Table 4. Techniques and applicability limitations of some NH_3 emissions reduction measures for pig housing

Technique	Category	Applicability
In case of a fully or partly slatted floor: – A vacuum system for frequent slurry removal. – Slanted walls in the manure channel. – A scraper for frequent slurry removal.	All pigs	May not be generally applicable to existing plants due to technical and/or economic considerations.
V-shaped manure belts (in case of partly slatted floor).	Fattening pigs	May not be generally applicable to existing plants due to technical and/or economic considerations.
Air scrubbing techniques: acid scrubber or bioscrubber, or biotrickling filter.	All pigs	May not be generally applicable due to the high implementation cost. Applicable to existing plants only where a centralised ventilation system is used.

Source: Bittman et al., 2014; Santonja et al., 2017.

Table 5. Techniques and applicability limitations of some NH3 reduction measures for poultry housing in case of non-cage systems

Technique	Category	Applicability
Forced ventilation system and infrequent manure removal	Laying hens	Not applicable to new plants, unless combined with an air cleaning system
Manure belt or scraper (in case of deep litter with a manure pit).	Laying hens	Applicability to existing plants may be limited by the requirement for a complete revision of the housing system.
Forced air drying of manure or litter:		
– via tubes (in case of deep litter with a manure pit)	Laying hens	Only with sufficient space underneath the slats
– using indoor air (in case of solid floor with deep litter)	Broilers	Depends on the height of the ceiling.
– on manure belt (in case of tiered floor systems).	Broilers	Depends on the height of side walls.
Heated and cooled littered floor.	Broilers	Depends on possibility to install closed underground storage for water.
Manure belts (in case of aviary).	Laying hens Broilers	Applicability to existing plants depends on the width of the shed.
Air scrubbing techniques: acid scrubber or bioscrubber, or biotrickling filter.	Laying hens Broilers	May not be generally applicable due to the high implementation cost. Applicable to existing plants only where a centralised ventilation system is used.

Source: Bittman et al., 2014; Santonja et al., 2017

In order to calculate the efficiency of the measures of ammonia emission reduction included in each priority group formula (2) has been applied and emission reduction coefficients were obtained, which are presented in Fig. 1.

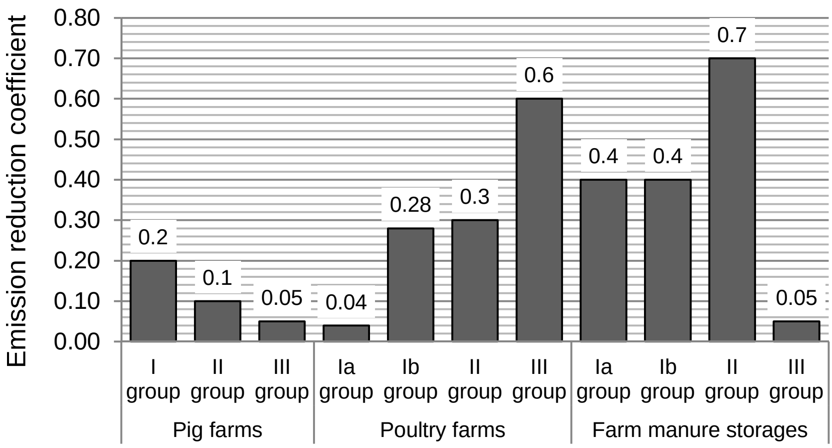

Figure 1. Estimated reduction coefficients for ammonia emissions by implementing measures included in different priority groups. Note: group Ia – deep litter poultry housing and storage of solid manure; group Ib – cage poultry housing and storage of slurry and liquid manure.

The presented in Fig. 1 coefficients have approximate value, because they are based on the maximum of emission reduction, which has obtained in the study. It could be concluded that a significant reduction in ammonia emissions can be achieved by implementation of Group I measures. Therefore, the measures of Group II and Group III should be implemented mainly in following cases: (i) receiving financial support from state managed funds, which are aimed to solve environmental issues; (ii) necessity to reconstruct or renovate the manure storage facilities or the particular farm buildings or animal houses in order to, for instance, improve the animal rearing/breeding technology, as well as for new farming activities. There are still problems, how to show the data of reduced emissions via the implemented measures in the National Inventory Report under the Convention on Long - Range Transboundary Air Pollution. For instance, despite the recent nature of the legislation, by 2015 almost 40% of the pig farms in the Netherlands had installed an air scrubber, although this is not yet reflected in the official emission inventory (Amann et al., 2017).

CONCLUSIONS

The reduction measures in pig and poultry farming should be aimed at larger or industrial farms, according to the latest EU and national regulations.

Notwithstanding, that involvement of various stakeholders (i.e., experts and representatives of farmers) in the evaluation of emissions abatement techniques is advisable, in some cases, they paid less attention to the economic aspects (investments, operating costs) of implementing, for example, air scrubbing techniques.

The implementation of a balanced combination of measures with comparatively low costs, for example, ensuring cleanness in the livestock building, periodical removal of manure, covering of poultry litter or solid manure stockpiles with plastic sheeting, etc., could effectively reduce overall ammonia emissions.

However, more effective abatement technologies and techniques, for example, air scrubbing techniques, replacement of lagoons for slurry storage with covered tanks, drying of litter on belts, etc., could be implemented mainly during reconstruction of farms and farm manure storages or during construction of new buildings/ animal houses. Moreover, implementation of these measures should receive some support by the state.

There is a lack of methodology or guidelines for quantification of the reduced amount of ammonia emissions for a large number of reduction measures, which are recommended by international (UNECE) and EU institutions, and probably could be successfully implemented. It means that the reductions at present cannot be represented in the national reports, particularly in Latvia.

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Effect of rotors on the parameters of hop drying in belt dryers

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Abstract. This article contains a design and verification for a technical solution aimed at optimising the hop drying process in belt dryer and at increasing the quality of the final product. Above the first belt of our belt dryer two evenly distributed double-arm rotors were installed and tested in operation to improve the permeability of the drying air through a flattened hop layer, as well as to improve the speed of drying. The measurements carried out in operation and comparing the drying process with the rotors switched on and off concluded that by inclusion of rotors the hop layer becomes more permeable, and when switched on, the rotors have a positive effect on faster reduction of the relative humidity and on increase of the drying air temperature. With rotors switched on, the percentage drop in the drying air relative humidity at the third inspection window of the first belt, compared to the first inspection window, was 41% on average (values obtained from data loggers and fixed sensors), the drying air temperature increased by 29%, and the hop moisture content decreased by 12%. Whereas with rotors switched off, the drop in the drying air relative humidity was only by 26% on average, the drying air temperature increased only by 14%, and the hop moisture content decreased by 12%. Based on long-term monitoring of fuel consumption during the whole harvesting season starting 2011 until 2017 inclusive, the average annual consumption of LFO (2011–2014) results in 494 L t^{-1} operating without rotors, and 431 L t^{-1} when operating with rotors (2015–2017). This implies that due to the implementation of rotors, the fuel saving being 13% is significant.

Key words: hop cones, hop drying, belt dryer, quality of hops.

INTRODUCTION

In terms of technology and structure, belt dryers are designed as three belt conveyors mounted one above the other, through which warm air passes and dries the conveyed hops. The drying air temperature ranges between 55 °C and 60 °C and is practically stable for the entire duration of drying, i.e. for 6 or 8 hours. Long-term drying at given temperatures is highly energy-intensive and has also other negative impacts. Our technical solution will enable easier permeability of the drying air, higher drying speed and has a positive impact on the quality of the final product (Doe & Menary, 1979; Aboltins & Palabinskis, 2016; Rybka et al., 2016).

When hop cones are poured into the dryer, on the first belt the layer flattens and hop cone bracts stick together due to surface moisture. That causes lower layer permeability (surface crust is created) for the passing air, thus the drying speed decreases (Jokiniemi et al., 2015; Rybka et al., 2018). After this problem had been eliminated, two double-arm rotors located above the first belt of the dryer were designed, installed and verified in operation following initial experiments (Fig. 1).

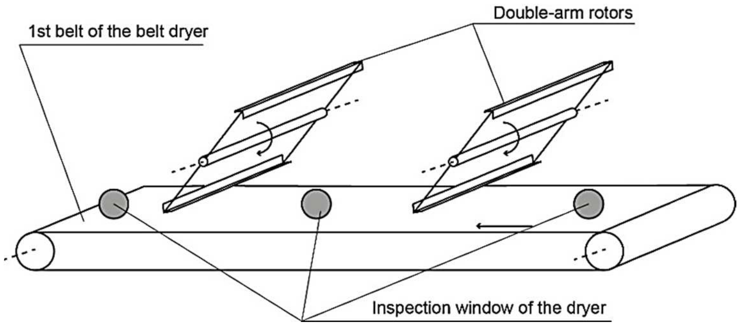

Figure 1. Scheme of placing of two double-arm rotors above the first belt of belt dryer (rotor diameter – 840 mm, rotor rotational frequency – 2.5–3 min^{-1}).

The first rotor is mounted between the first and second inspection window, the second rotor being between the second and third inspection window. Double-arm rotors have their arms fitted with reinforcement at their ends and rotate about their horizontal axis perpendicular to the belt motion (Heřmánek et al., 2018; Podsedník & Ježek, 2018). The rotors arms extend into the lower level of the hop layer moving on the dryer belt (Fig. 2). The shafts are fitted to the vertical walls of the dryer in bearing housings. They are driven by electric motors with transmission gearbox. The rotational frequency of the rotors is selected in a way so that their peripheral speed was greater than the belt speed, however, in order to ensure that the rotors would not push the hops off the belt, thus forming vacant spots without hops above the belt through which the drying air would freely penetrate. This, in turn, would lower the intensity of hop drying. The rotors arms in their actual operation break up and rearrange the flattened layer of hops stuck together, thus enable better penetration of the drying air and faster removal of hop moisture (Rybáček et al., 1980; Srivastava et al., 2006; Ma et al., 2015).

Figure 2. Rotor installed above the first belt of belt dryer.

MATERIALS AND METHODS

1. Measurement by inserted data loggers

To measure the temperature and relative humidity inside the hop layer continuously we used VOLTCRAFT DL-121-TH data loggers (Fig. 3) which enable to programme the frequency of data storage (Jech et al., 2011; Vitázek & Havelka, 2013). In the present case this frequency was set to 5 minutes. The data logger internal memory has its storage capacity of 32,000 measured data, which is absolutely sufficient. The data logger was integrated together with a sensor in a plastic casing and supplied by an inserted battery. The plastic casing had been fitted with a USB connector at one end via which the stored data were imported to a computer (Kumhála et al., 2016).

Figure 3. VOLTCRAFT DL-121-TH data logger.

To protect the data loggers against mechanical damage while carried throughout the dryer as well as against dirt we fixed the data loggers rigidly in polyurethane foam and inserted them between two stainless sieves half-spherical in form. This was the best guarantee of protection and at the same time the sieves did not impede the air permeability, hence no measurement error occurred (Fig. 4).

Figure 4. Placing of a data logger into a protective sieve.

Three data loggers were placed through the first inspection window onto the first (upper) belt of the dryer, two of them approx. 0.5 m far from both left and right wall, and one in the middle. The data loggers were inserted into a hop layer. The advantage of data loggers, compared to rigidly fixed sensors in a dryer, is that they pass through the dryer together with the hops, continuously sensing the whole drying process.

All the determined values relate to an individual hop layer passing separate inspection windows on the first belt (1^{st}, 2^{nd} and 3^{rd} window) with rotors being switched on and then off.

2. Measurement by fixed sensors

On the dryer wall the assembly of Comet T3419 temperature and relative humidity sensors (Fig. 5) was completed. The sets of sensors were connected to a Comet MS6D multi-channel data logger (Fig. 6), from which all data were automatically stored in the computer on its hard disc.

Figure 5. Comet T3419 sensor with transmitter.

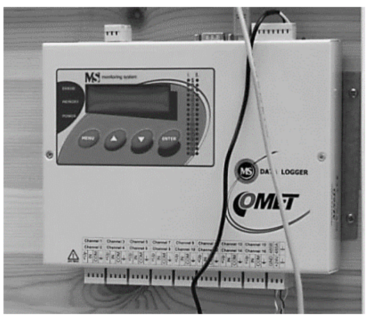

Figure 6. Comet MS6D multi- channel data logger.

The sensors had been installed nearby the inspection windows (Fig. 7). Inspection windows are part of the belt dryer basic equipment and they are intended for the purposes of visual and sensor monitoring of the drying process.

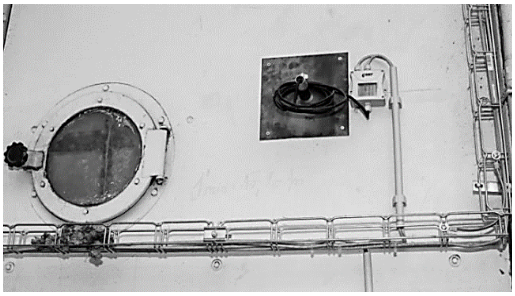

Figure 7. Sensor with a transmitter and display nearby an inspection window of the dryer (inspection window – on the left, fixed sensor – on the right).

The frequency of reading the values was in a way similar to the data loggers set to 5 min. Immediate measured values could be read on the connected two-line display, which at the same time showed the actual temperature in °C and relative humidity in %. Together with the data reflecting temperature and relative humidity the exact time of measurement was also stored by means of which the data collected from all the different ways of measuring could be matched up.

3. Laboratory analysis of samples

The laboratory analyses monitored the moisture content of all hop samples, which was subsequently compared to the drying medium relative humidity measured by means of data loggers and fixed sensors in the dryer. The moisture content in the hops was determined by the Mettler-Toledo HE53 moisture analyser (Fig. 8) from the inspection windows individual samples taken in a synchronised manner with passing data loggers. The measurements were carried out 3 times and the resulting values were compared against each other (Henderson & Miller, 1972; Forster & Gahr, 2013).

Figure 8. Mettler-Toledo HE43 moisture analyser.

We monitored the drying process on the 1st belt of the PCHB 750 belt dryer. All the values determined are related to specific hop layer passing individual inspection windows on the first belt (1st, 2nd and 3rd window) with the rotors switched on and off. The entry thickness of the hop layer on the first belt was 0.3 m, the drying temperature in 2016 was 58 °C and in 2017 it was 59 °C, and the initial hop moisture was 83–85%. The first belt speed was 0.0031 m s^{-1}. The drying air temperature and relative humidity were continuously monitored by means of three data loggers with a measurement frequency of 5 min. The data loggers had been inserted in a row (in the middle and at the edges of the belt) into a moving hop layer at the first inspection window and removed at the third inspection window. The measurements in 2017 were compared with the data obtained from the fixed sensors placed nearby the inspection windows slightly above the hop layer. The moisture content of hops was determined by means of the Mettler-Toledo HE53 moisture analyser using samples taken at given times at individual inspection windows (Chyský, 1977; Krofta, 2008; Mitter & Cocuzza, 2013).

RESULTS AND DISCUSSION

Measurement in 2016

During drying, the rotors were switched off for 50 min at three cycles (Table 1). Simultaneously with switching off the rotors, the data loggers were inserted into the dryer that measured the drying process between the 1st and 3rd inspection window of the first belt. These measurements were compared with the data obtained from the data loggers during drying with the rotors switched on in one cycle. The measurement results are shown in Table 1 and illustrated in graphs of Figs 9–11.

Table 1. Parameters of the drying process – 2016

Measurement date: 23.8.2016	Variety: Saaz	PCHB 750 belt dryer		
			Fixed sensors	
Inspection window	Rotors switched on, off	Reading time	Drying air temperature	Relative humidity of drying air
		h:min	°C	%
1	on	14:00	33.4	98.5
2	on	14:29	42.5	35.8
3	on	14:50	47.8	32.5
1	off	7:32	30.9	87.9
2	off	8:01	36.5	56.0
3	off	8:22	39.4	44.8
1	off	8:48	31.4	76.0
2	off	9:17	36.5	56.0
3	off	9:38	41.2	42.3
1	off	10:30	33.4	70.6
2	off	10:59	36.5	45.0
3	off	11:20	41.5	39.5

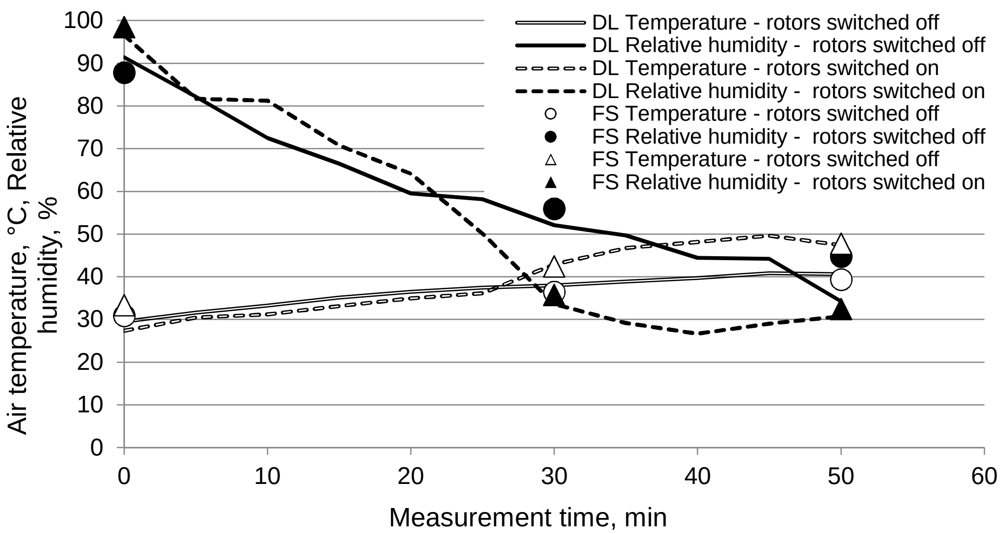

Figure 9. Dependence of drying air temperature and relative humidity on measurement time (time: 7:32–8:22 h); DL – data loggers, FS – fixed sensors.

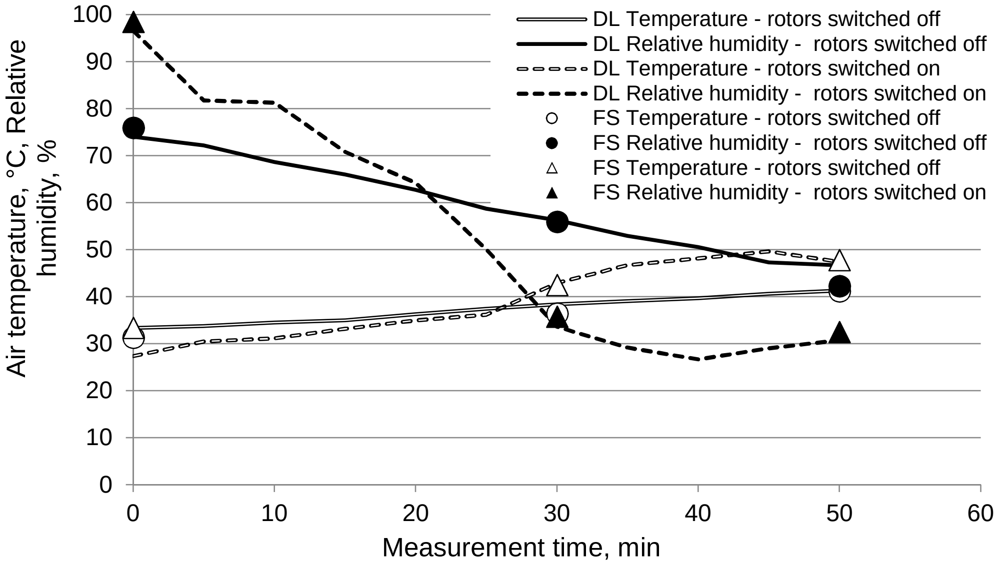

Figure 10. Dependence of drying air temperature and relative humidity on measurement time (time: 8:48 – 9:38 h); DL – data loggers, FS – fixed sensors.

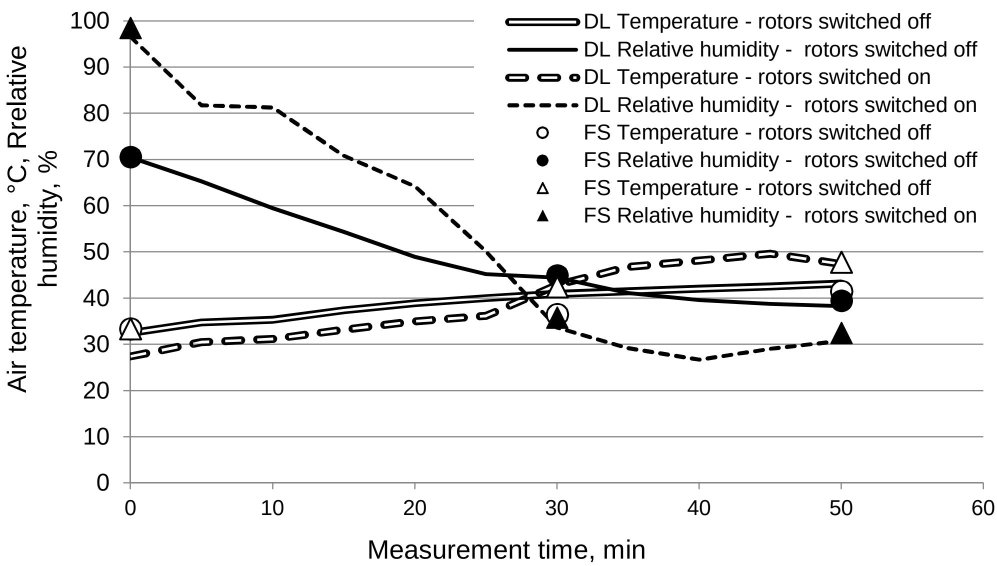

Figure 11. Dependence of drying air temperature and relative humidity on measurement time (time: 10:30–11:20 h); DL – data loggers, FS – fixed sensors.

Measurement in 2017

Table 2 presents the basic parameters and results of the measurement which are also documented in the graph of Fig. 12. The measurements using data loggers were in 2017 extended by temperature measurements and drying air relative humidity measurements by means of fixed sensors, and by determination of the hop moisture content by means of a moisture analyser.

Table 2. Parameters of the drying process – 2017

Measurement date: 29. 8. 2017	Belt dryer PCHB 750					Variety: Saaz
Sampling point	1st belt					
Rotors	Rotors switched on			Rotors switched off		
Inspection window	1	2	3	1	2	3
Sampling time, h:min	10:00	10:47	11:22	13:00	13:47	14:22
Measurement time, min	0	47	82	0	47	82
Data loggers – drying air temperature, ºC	31.1	37.7	41.5	36.3	41.0	40.7
Data loggers – drying air relative humidity, %	69.3	47.2	40.2	43.1	33.3	33.2
Fixed sensors – drying air temperature, ºC	29.2	34.3	36.5	30.8	35.1	35.6
Fixed sensors – drying air relative humidity, %	87.7	57.2	53.0	72.6	52.8	50.9
Hop moisture, %	75.4	70.3	66.1	68.1	62.0	60.1

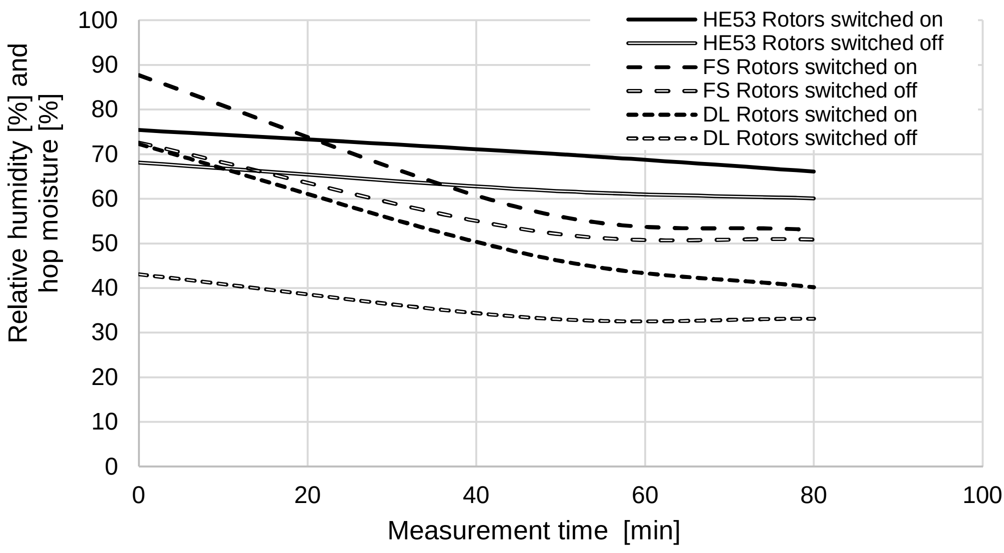

Figure 12. Dependence of drying air relative humidity and hop moisture on measurement time; HE53 – moisture analyser Mettler-Toledo HE53, DL – data loggers, FS – fixed sensors.

Long-term monitoring of fuel consumption

A significant outcome of all the measurements lay in long-term monitoring of fuel consumption when drying with and without rotors, always over the length of the harvesting season from 2011 to 2017 inclusive (Table 3).

Table 3. Fuel consumption in the PCHB 750 hop belt dryer

Year	Total consumption LFO, L	Dry hops, t	Average consumption of LFO per 1 t of dry hops, L t^{-1}	Note
2011	21 949	42.48	517	
2012	12 300	30.90	398	
2013	22 200	43.87	506	
2014	24 100	45.90	525	
2011–2014	80 549	163.15	493.70	without rotors
2015	13 600	32.94	413	
2016	29 369	69.47	423	
2017	28 444	63.30	449	
2015–2017	71 413	165.71	431.00	with rotors

DISCUSSION

The graphs in Figs 9–11, documenting the measurement from 2016, show that despite a significant impact of the initial hop moisture content, the relative humidity is lower and the air temperature is higher always after about 30 mins, i.e. from the 2nd inspection window. It can therefore be concluded that lower relative humidity and higher air temperature inside a hop layer are caused by rotors by disrupting its surface layer, that are placed between the 1st and 2nd and between the 2nd and 3rd inspection window. Such hop layer becomes more air-permeable, therefore the relative humidity inside the dried layer declines and its temperature rises causing the moisture in hop cones to dry out faster. When preliminarily measuring the layer height at individual inspection windows it was found out that with rotors switched off the hop layer is overall more compact, with a more solid surface, and it is apparent that the drying air penetrates through this layer with difficulty. The drying air temperature and relative humidity were measured by data loggers (continuous measurement) and fixed sensors independently of one another. These were placed above the hop layer nearby the inspection windows. The graphs document that the data obtained from the fixed sensors are practically identical to the continuous measurement by means of data loggers with rotors switched both on and off.

Table 2 and Fig. 12 document the measurement results from 2017. The measurement data obtained from data loggers (drying air temperature and relative humidity) in Table 2 represent the average data from three data loggers placed in a row. The values from individual data loggers placed in a row differed minimally, thus confirming a presumption about drying process being even over the whole width of the dryer. For reasons of clarity, drying air temperature courses have been excluded from the graph in Fig. 12.

As resulted from the in-process measurement (Table 2), the rotors on the first belt of the belt dryer have a positive impact on the efficiency of hop drying. The percentage drop in the drying air relative humidity at the third inspection window of the first belt was, compared to the first inspection window with the rotors switched on, 41% on average (values from both the data loggers and fixed sensors), while the drying air temperature increased by 29%, and the moisture content in hops decreased by 12%. Whereas with the rotors switched off, the drop in the drying air relative humidity was only 26% on average, the drying air temperature increased only by 14% and the hop moisture content decreased by 12%.

Based on the multi-annual monitoring, the average annual LFO (Light fuel oil) consumption (years 2011–2014) is 494 L t^{-1} when operating without rotors and 431 L t^{-1} with rotors (years 2015–2017). This implies significant fuel savings of 13% by using rotors.

CONCLUSION

The experiments in a belt dryer comparing drying with its rotors switched on and off above the first belt show that by involving rotors in the technological process a hop layer becomes more air-permeable and they also have a positive impact on faster decrease in the relative humidity and increase in the drying air temperature. By inclusion of rotors, the relative humidity of the passing drying air dropped by 14% compared to the operation with the rotors switched off, the drying air temperature on the contrary increased by 15%, and the hop moisture decreased by 0.6%. This comparison of results, however, may be influenced by the variable moisture of the hops coming into the dryer. It is ideal when hops on entering the dryer have identical moisture content for both variants of the measurement. Therefore, it will be appropriate to carry out repeated measurements in the following harvesting seasons. The inclusion of rotors also significantly positively reflected in the long-term monitoring of fuel consumption. After several seasons of monitoring, the average annual savings of LFO when using rotors is 63 L t^{-1} of dry hops, which corresponds to 13%.

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Possibilities of monitoring cattle via GSM and A-GPS

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Abstract. Nowadays, people and things can be localized using GNSS (Global Navigation Satellite System) or GSM technology. Devices using Differential Global Positioning Systems may not be suitable for they computing and energy intensity. The GSM and A-GPS systems have certain limitations and disadvantages. They are different in accuracy, energy intensity and therefore they are suitable for different applications. Trackers can't be effectively used to locate animals, monitor their movements, and observe their behaviour. They can also be used to search for stolen pets and farm animals. Unguarded herds of cattle are often the target of thieves. For reasons of crime, localization was tested by devices using GSM and A-GPS technology. Specifically, the quality of these localization methods has been tested. Has been addressed above all, accuracy, reliability, speed and consistency of individual methods. In addition, further measurements were made. Localization has been tested in different well-defined environments. This makes it possible to judge the quality of individual localization technology and to suggest the best use of individual technologies and their link.

Key words: localization, tracking, cattle care.

INTRODUCTION

Currently, unguarded cattle herds are increasingly becoming the target of thieves and many breeders do not report these cases to the police, as it is difficult to track and find the perpetrator. Some breeders resort to posting rewards for information leading to the recovery of their stolen property. The complication is that monitoring cattle aggregation is not often done. Therefore, it is impossible to determine exactly when the cattle were lost. (Černá, 2000). It is therefore advisable to locate and monitor all cattle and this monitoring can be done using GNSS or GSM technology (Raizman et al., 2013). The tracking of these animals is not only for theft prevention but can also help to locate stray cattle (Bowling et al., 2008). Motion monitoring can help monitor the animal's health or observe and determine the rut period. To do this, the monitored animal must have a locator attached to it, preferably in the form of a collar. The device must be constructed such a way that it does not endanger the animal or is unpleasant in any way. The most appropriate device should be light weight, as to not put stress on the animal, and the battery life of the device should be considered a priority, as the changing or charging of the device would be impractical and very complicated in large herds (Sikka, 2004).

The Global Satellite Positioning System enables global positioning via satellites. It is used to determine the position and track the parameters of movement of animals and objects. The current positioning systems in use are the American GPS, Russian GLONASS, European Galileo and the Chinese BeiDou. The A-GPS system has been used in our research. The fast development in the use of GPS devices occurred after 2000 when the use of Selective Availability was discontinued allowing for civil and commercial use. Due to this, the GPS system became more accurate and usable in multiple applications. Either the user devices by means of code measurement, phase measurement, or Doppler measurement takes the position calculations. Code measurements are most often used (Bhatta, 2011).

In addition to GNSS, GSM mobile networks can be used for localization. Designed in 1982, the cellular network or mobile network is a telecommunication network designed for telephone calls, data transfer and other services. GSM is the most widely used standard. The network consists of mobile devices, Base Transceiver Station (BTS), Serving Mobile Location Center (SMLC), Gateway Mobile Location Center (GMLC). These networks work most often at frequencies from 300 MHz to 3 GHz. Thanks to the principles of the GSM network, it is possible to locate a mobile device when it is connected to the network. (Lee, 2010) The article does not deal with the design of any specific device. The article compares the GPS and GSM and their suitability for locating cattle in case of theft. The goal of the undertaken investigations was to determine, which technology is more suitable for cattle localization.

MATERIALS AND METHODS

Localization using GPS and mobile networks has been tested. Equipment used methods E-OTD (The Enhanced Observed Time Difference method) in GSM and GPRS mobile networks and OTDOA (Observed Time Difference of Arrival) method in UMTS networks for localization in mobile networks. E-OTD method is a terminal based method. (Dzulkifli et al., 2017). OTDOA method works on the same principle as the E-OTD method. The accuracy of localization by mobile networks depends on the density of BTS (Orlich, 2006).

Another method that was tested for determining the position was A-GPS. The devices use code measurements to determine the position. The code measurement principle use the distance between the receiver and the transmitter to determine the position. This method is used in most ordinary GPS receivers (Bensky, 2016). SBAS (Satellite Based Augmentation Systems) and GBAS (Ground Based Augmentation Systems) were not used. The accuracy displayed by the equipment is an estimate of accuracy in meters. A medium position error is displayed. The magnitude of the medium positional error is affected by the number of received signals, the location of the transmitters and the signal strength. For GPS, it is the constellation of satellites, the number of satellites used and the strength of the received signal. For these localization methods, the accuracy of localization depends on the environment in which the receiver is located (Ge, 2017). Measurements took place in environments where can be found stolen or stray cattle.

Navigation equipment PRA type LX series 1 was used. It is a mobile low-cost receiver with localization via GSM and A-GPS. It has a CPU Kirin 655 Octa-Core, a triple virtual antenna, a battery with a capacity of 3,000 mAh, for long life and works on the android 7.0 platform. Is uses frequency 800 MHz, 900 MHz, 1,800 MHz, 1,900 MHz, 2,100 MHz and 2,600 MHz.

The measurement was done in three devices, from which the average value was made. Measurements took place in Central Bohemia Region in Czech Republic. Territory with coordinates 50° 3′0″ N, 14° 42′36″ E. The measurement took place during the day and on weekdays in 2018. It has always been recorded positioning time and positioning accuracy during measurement. Battery consumption was monitored, to avoid discharge during measurement however, without loss records. This battery monitoring was carried out only for measuring purposes. We expect reliably mobile signal coverage in Czech Republic. Mobile signal coverage is close to 100%.

- Forest

It is densely wooded environment in which trees hinder the view of the sky. Conifers and deciduous trees are higher than 5 m. We can assume a low BTS density and a weaker GPS signal. Therefore, may be less accurate and less reliable localization. Farmhouses are often found in the countryside, close to the forest. The cattle can stray into the forest.

- In trucks

The construction of the vehicle, by means of transport, does not allow for a sky view and the GPS signal is weak. The density of BTS depends on where the conveying medium moves. The conveying medium moved in the Central Bohemian Region. The stolen cattle can be transported by trucks.

- Countryside

The buildings are not more than 6 m high. The GPS reception conditions are good. There is good view of the sky. It is possible to assume great accuracy and reliability of GPS location. BTS density is low.

- Open landscape

This is an environment with an excellent view of the sky. Conditions for receiving GPS signals are ideal. The nearest building is located tens to hundreds of meters away. BTS density is low here.

- City

The city's environment is considered for cases of stray animals or the instance of a stolen animal transport vehicle. The city environment consists of dense building clusters where houses are over six meters high and the view of the sky is worsened. It is possible to assume a high density of BTS and a lower visibility of GPS satellites. The receivers were outside the buildings when measured.

- Farm buildings

The receivers were located inside buildings. There is no direct view of the sky. GPS signal is very weak. Measurements were carried out in farm buildings in the countryside.

RESULTS AND DISCUSSION

The GPS localization results are shown in Table 1. In environments with hindered views or no view of the sky, tracking accuracy is greatly worsened.

Accuracy is within hundreds of meters when localized by GSM. According to our results, we assume the accuracy depends on the density of BTS. The GSM localization results are shown in Table 2.

Localization by GSM appears to be highly inconsistent and less accurate. The advantage of the method is its reliability in an environment without a view of the sky. It does not matter if the receiver moves inside or outside the building. Localization is possible everywhere there is a mobile network signal. Localization usually takes tens of seconds. Another advantage of this method is the very low battery consumption. The device did not lose or disconnect from the signal of mobile networks during measurement. When measuring, it was always possible to determine the location.

Table 1. GPS measurement

Environment	Average accuracy (m)	Number of measurements
Forest	6.6	500
In trucks	45.5	500
Countryside	6.8	500
Open landscape	5.2	500
City	13.4	500
Farm buildings	47.5	500

Table 2. GSM measurement

Environment	Average accuracy (m)	Number of measurements
Forest	639.4	500
In trucks	863.6	500
Countryside	547.2	500
Open landscape	743.7	500
City	122.3	500
Farm buildings	384.2	500

The best accuracy was achieved in the city, 122.3 m and the worst was in the trucks 863.6 m. In low-density BTS environments as forest or open landscape, the accuracy of this method is hundreds of meters up to kilometre units. Accuracy was proportional to BTS density as expected. Therefore, the accuracy of GSM localization is not suitable for searching for stray or stolen cattle. It cannot be used to monitor cattle behavior and health. However, it is important in case of a GPS signal loss.

Localization with this technology is useful for monitoring wildlife migration, but only in areas where there is a mobile signal. The advantage may be the low cost of the GSM module over other used telemetry collars using different radio transmissions. In addition, all data is transmitted over the mobile network, so it is not necessary to approach the animal in any way and to move in the terrain.

GPS tracking is an accurate method. It is very accurate in ideal conditions with an excellent view of the sky, around 5 m. Localization accuracy is still good in the forest, 6.6 m. The least precision is in an environment with no sky view, as farm buildings 47.5 m and in trucks 45.5 m. This is enough accuracy for finding a stray or stolen cattle.

The reliability of this method is worse than the localization by mobile networks. Fisher et al. (2018) reported a small error rate of 8.2%, but they state that the error rate is not related to the type of environment, but we believe that reliability depends on the environment. Therefore, we recommend using GPS and GSM localization simultaneously. The combination of both technologies is most advantageous. GSM is more reliable, and GPS is more accurate. In monitoring wildlife movement, the loss of location information is not as critical as in the search for stolen cattle. Another disadvantage of this method is energy consumption.

The speed of A-GPS is surprisingly fast. Locating with A-GPS takes tens of seconds. Localization without A-GPS can take up to 12 minutes. Comparatively, this is a very long time and consumes a lot of the device's battery power.

Unlike the author Quaglietta (2012), we did not notice a significantly higher battery consumption in an environment with a worse view of the sky.

The device will send data over the mobile network network via SMS. Longer localization interval is enough to control cattle. For example, once a week. A shorter localization interval is required to locate stolen or stray cattle. Many researches have successfully used mobile networking to track animals (Dettki et al., 2004; Quaglietta et al., 2012).

However, both technologies do not have enough precision to monitor cattle behaviour. More information is needed to track the health and pregnancy of the cattle. For example feed intake, decrease efficiency, resting time, and physical activity a upravil bych na need to be monitored. Locators with GPS and GSM are not enough. Locators need to be supplemented with additional sensors. As confirmed by Hulbert & French (2001).

Further research could be about reducing energy consumption, as described by Ayatollahi et al. (2018). Locators could contain RFID tags to locate and track livestock, as the say Anu & Canessane (2017). Properly designed equipment does not affect cattle behaviour, as given by Manning et al. (2017) says. But it is necessary to test how the animal reacts to the device. It would also be possible to test other GNSS systems and integrate them.

CONCLUSIONS

It is advisable to use A-GPS for faster localization and less battery usage. The GPS itself is not suitable for the long-time of first position detection at start-up. The precision of localization by GMS is too inaccurate. It is a circle of hundreds of meters. This is not suitable for locating a stolen or stray cattle. The ideal tracker will be able to determine the location using both A-GPS and GSM. Use A-GPS for greater accuracy and use GSM for greater reliability. To check cattle, it is advisable to send data periodically, for example once a day or once a week. For localization of stolen or stray cattle is suitable to locate cattle on request. For example, in the form of an SMS alert. This form of alert is activated either when leaving the defined area where the device is to occur, or on demand from the system user in the form of an activation SMS sent to the device.

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Effect of nitrogen fertilization management on mineral nitrogen content in soil and winter wheat productivity

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Abstract. In recent years farmers must use integrated crop growing principles. One of the most important principle is to balance usage of mineral elements in crop cultivation, especially nitrogen management. Excessive and unbalanced usage of nitrogen fertilizer reduces nitrogen use efficiency and increases nitrate leaching in surface and groundwater. The dynamics of nitrogen forms in soil at different depths and different plant growth stages are studied to increase the productivity of winter wheat, promoting nitrogen uptake in plants and reducing nitrogen leaching during the vegetation period. Field experiments were carried out at the Research and Training Farm Vecauce of the Latvia University of Life Science and Technologies from 2012 till 2015. Researched factors were nitrogen (N) fertilizer rate: 0 – control, 85, 153, 187, and N rate determined by chlorophylmeter (Yara N-tester) 180 (2012/2013), 150 (2013/2014), 205 (2014/2015) N kg ha^{-1}, nitrogen and sulphur (S) fertilizer rate – N175+S21 kg ha^{-1}, and conditions of the growing seasons: 2012/2013, 2013/2014 and 2014/2015. The content of nitrate (NO_3–N) nitrogen and ammonium (NH_4–N) nitrogen was determined in the soil layers 0–20 cm, 20–40 cm and 40–60 cm at the growth stages (GS) 30–32, 49–51, 69 and 90–92. All trial years the amount of nitrate nitrogen and ammonium nitrogen in soil decreased during vegetation, but increased with increasing fertilization dose. Nitrate nitrogen content was significantly influenced by year in 0–40 cm soil layer ($P < 0.01$) and by nitrogen fertilizer in the 20–40 cm soil layer. Ammonium nitrogen content had significant influence only on nitrogen fertilizer at 20–40 cm soil layer ($P < 0.05$). Average grain yields did not show significant correlation with the nitrate nitrogen and ammonium nitrogen in different soil layers and plant growth stages, except nitrate nitrogen content in soil layer 40–60 cm at GS 30–32 and ammonium nitrogen content in soil layer 40–60 cm at GS 69 and GS 90–92.

Key words: ammonium nitrogen, nitrate nitrogen, fertilizer, wheat.

INTRODUCTION

In recent years farmers must use integrated crop growing principles. Integrated crop management based on high crop yield obtaining with lower inputs based on an understanding of high yield traits and better managing (Dianjun et al., 2016). The most important factors in integrated wheat fertilization are nutrient demands of macro- and micro-elements, dynamics of nutrient uptake in vegetation period and weather conditions (Pepo, 2002). One of the most important principle is balanced usage of mineral elements in wheat fertilization, especially nitrogen management. Excessive and unbalanced nitrogen fertilizer usage reduced nitrogen use efficiency and increased nitrate leaching in surface and groundwater. The European Union Nitrate Directive (91/676/EEC) also requires Member States to implement restrictive measures for minimazing water and soil contamination with nitrates from agriculture sources (Council Directive, 1991). High efficiency of nutrient use improves physical, chemical, biological properties of soil and enhances crop productivity and reduces soil contamination (Zhang et al., 2012, Dianjun et al., 2016). Weather, soil conditions and agrotechnics influenced organic compound mineralization, which include nitrogen availability for the crops (Ruza & Kreita, 2006, Osvalde, 2011, Līpenīte et al., 2016, Linina & Ruza, 2018). The amount of mineral nitrogen in soil substantially contributes to the nitrogen nutrition of the crops during the growth period (Olfs et al., 2005). Mineral nitrogen compounds in soil are very dynamic, plants can use them easily, but nitrogen may reduce losses from soil-plant system substantially and also soil-microbial nitrogen immobilization (Olfs et al., 2005, Līpenīte et al., 2016). Previous research in Latvia show that in spring at the wheat regrowth time, the ammonium and nitrate nitrogen forms in soil were observed aproximatelly in equal amount, but at the active vegetative growth period (in June) nitrate nitrogen reached it's highest amount (74%), but ammonium nitrogen (84%) – in July (Timbare, Bušmanis & Reinfelde, 2001). Determination of mineral nitrogen amount in soil at the vegetative growth period can help to understand plant provision with nitrogen and necessity of fertilizers.

The dynamics of nitrogen forms in soil at different depths and different plant growth stages is studied for increasing the productivity of winter wheat (*Triticum aestivum* L.), promoting nitrogen uptake in plants and reducing nitrogen leaching during the vegetation period. The hypothesis of the study was the soil nitrogen availability by plant affected wheat grain productivity. The aim of this study was to assess the effect of nitrogen fertilizer application timing on soil nitrogen availability for winter wheat high grain yield.

MATERIALS AND METHODS

Field trials with winter wheat variety 'Kranich' were carried out at the Research and Training Farm Vecauce (latitude: N 56° 48', longitude: E 22° 87') of the Latvia University of Life Science and Technologies from 2012 till 2015. In 2012, and 2013 the pre-crop was oilseed rape, but in 2014 – spring wheat. Trials were arranged randomly in four replications. Soil at the trial site was loam in 2012 and 2013, and sandy loam in 2014. Soil is characterized by the following agro-chemical parameters depending on the years: organic matter content 17–25 g kg^{-1} (Tiurin's method), soil exchange reaction pH KCl 6.6–7.2, phosphorus (P) content 50–153 mg kg^{-1} (Egner-Riehm's method) and potassium (K) content 118–150 mg kg^{-1} of the soil (Egner-Riehm's method). Wheat was fertilised with compound mineral fertilizer at the rate: nitrogen (N) 11–18, P 20–34, K 45–75 kg ha^{-1} before sowing depending on the years and agro-chemical properties. Wheat was sown in optimal time – the second decade of September, at the rate 450 germinal seeds per m^2. Weeds and diseases were controlled by using plant protection products in all trial years.

In spring, when the vegetation had renewed the first top-dressing of nitrogen fertilizer was applied. The second top-dressing was done at the stem elongation growth stage (GS 30–32) (Zadoks et al., 1974) of winter wheat and the third – at the beginning of heading (GS 49–51).

Researched factors were nitrogen (N) fertilizer rate: 0 – control, 85, 153, 187, and N rate determined by chlorophylmeter (Yara N-tester) 180 (2012/2013), 150 (2013/2014), 205 (2014/2015) N kg ha^{-1}, nitrogen and sulphur (S) fertilizer rate – N175+S21 kg ha^{-1}, and conditions of the growing seasons: 2012/2013, 2013/2014 and 2014/2015. Different nitrogen fertilizer rates were used according farmers traditional practice. The chlorophylmeter was used for determination nitrogen rate necessity in one variant, it's differ from year to year.

The content of ammonium nitrogen NH_4–N and nitrate nitrogen NO_3–N was determined in the soil layers 0–20 cm, 20–40 cm and 40–60 cm at the growth stages GS 30–32, 49–51, 69 and 90–92. Samples were analysed at the Agrochemical Laboratory of the Latvia State Plant Protection Service using standard method set out by LVS ISO/TS 14256–1 (determination of nitrate and ammonium in field-moist soils by extraction with potassium chloride solution). After harvesting grain yield was determined at 100% purity and 14% humidity in four recurrences.

Statistical analyses: standard errors, *Student's t-test*, impact factors influence (η^2), ANOVA procedures, correlation and regression analyses were done using software MS Excel. The differences were considered statistically significant when $P < 0.05$.

During the field trial years meteorological conditions differed considerably. Autumn in all trials years was warm and dry. Winter in 2012/2013 and 2014/2015 was good for wheat overwintering. In 2013/2014, wheat got serious wintering problems. Temperature below zero were observed only in the middle of January, soil frosted, but without snow. Frost continue until six of February, sometimes temperature dropped to -25 °C. Part of plants did not survive. In 2013, the vegetation renewed very late – at the end of April, but in 2014 and 2015 – at the end of March. Spring of 2013 and 2014 was wormer and dryer than obtained in long-term observations. In 2014, May was dry, but in 2013 was very rainy – rainfall exceeded long-term observations 2.6 times. In summer, June was dry in 2013 and 2015, and air temperature was lower than long-term observations in 2014 and 2015. July in 2014 was warm, average air temperature exceeded long-term observations per +2.9 °C. The beginning of August in all trial years was warm and dry, and it was favourable for wheat harvesting. Overall, meteorological conditions were suitable for winter wheat growing.

The effect of temperature and humidity presented by the hydrothermal coefficient (HTC) by Selianinov (Čirkovs, 1978).

$$HTC = \frac{\sum p}{\sum t_{>10^{\circ}C}} \cdot 10 \tag{1}$$

Where $\sum p$ is the sum of precipitation in crop growth period, mm, $\sum t_{>10\,^{\circ}C}$ is the sum of active (> 10 °C) air temperature of the same period. Optimal value of the coefficient indicate 1, values below and above 1 – drought and humid period respectively.

During the vegetation period an average drought (HTC 0.59–0.80) were recorded in 2013 GS 51–69, 2014 GS 30–51 and 2015 GS 51–90, but humid period (HTC 2.15–9.52) – in 2013 GS 24–51, 2014 GS 24–30 and GS 51–69, and in 2015 GS 24–30 (Fig. 1).

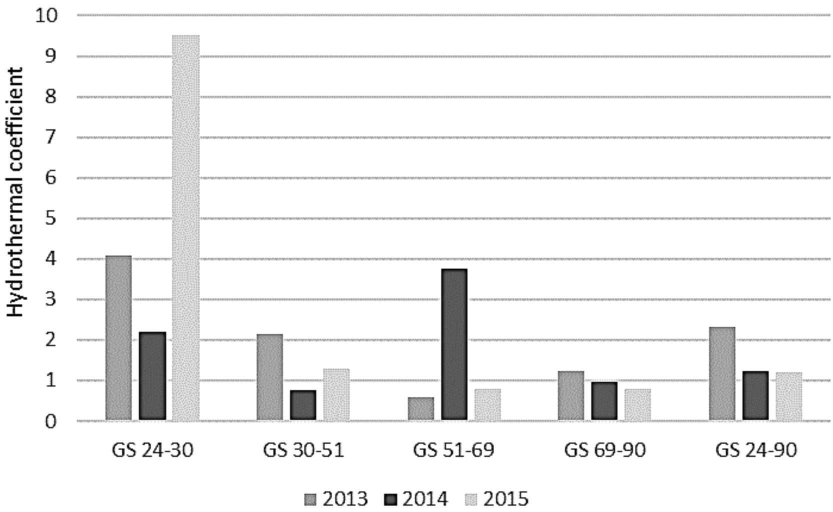

Figure 1. Values of the hydrothermal coefficient in wheat vegetation period, 2013–2015.

RESULTS AND DISCUSSION

The ammonium and nitrate nitrogen accumulation in soil were different in all trial years. Across 3 trial years at the end of winter period, in spring 2013, the highest ammonium and nitrate nitrogen content were obtained 54.72 and 55.68 kg ha^{-1} respectively, in soil layer 0–60 cm (Figs 2, 3). In 2013 plant wintering conditions was favourable, winter was stable with snow and soil was frozen long period, vegetation started very late – at the end of April. According literature data (Timbare, Bušmanis & Reinfelde, 2001, Ruza, & Kreita, 2006, Staugaitis et al., 2015) nitrogen content in soil are affected by precipitation level, soil and air temperature, soil texture and other factors. In 2014 absolute minimum of NO_3–N was recorded at GS 49–51 with 2.88 kg ha^{-1} for the treatment with 85 kg N ha^{-1}, while the maximum value (139.92 kg NO_3–N ha^{-1}) was determined for a plot fertilized with 150 kg N ha^{-1} at stem elongation stage in the same year. In 2013 at the end of vegetation (GS 90–92) NH_4–N content minimum (6.72 kg ha^{-1}) obtained for the treatment with 85 kg N ha^{-1}, but maximum (73.68 kg ha^{-1}) at GS 69 for the treatment with 187 kg N ha^{-1} in comparison with other trial years.

Our trials showed that year meteorological conditions had a significant influence on nitrate nitrogen content at 0–40 cm soil layer ($P < 0.01$), but not significant on ammonium nitrogen content in soil. Nitrate and ammonium nitrogen content in soil 20–40 cm layer were significantly dependant on the level of nitrogen fertilizer ($P < 0.05$).

In 2013 from the renewal of vegetation NO_3–N and NH_4–N content decrease till GS 49–51 and minimum value (4.56 and 10.80 kg ha^{-1} respectively) obtained in treatment of 180 kg N ha^{-1}, further NO_3–N and NH_4–N content increase till GS 69 – maximum value (53.04 and 73.68 kg ha^{-1} respectively) obtained in treatment of 187 kg N ha^{-1} in the soil layer 0–60 cm. Similar results were obtained in other trials (Corbeels et al., 1999, Līpenīte et al., 2016), where found that ammonium and nitrate nitrogen content rapid decrease in soil during plant vegetation due to its consumption. The NO_3–N and NH_4–N content varied depending on the fertilizer treatment and sampling time, it's also reported in other trials (Līpenīte et al., 2016, Juriščˇ et al., 2014). The highest content of NO_3–N and NH_4–N were observed in the top layer (0–20 cm) from GS 30–32 till GS 49–51, further on till the end of flowering stage NO_3–N content increase in deeper layer (40–60 cm) and get greatest value 35.76 kg ha^{-1} for the treatment with 180 kg N ha^{-1}, but NH_4–N – 73.5 kg ha^{-1} for the treatment with 187 kg N ha^{-1} at the GS 69. Similar findings were reported in studies by Ruza & Kreita (2006). In 2013 it was found that wheat growth stage significantly influenced (*P* < *0.05*) NO_3–N and NH_4–N content in all soil layers, except NH_4–N content in 20–40 cm.

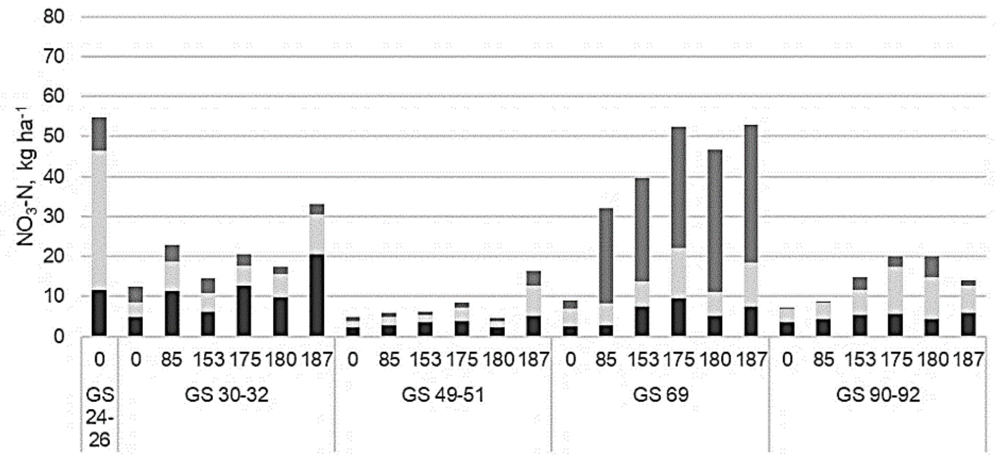

Figure 2. NO_3–N nitrogen accumulation in different soil layers in vegetation period 2013, kg ha^{-1}. (0, 85, 153, 175, 180, 187 – N norm, growth stage; ■ – 0–20 cm; $LSD_{0.05}$ = 3.96; ■ – 20–40 cm; $LSD_{0.05}$ = 3.36; ■ – 40–60 cm*); *not significant at the probability level 0.05.

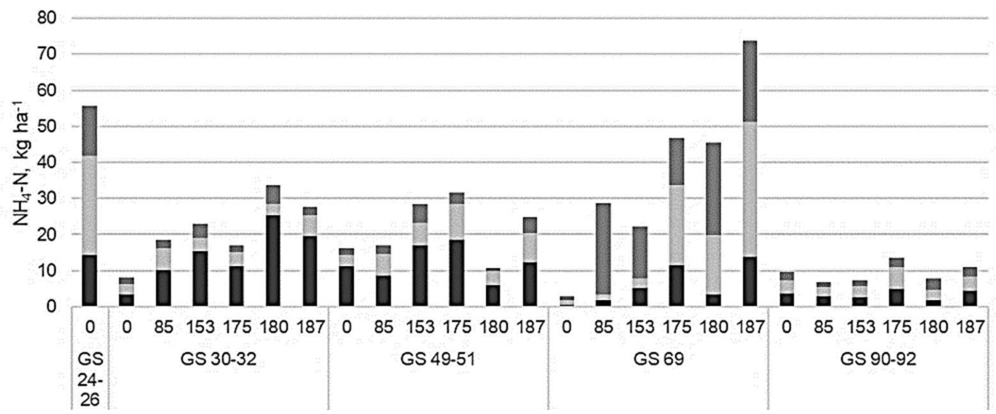

Figure 3. NH_4–N nitrogen accumulation in different soil layers in vegetation period 2013, kg ha^{-1}. (0, 85, 153, 175, 180, 187 – N norm, growth stage; ■ – 0–20 cm*; ■ – 20–40 cm*; ■ – 40–60 cm*); *not significant at the probability level 0.05

During the 2014 growing season the amount of nitrate and ammonium nitrogen decrease from stem extension till full ripening in 0–60 cm soil layer. Maximum content of NO_3–N (140 kg ha^{-1}) was determined in GS 30–32 in the fertilised plot with

150 kg N ha^{-1}, where chlorophyllmeter was used to determine needed nitrogen fertilizer (Fig. 4). Highest NH_4–N content (67 kg ha^{-1}) also was observed in the same growth stage in variant N187 (Fig. 5). The optimal temperature and moisture conditions in vegetation renew period activated rapid increase of NO_3-N nitrogen content in soil. Similar results were reported by Līpenīte et al. (2016) where in mucky – humus gley soil nitrate nitrogen content decrease from GS 30–32, when plants intensive consumes nitrogen. Jurišč et al. (2014) reported that winter wheat at steam extension and ripening growth stage consumes more nitrates from soil and less nitrate-nitrogen was presented in lysimeter outflow. In our trial the highest values of nitrate and ammonium nitrogen content were observed in the top layer (0–20 cm) all vegetation period in 2014, and it decrease in deeper soil layers. Karkliņš et al. (2017) also reported NO_3–N main amount was placed in the 0–30 cm soil layer. In our experiment in 2014 it was found that wheat growth stage significantly influenced ($P < 0.05$) NO_3–N and NH_4–N nitrogen content in all soil layers.

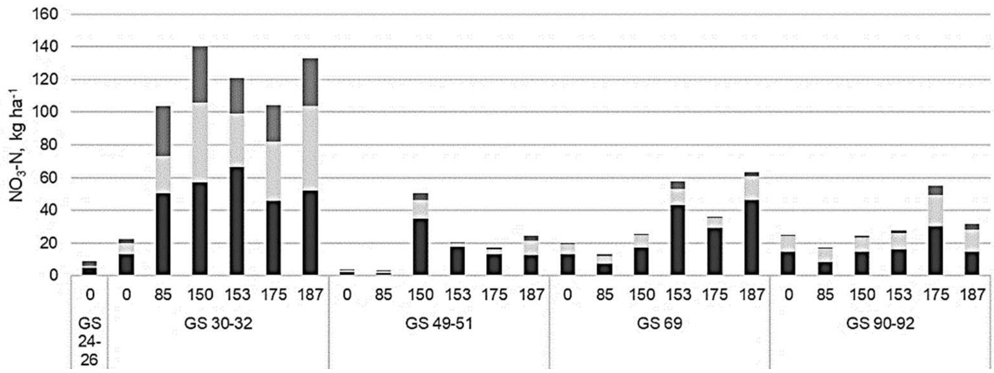

Figure 4. NO_3–N nitrogen accumulation in different soil layers in vegetation period 2014, kg ha^{-1}. (0, 85, 150, 153, 175, 187 – N norm, growth stage; ■ – 0–20 cm*; ■ – 20–40 cm*; ■ – 40–60 cm*); *not significant at the probability level 0.05.

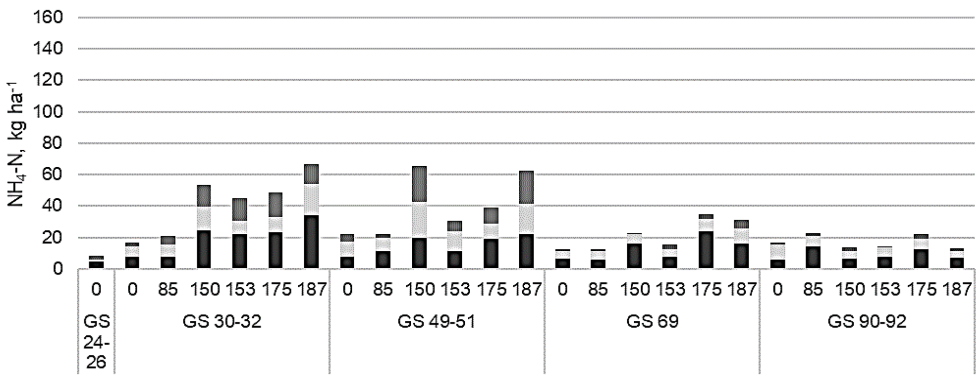

Figure 5. NH_4–N nitrogen accumulation in different soil layers in vegetation period 2014, kg ha^{-1}. (0, 85, 150, 153, 175, 187 – N norm, growth stage; ■ – 0–20 cm; $LSD_{0.05}$ = 8.31; ■ – 20–40 cm*; ■ – 40–60 cm*); *not significant at the probability level 0.05

Rapid nitrate and ammonium nitrogen content increase in soil layer 0–60 cm was observed from the renew vegetation till the GS 49–51 in 2015 (Figs 6, 7). During the subsequent growth period, decline of nitrate and ammonium nitrogen content was observed in all variants, except N187 and N205, where content increased till GS 69. Chlorophyllmeter was used to determine needed amount of fertilizer in variant N205. Nitrogen fertilizer uptake in wheat was affected negatively because of dry weather conditions and lower air temperatures than long-term observations at the end of flowering stage and it influenced plant mineral nutrition. Corbeels et al. (1999) reported that nitrification process was considerably reduced at low soil moisture level.

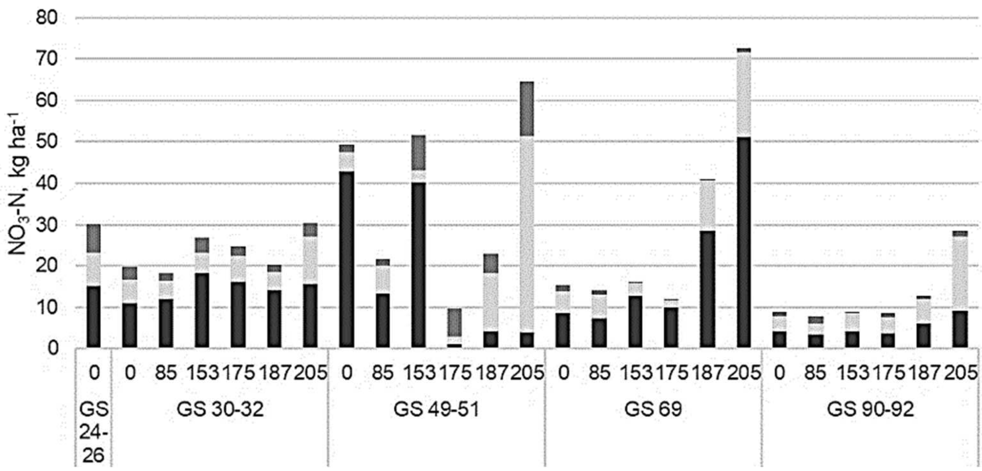

Figure 6. NO_3–N nitrogen accumulation in different soil layers in vegetation period 2015, kg ha^{-1}. (0, 85, 153, 175, 187, 205 – N norm, growth stage; ■ – 0–20 cm*; ■ – 20–40 cm; $LSD_{0.05}$ = 10.04; ■ – 40–60 cm*); *not significant at the probability level 0.05.

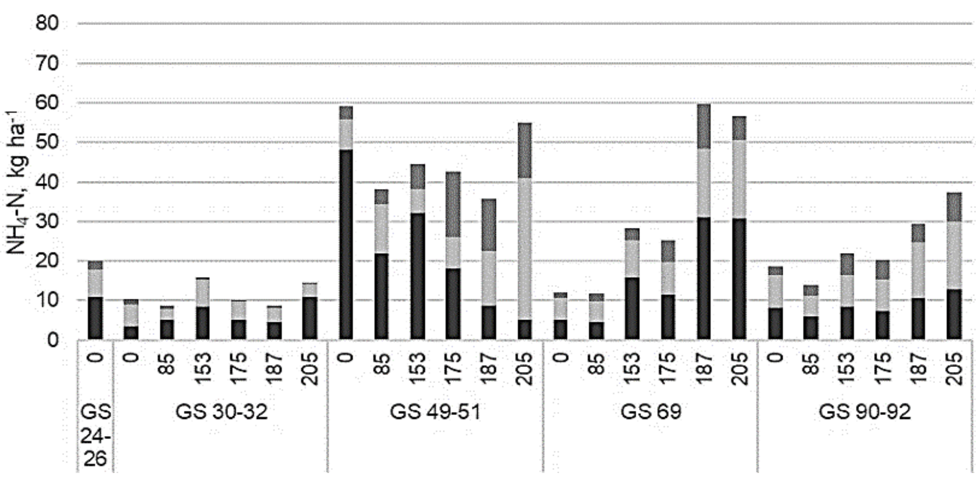

Figure 7. NH_4–N nitrogen accumulation in different soil layers in vegetation period 2015, kg ha^{-1}. (0, 85, 153, 175, 187, 205 – N norm, growth stage; ■ – 0–20 cm*; ■ – 20–40 cm; $LSD_{0.05}$ = 8.11; ■ – 40–60 cm*); *not significant at the probability level 0.05.

In 2015 was similar situation like in 2013 when nitrate and ammonium nitrogen content highest values were observed in the top layer (0–20 cm) from the renew of vegetation till GS 69, except variants with high nitrogen application doses (N175, 187, 205) in GS 49–51. Further on till the ripening stage NO_3–N and NH_4–N nitrogen content increase in deeper soil layer (20–40 cm). In 2015 it was found that wheat growth stage significantly influenced ($P < 0.05$) NO_3–N and NH_4–N nitrogen content in soil 40–60 cm layer.

Nitrogen surplus in soil at the end of vegetation is harmful to the environment. Data obtained in our experiments shows that maximum nitrate content at the end of vegetation GS 90-91 (2.3–12.6 mg kg^{-1}) did not exceed the Nitrate directive determined NO_3–N norm – 50 mg kg^{-1}.

In our research the linear relation between the mineral nitrogen (NO_3–N and NH_4–N) content in the soil layer 0–60 cm and climatic conditions according to HTC during the growing season was statistically significant ($P < 0.05$) in 2013 variants with high nitrogen application norm (> 153 kg N ha^{-1}) and in 2015 N175 (Table 1). In 2013 plants overwintering was very good, spring was late and period of plant active growth was warm and wet. Precipitation in May was high – 2.5 times over annual data, air temperature 3 °C above annual data. 2013 vegetation period was high moisture availability: HTC – 2.33. Research data correspondent with data Timbare et al. (2001) where was found relationship between the content of mineral nitrogen in soil and the value of HTC (0.5–4.2) in depth 0–40 cm. A significant correlation was not found in 2014, when part of plants did not survive after wintering. The effect of temperature and precipitation on nitrate and ammonia nitrogen content in soil are not simple, it means that non-controllable factors such us mineralization of soil organic matter, nitrification and soil aerobicity were affecting results (Haynes et al., 1986, Līpenīte et al., 2016).

Table 1. Dependence of mineral nitrogen (N_{min}) content (0–60 cm soil layer) in relation of fertilizer norm on HTC in vegetation period, 2013–2015

Fertilization norm, Kg N ha^{-1}	Year/ coefficient of correlation			Regression equation
	2013	2014	2015	
Control – without fertilizer	0.808	0.496	0.898	n/s
85	0.949	-0.248	0.917	n/s
153	0.952*	-0.553	0.942	y = 4.5645x+18.637
175	0.989*	-0.268	0.961*	y = 10.231x+5.8067 (2013) y = 46.305x-5.6493 (2015)
180 (2013), 150 (2014), 205 (2015)	0.991*	-0.517	0.792	y = 11.814x+2.6637
187	0.998*	-0.663	0.429	y = 8.8617x+15.793

*Significant at probability level 95%, n/s – not significant, n = 4.

Influence (η^2) of factors: growth stage and fertilizer application were calculated for nitrogen forms (NO_3–N and NH_4–N) content on soil different layers in all trial years (Table 2). Results suggest, that growth stage had highest factors influence – 76% on NO_3-N content in 2013 and 2014 in soil 40–60 cm layer, and 66% on NH_4–N content in the same soil layer in 2013. Growth stage smallest influence on NO_3–N and NH_4–N content were found (9% and 7% respectively) in the soil 20–40 cm layer in 2015. The fertilizer application highest influence on NO_3-N and NH_4–N content (61% and 40% respectively) was observed in soil 20–40 cm layer in 2015. The lowest value (7%) of fertilizer application influence on NO_3-N content were found in the soil 40–60 cm layer in 2013, but on NH_4–N content – 6% in the soil top layer (0–20 cm) in 2015.

Table 2. Influence of growth stage and fertilizer application on NO_3–N and NH_4–N content in soil different layers, 2013–2015, %

Soil layers, cm	2013		2014		2015	
	growth stage	fertilizer application	growth stage	fertilizer application	growth stage	fertilizer application
NO_3–N						
0–20	49	26	52	23	18	13
20–40	31	38	64	16	9	61
40–60	76	7	76	8	50	14
NH_4–N						
0–20	45	19	41	27	32	6
20–40	25	25	41	23	23	40
40–60	66	9	47	23	48	25

Winter wheat grain yield ranged from 4.07–7.64 t ha^{-1} ($LSD_{0.05}$ = 0.47), in 2013, from 2.79–5.20 t ha^{-1} ($LSD_{0.05}$ = 0.12) in 2014, and 4.23–10.20 t ha^{-1} ($LSD_{0.05}$ = 0.81) in 2015. In 2013 and 2015 the highest grain yield (7.64 and 10.20 t ha^{-1} respectively) were observed in variant with fertilizer norm 175 kg N ha^{-1}, but in 2014 – N187 (5.20 t ha^{-1}). In 2015 highest amount of nitrogen fertilizer (205 kg N ha^{-1}) determined by chlorophylmeter not provide high grain yield (7.27 t ha^{-1}), because of dry weather conditions. Trial years average grain yields did not showed significant correlation with the nitrate and ammonium nitrogen content in different soil layers and plant growth stages, except nitrate nitrogen content in soil layer 40–60 cm at GS 30–32 where obtain negative correlation -0.52 and ammonium nitrogen content in soil layer 40–60 cm at GS 69 and GS 90–92 (0.54 and 0.58 respectively) at probability level 95% (Table 3). Scientists Joseph & Prasad (1993) have found close correlation between wheat yield and nitrate nitrogen content in soil at 30, 45 and 60 days after sowing, but ammonium nitrogen content at 15 and 30 days after sowing. Staugaitis et al. (2007) observed similar results: crop yield correlated less with nitrate nitrogen and least with ammonia nitrogen.

Table 3. Correlation between winter wheat grain yield and ammonium nitrogen and nitrate nitrogen content in soil different levels

Growth stage	NO_3–N			NH_4–N		
	0–20 cm	20–40 cm	40–60 cm	0–20 cm	20–40 cm	40–60 cm
GS 24	0.96	0.59	0.93	0.89	0.58	0.41
GS 30–32	-0.43	-0.40	-0.52*	-0.08	-0.37	-0.42
GS 49–51	-0.23	0.17	0.47	-0.09	0	0.14
GS 69	-0.09	0.10	0.42	0.23	0.45	0.54*
GS 90–92	-0.46	-0.15	0.15	-0.26	0.07	0.58*

*Significant at probability level 95%.

CONCLUSIONS

Trials results indicate that the soil NO_3–N and NH_4–N content significantly varied depending on the fertilizer treatment and sampling time. The content of ammonium nitrogen NH_4–N and nitrate nitrogen NO_3–N in the soil layers 0–20 cm, 20–40 cm and 40–60 cm mostly years decreased during vegetation and increased with increasing nitrogen dose. Year meteorological conditions had significant influence on nitrate nitrogen content at 0–40 cm soil layer ($P < 0.01$). Nitrate and ammonium nitrogen content in 20–40 cm soil layer were significantly dependant on the level of nitrogen fertilizer ($P < 0.05$). Average grain yields showed significant correlation with the nitrate nitrogen content in soil layer 40–60 cm at GS 30–32 and ammonium nitrogen content in soil layer 40–60 cm at GS 69 and GS 90–92. Nitrogen fertilizer management based on mineral nitrogen amount in soil can improve wheat nitrogen use efficiency and can reduce potential pollution of ground water with nitrogen compounds.

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Single cell oil production from waste biomass: review of applicable agricultural by-products

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Abstract. Single cell oil (SCO) is an attractive alternative source of oils, since it can be used as feedstock in biofuel production and also have been recognized as viable option in production of essential fatty acids suitable for either human nutrition or as supplementary in animal feeds. However, the usability of SCO is limited due to the high price of raw materials used in the fermentation process. This problem can be tackled by using low-cost agro-industrial residues which are applicable for SCO production. Use of these by-products as the main carbon source in fermentations not only significantly reduces the overall production costs of SCO, but also enables treatment of generated waste streams, thus reducing the negative impact on environment. Since various biodegradable agro-industrial by-products can be used in microbial fermentations, this review aims to categorize and compare applicable agricultural residues by their availability, necessary pre-fermentation treatments, SCO yields and current usability in other competing sectors.

Key words: microbial oil, oleaginous microorganisms, low-cost substrate, agricultural residues, animal feed, biodiesel.

INTRODUCTION

In order to reduce the costs associated with waste recycling, it is important to look at the possibility of using available waste streams as raw materials for the production of new value added products. Nowadays, a large part of biodegradable waste is incinerated (Johnson & Taconi, 2007) or used as feedstock in biogas (Kost et al., 2013), bioenergy or biofuel (Browne et al., 2011) production, which are products with relatively low added value (Spalvins et al., 2018a). However, thanks to new technological solutions, the same waste products can be used as raw materials for production of products with high added value (Werpy & Petersen 2005; FitzPatrick et al., 2010; El-Bakry et al., 2015; Finco et al., 2016). One such product is single-cell oil (SCO).

Single cell oils are oils derived from oleaginous fungi, yeasts, bacteria, microscopic algae and protists. These oils can be used for animal and human consumption, in pharmaceuticals and as feedstock in production of biofuels (Ratledge, 2013). The chemical and biochemical properties of these oils are similar to those derived from plants and animals (Ward & Singh, 2005; Ratledge & Cohen, 2008; Meng et al., 2009;

Dewapriya & Kim, 2014), however, SCO advantages include the high diversity of applicable oleaginous microorganism species, the ability to accumulate large amounts of lipids in cells, faster growth of biomass compared to plants and animals, and reduced production costs (Huang et al., 2013; Thevenieau & Nicaud, 2013; Garay et al., 2014). In addition, SCO production is a good alternative to plant-derived oils because the production of SCO is more environmentally friendly (Tilman, 1999), consumes less water (Mekannen & Howkstra, 2014), production requires significantly smaller land areas and has a significantly lower negative impact on climate change (Vermeulen et al., 2012), as it is in the case with oils derived from plants or animals (Spalvins & Blumberga, 2018). Another advantage of SCO is the ability to use a wide range of biodegradable agricultural by-products in the cultivations of SCO-producing microorganisms. SCOs used in nutritional supplements, baby foods and pharmaceuticals are produced in microbiological fermentations where refined sugars are used as the main carbon source. Given that the carbon source accounts for 60-75% of the total cost of SCO production (Finco et al., 2016), the total cost of production is considerably increased by the use of refined sugars in fermentations. The increase in costs of using refined sugars makes SCO production not profitable in sectors with relatively lower added value, such as animal feeds and biofuels. Consequently, these sectors would need to use cheaper substrates for SCO production, such as by-products from other industries, waste products, wastewaters and production residues (Spalvins & Blumberga, 2018). The use of waste products in SCO production reduces total oil production costs and waste treatment reduces the negative environmental impact that these wastes would have if they were discharged untreated (Spalvins et al., 2018b).

In the context of this review, agricultural waste is any biodegradable by-product from agriculture or food production industries that is suitable for cultivation of SCO-producing microorganisms and is not further utilized in the relevant production systems or their use in SCO production would lead to higher added value than already existing solutions. In other reviews (Leiva-candia et al., 2014; Jin et al., 2015; Finco et al., 2016; Patel et al., 2016; Qin et al., 2017) which summarize reported findings on the use of suitable waste in cultivations of SCO-producing microorganisms, information focuses mainly on the used microorganisms and not so much on the properties of the waste products themselves. However, nowadays, for research and industrial purposes, access to the various strains of microorganisms is relatively simple, but the availability of suitable waste products is very specific to each particular local economy and nearby industries that generate these wastes. In order to facilitate selection of the most appropriate by-products, the wastes in this paper will be categorized and compared according to availability, pre-fermentation treatment, SCO yields and current use in other competing industries. However, it should be emphasized that a full availability analysis for any waste product that is potentially suitable for SCO production needs to be done by taking into account the costs, local availability, transportation and required logistics systems. Performing such analysis is beyond the scope of this review, but further discussion on the topic of complete availability analysis of waste materials is reviewed by Spalvins & Blumberga (2018).

WASTE TYPES

Spalvins et al. (2018a) categorized the most suitable agricultural wastes for single cell protein (SCP) production in 4 groups: monosaccharide and disaccharide rich sources; starch rich sources; structural polysaccharide rich sources; protein or lipid rich sources. These groups will also be used to categorize waste products in this review. Although the waste products described in the previous review (Spalvins et al., 2018a) were reviewed in regard to SCP production, they are also suitable for SCO-producing microorganisms and vice versa. For this reason, previously reviewed waste products such as whey, bran, monosodium glutamate wastewater etc. were not repeatedly described in this review, although they were listed in the summary tables (Table 1, 2, 3, 4) to compare SCO yields. New or additional information in the regard to SCO production was provided for previously described waste products such as molasses, cereal residues, various starchy wastewaters etc.

COMPARISION OF AGRICULTURAL BY-PRODUCTS

Monosaccharides and disaccharides rich sources

Monosaccharides and disaccharides rich waste products can be directly used in microbial fermentations with good SCO yields. Thus, the main advantage of this waste product group is that they do not require pre-treatment or that the pre-treatment is minimal, which in turn significantly reduces the total cost of SCO production.

Molasses

During sugar beet and sugarcane processing, by-products such as molasses, filter mud, bagasse, straw and tops are produced during the sugar production process (FAO, 1987). For every tonne of sugar produced, approximately 320 kg of molasses are generated, which equals about 60 million tonnes of molasses generated in 2017 (FAO, 1987; OECD-FAO, 2018). Depending on the annual yield and market price changes, about 90% of molasses are used in the production of industrial alcohol. Since SCO is a product with higher added value than ethanol (Duncan, 2003; Thompson et al., 2009; Shepherd & Bachis, 2014), fermentation operations adapted to SCO production can compete with alcohol production for molasses as raw material.Molasses usually contain large amounts of fermentable carbohydrates (45–60%) (Ren et al., 2013) and since molasses do not require pre-treatment (Kopsahelis et al., 2007), the use of molasses in the cultivation of SCO-producing microorganisms has been extensively studied (Voss & Steinbüchel, 2001; Gouda et al., 2008; Zhu et al., 2008; Karatay & Dönmez, 2010; Ren et al., 2013). Depending on used extraction methods and plant species molasses usually also contain mineral elements and small amounts of proteins and lipids (Ren et al., 2013). Very high SCO concentrations have been reported by cultivating bacteria *Gordonia sp.* and *Rhodococcus opacus*, when molasses was used as the main source of carbohydrates (Gouda et al., 2008). High cell densities and SCO rich in unsaturated fatty acids were obtained by cultivating microalgae *Schizochytrium sp.* (Ren et al., 2013) (Table 1).

Brewery wastewater

Most brewery wastewaters are generated during the production, packaging, washing and discharge of beer. Breweries in general have very high water consumption for their operations and the total volume of wastewater generated per 1 litre of beer produced in well managed breweries is 2 litres, while in average breweries from 3 to 6 litres of wastewaters are generated per every litre of beer produced (BA, 2017). Considering that in 2017 the global production of beer amounted to 1 900 million hectolitres (FAO, 2009; KHC, 2018), the amount of wastewater generated from the beer industry is huge. Untreated brewing wastewater is characterized by biological oxygen demand (BOD) and chemical oxygen demand (COD) values from 600 to 5,000 ppm and from 1,800 to 5,500 ppm respectively, with pH varying from 3 to 12 depending on the use of cleaning agents and high nitrogen, phosphorus and suspended solids concentrations (BA, 2017). Since brewery wastewaters are not reutilized in other processes, the huge wastewater volumes that are generated in breweries need to be pre-treated, which in turn considerably increase the overall expenses for the brewery, or heavily overloads local water treatment systems, if appropriate pre-treatment is not carried out in the brewery itself. Brewery wastewaters contain cellulose, sugars, amino acids, spent grains, proteins, sludge, wort, yeast suspended solids and beer residues (BA, 2017). If these wastewaters do not contain microorganism growth inhibiting compounds from cleaning agents, then brewery wastewaters are suitable for cultivating SCO-producing microorganisms such as *Rhodococcus opacus* (Schneider et al., 2013), although biomass and accumulated SCO concentrations are relatively low (Table 1). Additional research and finding of more suitable microorganisms for brewery wastewaters is necessary to ensure more efficient treatment of these wastewater and obtain higher SCO yields.

Sugarcane juice

Sugarcane juice is a popular drink in South America and other regions where sugarcane is widely grown (Soccol et al., 2017). Juice itself is considered a cheap source of sugars and variable amount of juice is spilled during squeezing and cannot be used in human consumption. Since sugarcane juice has high monosaccharide and disaccharide content (15% w/w), sugarcane juice is a suitable raw material for SCO production without requiring addition pre-treatment (Soccol et al., 2017). Sugarcane juice as a cheap raw material is one of the few by-products tested in industrial scale pilot fermentation to produce SCO suitable for biofuel production from oleaginous yeast *Rhodosporidium toruloides* (Soccol et al., 2017).

Sweet sorghum juice

Juice from sweet sorghum plant is used in sugar production (Gnansounou et al., 2005; Liang et al., 2010). In 2017, 57 million tons of sweet sorghum was harvested, which is a miniscule amount compared to sugarcane and sugar beet yearly harvests, but since sweet sorghum juice is being evaluated as a raw material for ethanol production, SCO production as a competitive alternative is also being explored (Liang et al., 2010). Using sorghum juice as a raw material to cultivate *Schizochytrium limacinum* Liang et al. (2010) managed to obtain high SCO concentrations, although biomass concentrations in media were relatively low for this microalgae strain (Table 1).

Table 1. Monosaccharaides and disaccharides rich sources. Recent reports of obtained dry cell weight (DCW) (grams per litre of medium) and lipid content (LC) (% of DCW) by using mono and disaccharide rich wastes as substrates for microbial fermentations

Substrate	Microorganisms	DCW ($g\ L^{-1}$)	LC (%)	References
Sugarcane molasses	*Rhodococcus opacus*	-	93	Gouda et al., 2008
	Gordonia sp.	-	96	”
	Cunninghamella echinulata	12.1	32	Chatzifragkou et al., 2010
	Mortierella isabellina	9.5	54	”
	Trichosporon fermentans	28.1	62.4	Zhu et al., 2008
	Schizochytrium sp.	35.32	41.2	Ren et al., 2013
Molasses	*Candida lipolytica*	-	59.9	Karatay & Dönmez, 2010
	Candida tropicalis	-	46.8	”
	Rhodotorula mucilaginosa	-	69.5	”
Sugar beet molasses and sucrose	*Rhodococcus opacus*	18.4	38.4	Voss & Steinbüchel, 2001
Cheese whey	*Mortierella isabellina*	32.0	25.3	Vamvakaki et al., 2010
	Thamnidium elegans	18.1	3.3	”
	Mucor sp.	21.7	3.2	”
Sweet whey	*Rhodococcus opacus*	-	84	Gouda et al., 2008
Brewery effluents	*Rhodotorula glutinis*	5.22	12.5	Schneider et al., 2013
Sugarcane juice	*Rhodosporidium toruloides*	0.44 g/L/h (pilot scale)		Soccol et al., 2017
Sweet sorghum juice	*Schizochytrium limacinum*	9.4	73.4	Liang et al., 2010

Starch rich sources

Starch-rich wastes, such as cereal and vegetable processing residues and food waste, make up a large part of the biodegradable agricultural and household wastes. Although these waste products are available in large quantities, they need to be hydrolysed before they can be used in microbial cultivations, which in turn increases the total cost of production of SCO. Costs can be reduced by replacing applied mechanical or chemical hydrolysation treatments with enzymatic using amylolytic microorganisms in pre-fermentations (Pleissner et al., 2013; Lau et al., 2014; Johnravindar et al., 2018) or by using enzymatic hydrolysis (Pleissner et al., 2014; Pleissner et al., 2017; Sloth et al., 2017) to digest the starch present in the waste products.

Food waste

Globally food waste constitutes to approximately 1.3 billion tonnes annually (Gustavsson et al., 2011; Pleissner et al., 2013). The composition of food waste varies depending on the source, but usually contains 30–60% carbohydrates (mostly starch), 6–10% protein and 7–30% fat (Leung et al., 2012; Lau et al., 2014; Pleissner et al., 2014), therefore, after appropriate hydrolysis, these residues can be used for SCO production (Pleissner et al., 2013; Lau et al., 2014; Pleissner et al., 2014; Pleissner et al., 2017; Sloth et al., 2017; Johnravindar et al., 2018). Although the amount of generated food waste is huge, a large proportion of these residues is mixed with non-biodegradable residues (other municipal residues), so the availability of real food residues is considerably lower. If local households and catering business chains sort food waste separately and effective collection of these residues is organized, then amounts of locally available food waste can be sufficient for industrial scale SCO production. By using hydrolysed food waste the highest reported SCO yields have been achieved by cultivating oleaginous yeast *Yarrowia lipolytica* (Johnravindar et al., 2018) (Table 2).

Table 2. Starch rich sources. Recent reports of obtained dry cell weight (DCW) (grams per litre of medium) and lipid content (LC) (% of DCW) by using starch rich wastes as substrates for microbial fermentations

Substrate	Microorganisms	DCW ($g\ L^{-1}$)	LC (%)	References
Food waste hydrolysate	*Schizochytrium mangrovei*	14	16	Pleissner et al., 2013
	Chlorella pyrenoidosa	20	20	”
	Galdieria sulphuraria	3.5	-	Sloth et al., 2017
	Chlorella vulgaris	20	35	Lau et al., 2014
	Yarrowia lipolytica	20.9	49.0	Johnravindar et al., 2018
	Rhodotorula glutinis	14	47	
	Cryptococcus curvatus	9.4	29	”
	Chlorella pyrenoidosa	31.7	14.1	Pleissner et al., 2017
Potato processing waste-water	*Aspergillus oryzae*	3.5		Muniraj et al., 2013
Corn steep water and corn gluten water	*Rhodotorula glutinis*	26.4	28.9	Liu et al., 2016
Corn starch wastewater	*Rhodotorula glutinis*	40	35	Xue et al., 2010
Cassava starch hydrolysate	*Rhodosporidium toruloides*	22.0	63.4	Wang et al., 2012
Corn starch hydrolysate and defatted soybean meal	*Mortierella isabellina*	29.5	31.1	Zhu et al., 2003

Potato processing wastewater

Potato is one of the most popular staple foods in many parts of the world, as well as an important source of carbohydrates. Potato processing industries generate large amounts of wastewater during production of potato chips, peeled whole potatoes, potato slices and many other potato products. In 2017, 388 million tons of potatoes (FAO, 2019) were harvested globally and the global potato processing industry generated approximately 30 million tonnes of wastewater (Stevens & Gregory, 1987; Hung et al., 2004). Potato wastewaters are rich in starch and protein and these effluents have high COD (10,000–11,000 ppm), BOD (4,000–6730 ppm) and suspended solids (5,150–18,000 ppm) values (Gray & Ludwig, 1943; Cooley et al., 1964; Hung et al., 2004). Consequently, the potato processing industry poses a risk to local environments if these wastewaters are discharged untreated (Hung et al. 2004). Such technological solutions as screening, sedimentation, flotation, earthen ponds, activated sludge, anaerobic treatment, microstraining, chemical coagulation and many others have been developed and are being actively used for potato processing wastewater treatment. However, the effective use of these wastewaters in microbial fermentations have been scarcely reported (Muniraj et al., 2013) and more research on suitable microorganism strains is needed.

Corn starch processing wastewater

In 2017, global corn starch production was 70 million tonnes, resulting in more than double the amount of wastewater (Xue et al., 2010; FAO, 2019). Because corn starch wastewater is rich in starch, its release into natural water bodies can cause environmental pollution (Lu et al., 2009). However, due to the high carbohydrate content, corn starch wastewater can be used in microbial fermentations (Xue et al., 2010). By using this wastewater in SCO production, its suitability has been studied using it either as a carbon source (Xue et al., 2010) or as a nitrogen source (Liu et al., 2016) in cultivations of oleaginous yeast *Rhodotorula glutinis* (Table 2).

Low cost products

Although not waste products, low cost substrates such as cassava and corn starch and soybean meal are widely used in industrial fermentation processes, where starch compounds are used as carbon source and soybean residues are used as nitrogen source (Wang et al., 2012; Zhu et al., 2003). By using *Rhodosporidium toruloides* on cassava starch high biomass and SCO concentrations have been reported (Wang et al., 2012). By using corn starch hydrolysate and defatted soybean meal as combined substrate, very high biomass concentrations have been reported (Zhu et al., 2003), although lipid content could be higher considering that SCO concentrations as high as 65% have been reported in *Mortierella isabellina* biomass (Fakas et al., 2009) (Table 2).

Structural polysaccharide rich sources

Cereals residues

Wheat, maize and rice make up 43% of the world's food calories (FAO, 2019). Cereals are the most widely grown agricultural crop and during the processing of cereals a huge amount of residues are generated, which are widely available (Spalvins et al., 2018a). Due to the vast amounts, the use of cereal residues in the cultivation of microorganisms is of great economic and ecological importance. Cereal processing residues are rich in lignocellulose, therefore, the use of these residues as a carbon source for microbiological fermentations is much more complicated because of the need for extensive mechanical, chemical or biochemical pre-treatment, which increase the overall production costs. Additionally, during pre-treatment, hydrolysates release microorganism growth inhibiting compounds such as furfural, vanillin, phydroxybenzaldehyde, syringaldehyde, and others (Yu et al., 2014), therefore, hydrolysates need to be diluted or detoxified, which further complicates the use of these materials in SCO production. Despite these challenges, the use of cereal residues in SCO production has been extensively studied, and researchers have managed to obtain high concentrations of microbial biomass and SCO in mediums derived from cereal residues such as straw, stover, corncob residues and grain hulls (Zhu et al., 2003; Gouda et al., 2008; Huang et al., 2009; Huang et al., 2011; Yu et al., 2011; Galafassi et al., 2012; Huang et al., 2012a; Ruan et al., 2012; Gao et al., 2014; Yu et al., 2014; Chang et al., 2015; Kahr et al., 2015; Poontawee et al., 2017; Guerfali et al., 2018). The highest SCO yields for cereal residue substrates were reported using the yeasts form *Trichosporon* genus - *Trichosporon cutaneum* (Gao et al., 2014), *Trichosporon fermentans* (Huang et al., 2009) and Trichosporon dermatis (Huang et al., 2012a) (Table 3).

Fruit and vegetable waste

The composition of the fruit processing residues depends on which parts of the fruit or plant make up most of the generated waste. Waste products such as date fruit and tree residues have been extensively studied for their use in various microbiological fermentations (Chandrasekaran & Bahkali, 2013), however, the use of these waste products in SCO production requires further studies (Gouda et al., 2008). In 2017, global production of date fruit amounted to 8 million tonnes (FAO, 2019) of which at least 10% end up as waste in the form of date pits and spoiled date fruits (Chandrasekaran & Bahkali, 2013).

Tomato processing industry generates a large amount of residues during peeling of tomatoes. Approximately 10–40% of the total volume of the processed tomatoes ends up as waste. Considering that around 70% of all produced tomatoes are processed (Strati & Oreopoulou, 2011), about 32 million tonnes of tomato residues are generated each year (FAO, 2019). Tomato residues are rich in lignocellulose, proteins and lipids, and these residues are also good source of vitamins and mineral elements (Al-wandawi et al., 1985). Thus, if these residues cannot be used in animal nutrition due to transportation, these residues could be used as rich medium for SCO-producing microorganisms. Results reported so far using *Cunninghamella echinulata* (Fakas et al., 2008), *Rhodococcus opacus*, *Gordonia sp*. (Gouda et al., 2008), shows that tomato residues are an effective substrate for SCO production (Table 3).

Sugar processing waste

The main fibre-rich sugar processing residues are bagasse and straw. During processing, approximately 250 kg of bagasse and 60 kg of straw are generated from one tonne of processed sugarcane, resulting in an annual production of around 460 million tonnes of bagasse and 110 million tonnes of straw (FAO, 1987; OECD-FAO, 2018; FAO, 2019). Bagasse is widely used as a fuel and as raw material for biofuel production or paper production (Hofsetz & Silva, 2012). Since the amount of fibre-rich residues generated by the sugar processing industry is huge, more efficient uses and the production of products with higher added value using sugar processing residues have been extensively studied (Tsigie et al., 2011; Huang, et al., 2012b; Bonturi et al., 2017; Unrean et al., 2017; Poontawee et al., 2018). The highest SCO yields using begase hydrolysates have been reported using yeast *Trichosporon fermentans* (Huang et al., 2012b) (Table 3).

Sugarcane bagasse hydrolysate is characterized by relatively low C/N ratios due to its high concentration of proteins and other nitrogen compounds (Bonturi et al., 2017). Hence, these hydrolysates require additional carbon sources to increase the C/N ratio in the medium and promote oil accumulation in the microorganisms.

Table 3. Structural polysaccharides rich sources (agricultural waste). Recent reports of obtained dry cell weight (DCW) (grams per litre of medium) and lipid content (LC) (% of DCW) by using structural polysaccharides rich wastes as substrates for microbial fermentations

Substrate	Microorganisms	DCW ($g L^{-1}$)	LC (%)	References
Wheat straw hydrolysate	*Cryptococcus curvatus*	17.2	33.5	Yu et al., 2011
	Rhodotorula glutinis	13.8	25.0	”
	Rhodosporidium toruloides	9.9	24.6	”
	Lipomyces starkeyi	14.7	31.2	”
	Yarrowia lipolytica	7.8	4.6	”
Rice straw hydrolysate	*Trichosporon fermentans*	28.6	40.1	Huang et al., 2009
Corn stover hydrolysate	*Rhodotorula graminis*	-	34	Galafassi et al., 2012
	Trichosporon cutaneum	17.35	23.5	Huang et al., 2011
	Mortierella isabellina	14.08	34.5	Ruan et al., 2012
Corncob hydrolysate	*Trichosporon cutaneum*	38.4	32	Gao et al., 2014
	Cryptococcus sp.	12.6	60.2	Chang et al., 2015
	Trichosporon dermatis	24.4	40.1	Huang et al., 2012a
	Yarrowia lipolytica	16.6	19.4	Kahr et al., 2015
Rice hulls hydrolysate	*Mortierella isabellina*	-	64.3	Economou et al., 2011
Wheat bran	*Rhodococcus opacus*	-	56	Gouda et al., 2008
	Gordonia sp.	-	41	”
Barley hull hydrolysate	*Trichosporon cutaneum*	17.5	38.2	Guerfali et al., 2018
Orange waste	*Gordonia sp.*	1.88	80	Gouda et al., 2008
Apple pomace	*Rhodococcus opacus*	-	83	”
	Gordonia sp.	-	70	”
Date waste	*Rhodococcus opacus*	-	57	”
	Gordonia sp.	-	61	”
Tomato waste hydrolysate	*Cunninghamella echinulata*	11.8	48	Fakas et al., 2008
Tomato peel waste	*Rhodococcus opacus*	-	73	Gouda et al., 2008
	Gordonia sp.	-	52	”
Sugarcane bagasse hydrolysate	*Trichosporon fermentans*	31	39.9	Huang et al., 2012b
	Rhodosporidium toruloides	19.0	53.6	Bonturi et al., 2017
	Yarrowia lipolytica	13.7	78.5	Unrean et al., 2017
	Yarrowia lipolytica	11.42	58.5	Tsigie et al., 2011
Sugarcane top hydro-lysate and crude glycerol	*Rhodosporidiobolus fluvialis*	24.3	75.0	Poontawee et al., 2018
Olive mill waste	*Rhodococcus opacus*	-	20	Gouda et al., 2008
	Gordonia sp.	-	29	”
Olive oil wastewater	*Lipomyces starkeyi*	0.054	29.5	Yousuf et al., 2010

Olive processing waste

Olive processing and olive oil production is an important source of income for local economies in the Mediterranean region. Depending on the used milling process, from

500 to 1500 litres of wastewaters are generated from each ton of processed olives. Olive processing wastewaters are rich in carbohydrates, polysaccharides, polyphenols, nitrogen compounds and polyalcohols (Canepa et al., 1988). These wastewaters have very high COD (around 100,000 ppm) and BOD (around 40,000 ppm) values, therefore they need to be treated. Often, these wastewaters are discharged on fields, in lakes, rivers and seas or stored in evaporation lagoons. Such disposal of these wastewaters cause pollution of soil, local water bodies, groundwater and also cause odour pollution (Canepa et al., 1988). Currently, the most effective solutions for olive processing wastewater treatment are biological treatment using anaerobic, aerobic and co-digestion processing techniques. Since olive processing wastewater contains phenolic compounds which inhibit microbial growth, it is necessary to dilute these wastewaters so that they can be used effectively in SCO production (Yousuf et al., 2010). However, even after diluting these wastewaters, the resulting SCO and biomass concentrations have been low (Gouda et al., 2008; Yousuf et al., 2010) (Table 3).

Protein or lipid rich sources

Oils and fats can be used as a carbon source in microbiological fermentations if the used microorganism strain is capable of utilizing these lipids (Fickers et al., 2005). For efficient use of waste oils and fats, mechanical (ultrasonic homogenisation, high-shear emulsifiers, etc.) or chemical (various polysorbates) emulsification solutions are needed during the preparation of the media. Although lipid emulsification is not as costly pre-treatment as the polymer hydrolysation, it still increases the overall cost of production when compared to monosaccharide and disaccharide-rich sources.

In addition to the carbon source, microorganisms require nitrogen, amino acids, fatty acids and micro and macro elements to ensure optimal growth and production of SCO. To break down fibrous proteins in the waste and use them as a source of nitrogen and amino acids in fermentations, these protein compounds need to be hydrolysed using physical, chemical or biochemical pre-treatment techniques (Atalo & Gashe, 1993).

Waste cooking oil

Cooking oils are widely used throughout the world for food preparation in households, canteens and also at industrial scale. During cooking, harmful compounds such as lipid peroxidation products, aldehydes, etc. are released in oils (Wei et al., 2011). Therefore, it is necessary to change the cooking oil regularly and dispose of the waste cooking oils (WCO). Every year, more than 10 million tonnes of WCO are generated globally (Wei et al. 2011). These oils are two to three times cheaper than vegetable oils, therefore, their use in both biodiesel production and as ingredient in animal feeds offers significant economic benefits (Phan & Phan 2008; Talebian-Kiakalaieh et al., 2013). However, since 2002, the European Union has banned the use of WCO in animal feed, as there is a risk that harmful compounds present in oils may be carried over to animal products (Cvengros & Cvengrosova, 2004; Kulkarni & Dalai, 2006). As a result, the main use of spent cooking oils remains in the production of biodiesel, which, compared to SCO production, is a solution with lower added value (Lipinsky, 1981; Browne et al., 2011; Spalvins et al., 2018a). The use of WCO in the cultivation of microorganisms is problematic as it is necessary to emulsify the oils in the prepared media using either chemical emulsifying agents or mechanical emulsification solutions (Michely et al., 2013). An interesting approach to the use of WCO in the cultivation of microorganisms is by using microorganism strains that themselves produce oil emulsifying compounds such as oleaginous yeast *Yarrowia lipolytica* (Michely et al. 2013). When WCO were used as carbon source in the fermentations the reported SCO yields have been miniscule (Table 4), thus additional research is needed to find oleaginous microorganisms that can effectively utilize lipids in media.

Table 4. Protein or lipid rich sources. Recent reports of obtained dry cell weight (DCW) (grams per litre of medium) and lipid content (LC) (% of DCW) by using protein or lipid rich wastes as substrates for microbial fermentations

Substrate	Microorganisms	DCW ($g\ L^{-1}$)	LC (%)	References
Olive oil	*Rhodococcus opacus*	0.21	19	Gouda et al., 2008
	Gordonia sp.	0.56	13	”
Sesame oil	*Rhodococcus opacus*	0.45	67	”
	Gordonia sp.	1.21	50	”
Castor oil	*Rhodococcus opacus*	0.38	58	”
	Gordonia sp.	0.41	49	”
Cotton oil	*Rhodococcus opacus*	0.32	38	”
	Gordonia sp.	0.48	50	”
Peanut oil	*Rhodococcus opacus*	0.23	52	”
	Gordonia sp.	0.35	40	”
Maize oil	*Rhodococcus opacus*	0.63	40	”
	Gordonia sp.	0.85	40	”
Sun flower oil	*Rhodococcus opacus*	1.06	44	”
	Gordonia sp.	1.18	52	”
Rapeseed oil	*Yarrowia lipolytica*	-	-	Papanikolaou & Aggelis, 2003
Monosodium glutamate wastewater	*Rhodotorula glutinis*	2.44	9.04	Xue et al., 2006
Monosodium glutamate wastewater	*Rhodotorula glutinis*	25	20	Xue et al., 2008

CONCLUSIONS

In this review, most of the agricultural wastes that can be used in SCO production have been categorized and discussed more closely. Since agricultural waste groups were categorized in the same way as it was done previously for SCP production (Spalvins et al., 2018a), the same advantages and disadvantages can be referred to these wastes as well with few additions.

Monosaccharides and disaccharides rich sources require minimal pre-treatment which give these wastes technological and economic advantages over other waste types. However, these wastes are already widely used in other fermentation processes and as feedstock in animal feeds. Therefore, each waste material must be evaluated in regard to its economic feasibility and compared with already existing or potentially emerging competing sectors.

Use of starch, protein or lipid rich sources and their hydrolysates in SCO production result in comparatively lover SCO yields than if monosaccharaides and disaccharides or fibre-rich materials are used in fermentations. Regardless of this, waste products such as food waste, potato and corn starch processing wastewaters and waste cooking oils are generated in huge amounts each year in all parts of world. In order to reduce the negative environmental impact and improve SCO production efficiency, additional research is needed to develop more efficient methods of waste hydrolysis and medium detoxification.

Structural polysaccharides rich wastes are available in huge quantities all over the world; therefore, using these wastes have limited competition with other industries which use waste as resource for production of other value-added products. These wastes require extensive pre-treatments and during hydrolysation microbial growth inhibiting compounds may be released, which, in turn, require additional detoxification of the substrate, before these wastes can be used in microbial fermentations.

The key considerations for choosing the most suitable waste product for SCO production are similar with the ones concluded in previous reviews (Spalvins et al., 2018a; Spalvins et al., 2018b) with few changes for details specific to SCO production. Key consideration are: target market for the final oil (biodiesel production; animal feeds); which microorganism strain produces necessary fatty acid profile for the target market; local availability of the particular waste product; pre-treatment costs of the waste product before using it in fermentation; the costs of transportation of the waste product; maximum obtainable cell densities in the substrate; SCO concentrations in the final biomass after fermentation; estimation whether cultivation conditions can be efficiently maintained (energy and heat consumption); efficiency of biomass and waste separation, and SCO extraction (oil extraction from biomass and removal of impurities) methods.

In the future, it is also necessary to review and compare different industrial wastes in regard for their use as substrates for SCO production.

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Role of humic substances in agriculture and variability of their content in freshwater lake sapropel

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Abstract. The term 'humic substances' (HS) refers to a general category of naturally occurring, biogenic, heterogeneous organic substances. They create the most widespread natural organic matter found in sediments, soils and waters. Organic carbon in soil (up to 70%) and peat (up to 90%) usually occurs in the form of HS. HS influence the formation process of fossil fuels, as well as they are involved in the plant nutrition process, have an influence on availability and toxicity of metallic and other elements. Furthermore, HS play a significant role in the global carbon geochemical cycle. Properties and application efficiency of humus depend on the source of HS. Freshwater sapropel is a huge reservoir of HS with superior biological activity, although their total content is lower than in peat. The aim of this paper, firstly, was to present the information about the options of HS in agriculture and their main effects on plant growth. Secondly, determination and characterization of HS content in freshwater lake sapropel was performed as sapropel nowadays becomes a popular natural organic-mineral fertilizer and soil conditioner. Sapropel samples were derived from Lake Pilvelis, Lake Pilcines, Lake Vevers, Lake Liducis and Lake Padelis situated in Eastern Latvia. Investigation of HS content in sapropel is significant for the Baltic States and Northern Europe due to wide distribution and availability of sapropel in freshwater bodies. That promotes a search for new ways of extraction methods and bioeconomically effective utilization of this natural resource, obtainable in economically significant amounts, with high opportunities of its use especially in agriculture. Contemporary agriculture strongly desiderates in new products of high effectivity enhancing soil and crop productivity and quality hand in hand with sustainable development and careful attitude to the nature and surrounding environment, thus, one of the ways how it can be achieved is understanding how, where and how much HS preparations can be applied.

Key words: humic substances, freshwater sapropel, organic fertilizer, bio-stimulant, soil conditioner.

INTRODUCTION

The most widespread natural organic substances are humic substances (HS) containing up to 90% of dissolved organic carbon in the aquatic environment and up to 70% of organic carbon in the terrestrial environment (Kļaviņš, 1997). HS form large pools of the organic component of soils (Kelleher & Simpson, 2006), peat (Šīre, 2010; Purmalis, 2015), composts (Lima et al., 2010) and sapropel (Rūtiņa et al., 2013).

HS are formed during the humification process, i.e., decay of living matter (organic carbon reservoir) in an intermediate phase of the transformation process of organic carbon in the organic carbon cycle, or are deposited in fossil materials (Kelleher & Simpson, 2006; Šīre, 2010). Humification begins immediately after the downfall of an organism when easily degradable substances in cytoplasm are destroyed by extracellular ferments and ferments bound in cell membrane (MacCarthy, 2001). After the decomposition of the cell membrane, microorganisms start to participate in the process of humification; they are involved in breakdown and utilisation of carbohydrates, lipids, nucleic acids, proteins which are the components of the labile fraction of organic matter (Prentice & Webb, 2010; Ziechmann et al., 2000).

Formation of HS is influenced by many factors from which as the most important following can be mentioned: climate, composition of residues to be humified (parent material), dominant group of destructive organisms, pH, oxidation-reduction conditions, presence of oxygen, catalysts or inhibitors of humification (Eglīte, 2007; Kukuļs, 2018), for example, even newly formed HS itself can inhibit degradation and humification of the remains (Ziechmann et al., 2000).

Commonly HS are subdivided into three fractions depending on their solubility: humic acids (HA), fulvic acids (FA) and humins (Eglīte, 2007). Several terms summarized and explained in Table 1 will help to understand structural and functional properties of HS. It is assumed that fractions of humic substances contain organic compounds with similar general properties, while their structure, composition and specific properties in various environmental conditions may differ (Hayes, 1997).

Table 1. Important terms used in the studies of humic substances (MacCarthy et al., 1990; Heiri et al., 2001; Perminova et al., 2003; Vassilev et al., 2012)

Term	Definition
Organic matter	Total amount of the organic matter which is oxidised to carbon dioxide and ash at 500–550 °C during the first reaction of the loss-on-ignition method.
Humus (Soil organic matter)	Total amount of the heterogeneous organic substances in soil with low molecular weight (non-humic substances) and substances with high molecular weight (humic substances), except the soil biomass, undecomposed and partially decomposed products of plant and animal tissues.
Humic substances	The category of naturally occurring, biogenic, heterogeneous organic substances that can generally be characterized by colour (yellow to black), and of high molecular weight and refractory.
Humic acids	Fraction of humic substances that is soluble in water at pH > 2 and insoluble in water under pH < 2. Molecular weight of different humic acids ranges approximately 15–20 kDa.
Fulvic acids	Fraction of humic substances soluble in water under all pH conditions. Molecular weight of fulvic acids of different origin ranges approximately 0.5–15 kDa.
Humins	Fraction of humic substances insoluble in water, alkali and acid. Humins are the most resistant to decomposition of all other fractions of humic substances. They play important role in water holding capacity, structure, stability and fertility of soil.
Humates	Mineral salts of soluble humic substances fractions.

General definition of humic substances determine them as high molecular weight compounds that together form brown to black coloured substances formed by secondary synthetic reactions and which do not belong to substance's classes of biochemistry such as amino acids, carbohydrates, fats, waxes, resins and organic acids. The term is used as a generic name to describe coloured material or its fractions obtained on the basis of solubility characteristics as described in Table 1 (Stevenson, 1994).

Fulvic acids usually form low-molecular weight fraction of HS with low concentration of aromatic groups and high concentration of carboxyl groups (Thomsen et al., 2002; Eglīte, 2007).

Humic acids are complex of molecules where amino acids, amino sugars, peptides and aliphatic compounds are incorporated in the aromatic structures (Purmalis, 2015; Kukuļs, 2018).

Humins are insoluble components of HS that remain after the extraction of all other substances soluble in aqueous base. The major components of humins are aliphatic hydrocarbon functionalities predominantly, but in small amounts carbohydrates, peptides and peptidoglycans. However, composition of humins differs considerably from the base-soluble components of humus (Hayes et al., 2017).

The aim of this paper, firstly, is to present an overview about the options of HS in agriculture and their main effects on plant growth. Secondly, determination and characterization of HS content in freshwater lake sapropel was performed as sapropel nowadays becomes a popular natural organic-mineral fertilizer and soil conditioner.

MATERIALS AND METHODS

Sediment sampling

To implement this study, 191 freshwater lake sediment samples from full profiles of five lakes (Padelis, Pilcine, Pilvelis, Liducis, Vevers) located in Eastern Latvia were collected (Fig. 1). Derived sediment samples were recognized predominantly as sapropel.

Figure 1. Freshwater sediment sampling sites in Eastern Latvia: (A) Lake Padelis, (B) Lake Pilcine, (C) Lake Pilvelis, (D) Lake Lidučis, (E) Lake Vevers.

Sediment profiles were obtained using a 10 cm diameter Russian-type peat sampler with a 1.0 m long camera. Sediment monoliths were subsampled with interval 10 cm, homogenized and placed into plastic bags for transportation to the laboratory according to previously developed methodology (Givelet et al., 2004).

Sediment characterization

Assessment of sediment properties is more significant for characterization of HS in sapropel than distribution by sampling sites (BSSC Institute, 2010; Kurzo, 2005; Stankevica et al., 2015); therefore, all sapropel samples were classified applying sapropel type classification methodology (Stankeviča et al., 2017) as shown in Table 2. Furthermore, sapropel samples of organic and organic silicate types were subdivided considering the origin of organic matter in sapropel, i.e., algal and water animals (OS_{alg}, OSS_{alg}) and vascular, thelmatic plants (OS_{pla}, OSS_{pla}).

Table 2. Type and quantity of analysed sediment samples

Abbreviation	Characteristic type	Number of samples
OS	Organic sapropel	98
OSS	Organic silicate sapropel	61
CS	Carbonate sapropel	19
SS	Silicate sapropel	13

For classification of sediments the loss-on-ignition (LOI) method was applied in order to estimate content of ashes, organic matter and carbonate matter in the samples (Dean, 1974; Heiri et al., 2001), concentration of Ca and Fe was estimated using flame atomic absorption spectrometry equipment (Perkin Elmer 503). Reliability and accuracy of the analytical results were checked using blank and reference samples (ISE 1998.3-921 (Wageningen Evaluating Programmes for Analytical Laboratories), SLRSS-2 river water, BCSS- coastal marine sediments (Analytical Chemistry Standards NRC, Canada)).

Origin and composition of sediment organic matter were identified using Motic DM-B1 Digital Microscope with magnification by 400–1,000 times.

Extraction of humic substances, isolation of humic and fulvic acids, detection of total organic carbon

HS from sediment samples were extracted using conventional extraction technique such as low temperature treatment procedure; humic and fulvic acids were isolated and purified using techniques recommended by the International Humic Substances Society (Tan, 2005). Briefly, 0.5 g of air-dried and finely grounded sapropel sample was treated in N_2 with 25 mL of 2% NaOH for 24 h applying stirring. Obtained suspension was filtered, and 1 mL of it was diluted by 100 times; subsequently, absorption at 410 nm was measured to estimate total content of HS. Afterwards, the remaining solution was acidified with concentrated HCl to $pH < 2$ to precipitate humic acids, leaving fulvic acids in the solution (Tan, 2005).

Calculation of the content of humic acids and fulvic acids was performed using a calibration method. For each lake calibration equations for both, humic and fulvic acids, were done individually.

Total organic carbon of HS was detected using TOC-V CSN analyser (Shimadzu).

Data statistical analysis and data visualisation

Correlation analysis with a data set (N = 178) of humic substances, total content of humic, fulvic acids and quantity of total organic carbon in humic substances was performed using the MS Excel correlation analysis tool. Statistically significant correlation was applied with probability lower than 5% ($P < 0.05$) if critical value for the Pearson's correlation coefficient was $r_{0.05} = 0.15$. Obtained data were plotted and visualised using the Adobe Illustrator CC.

RESULTS AND DISCUSSION

Overview of humic substances' applicability in agriculture

Contemporary ways of soil cultivation in agricultural practice lead to faster decomposition of humus, including humic substances, therefore, soil enrichment with humus in natural way occurs too slowly (Rode et al., 1993). HS in environment can be found even in depleted soils at various concentrations, but their impact on living organisms and plants is not as intensive as it appears from refined preparations made from purified HS and humates – in literature they are named as biostimulants (Canellas et al., 2015) and plant regulators (Baldotto & Baldotto, 2014). This difference occurs due to the fact that HS in soil exist in the form of inactive or low-activity compounds (Eshwar et al., 2017). Functional groups of HS may actively react with mineral components of soil such as cations, oxides, hydroxides, aluminosilicates; as a result, these functional groups are bound and blocked leading to decreased physiological activity and elevation of ashiness (Orlov, 1993; Dūdare, 2015).

During the production of preparations from humates and HS the state of HS is changed. By elimination and purification of HS from mineral components their functional groups are released that allows involvement of HS in various chemical and biochemical processes. Furthermore, during the process of production, molecules are partly destructed that increases amount of free radicals and distribution of molecular mass resulting in enhancement of low molecular fraction. Both, increase of free radicals and decrease of molecular mass of HS, facilitate entrance of humates and other kind of HS preparations into plant tissues and involvement in biochemical processes (Orlov, 1993).

HS form 85–90% of humus or soil organic matter, while the remaining 10–15% are amino acids, carbohydrates, fats, waxes, resins and organic acids (Orlov et al., 1996). Properties and composition of humic substances vary in large ranges depending on many factors including parent material. In biosphere HS play vital role in sustainable life processes as they are involved in common functions like element accumulation, transportation, regulation, protection and regulate physiology of living organisms (Table 3).

Furthermore, HS preparations have accelerating effect on the production cycle of plants as well as enlarge initial growth rates while plants acclimatize to new conditions acting especially effectively on root system (Hernandez et al., 2015). In addition, HS act as carriers for beneficial microorganisms in cropping system (Canellas et al., 2015). All these findings are significant to rise popularity for HS to be used in various agricultural practices.

Table 3. Functional mechanism of humic substances (HS) in nature and their effects on plants (Orlov, 1993; Orlov et al., 1996; Trevisa et al., 2010; Canellas et al., 2015; Palanivell et al., 2015; Olaetxea et al., 2018; Yildiztekin et al., 2018)

HS function	HS mechanism	HS effect	HS fraction
1. Accumulation in soils, natural waters and sediments where HS are a source of energy and nutrition for biota	1. Long-term deposition (in the form of HS) of nutritional elements and organic compounds with high energy value.	1.1. Accumulation of 90–99% of soil total N, more than 50% of total P, S. 1.2. Long-term remain of K, Ca, Mg, Fe, almost all necessary microelements for microorganisms 1.3. Determination of cation exchange capacity 1.4. Plant nutrition regulation	Humic acids Humins
2. Protection of soil biota, vegetation and groundwater	2. Incorporation of radionuclides, detergents, pesticides	2.1. Soil resistance elevation of dryness, wetting, erosion and deflation 2.2. Soil resistance of technogen loads 2.3. Decrease plant toxicity of heavy metals pollution 2.4. Groundwater protection from mineral and organic pollutants	Humic acids Humins
3. Transformation in soil, sediments and waters	3. Cation metallic elements (except alkali and some alkaline earth metals) migration form as complex organic-mineral compounds with fulvic acids ligands	3.1. Metallic element migration in environment at any pH 3.2. Unavailable soil mineral resolution for living organisms 3.4. Determination of cation exchange capacity 3.3. Plant nutrition regulation	Fulvic acids
4. Regulation of almost all necessary properties of soil	4.1. Setting down of soil colour	4.1. Regulation of soil temperature regime	Humic acids Humins
	4.2. Reflection of small amount of solar energy	4.2. Effective soil heating, elevating of soil heat capacity, decrease thermal conductivity	Humic acids
	4.3. Binding of soil particulate elements	4.3. Formation of soil structure	Humic acids Humins
5. Physiological regulation of live organisms and plants	5.1. Amino acids, vitamins and antibiotics transportation	5.1. Alleviate adverse conditions effects on plants and live organisms	Humic acids Fulvic acids
	5.2. Auxin-like activity	5.2. Increase plant root, shoot development and plant production of dry matter	Humic acids Fulvic acids

Maximum efficacy at minimum costs is the main principle on which farmers rely when evaluating utility and efficiency of any preparation applicable in agriculture for soil improvement. If assessing a possibility of direct applications of HS into soil, then according to the data derived at Alibaba.com price of HS varies from 80 EUR to

1750 EUR per ton. The price mainly is dependent on used raw material and producer country, i.e., HS derived from coals are cheaper than those from peat, and the cheapest HS preparations are produced in China. At HS application rate of 100 mg kg^{-1}, approximately equivalent to 100 kg ha^{-1} in topsoil (incorporation in top 10 cm) (Rose et al., 2014), costs may vary from 8 EUR to 175 EUR per hectare, but using liquid preparation of HS for watering or spraying of plant the expenses are significantly lower.

As it was stated previously, HS themselves are not a fertilizing agent because do not contain nutrients necessary for plants in sufficient quantities and in the right proportions. However, they are involved in various functional processes, e.g., promote accumulation of mineral substances in form of humates in soil and stimulate uptake of these elements into plant tissues (Table 3). Such a wide range of direct and indirect impacts of HS in open uncontrolled field environment leads to ambiguous results. Some studies reveal that yield growth at open fields does not exceed 5% that actually is a range of uncertainty in agricultural studies. However, in general, the studies reveal that biostimulants derived from HS cause positive influence on development of horticultural and ornamental plants, i.e., shoot and root growth can be increased by 15–25% for various plant species depending on the application form of preparation (Rose et al., 2014). Moreover, HS act more effectively on monocotyledonous than on dicotyledonous plants after spraying plants, not applying into growing media. The reason for such impact is not investigated in details (Canellas et al., 2015). Significant is also a nature of HS. Plant physiological response is stronger to HS which are derived from non-charred sediments such as peat, compost, biohumus and sapropel in comparison to brown coal, leonardite, subbituminous coals (Canellas & Olivares, 2014). Another study revealed that HS which are derived by composting solid household waste in a mixture with waste water from olive oil production could be used as valuable biostimulants in agricultural practices due to their capacity to promote plant growth, activity of marker enzyme (nitrate reductase, glutamine synthase, phosphoglucose isomerase and pyruvate kinase), the amount of total proteins and nutrient accumulation (Palumbo et al., 2018). Such HS applied on maize at concentration 0.5 mg C L increased the dry weight of leaves and roots by 32–68%; but higher concentrations did not affect plant growth significantly. Furthermore, at tested concentration of HS elevated content of micro- and macroelements was detected in leaves and roots (Palumbo et al., 2018).

Experiment with HS preparation derived from vermicompost revealed that its spray applications on lettuce at concentration 15 mg C L resulted in shorter harvesting period (reduced by 6 days), increased number of leaves (on average by 4 leaves), increased content of enzymes that are involved in sugar metabolism and reduced content of carbohydrates. Lettuce after HS applications was growing healthier and thicker (Hernandez et al., 2015).

Assessment of humic substances' content in sapropel

Sapropel, also called as 'gyttja' or 'dy' (Hansen, 1959), is a type of sediments formed from the remains of water plants, plankton and benthic organisms which undergo the transformation performed by microorganisms and by chemical and physical reactions (usually at oxygen-free conditions), as well is mixed with mineral components supplied from the water basin (Vincevica-Gaile & Stankevica, 2018). Sapropel is a renewable natural resource with a wide range of possible application ways in broad spectrum of fields of national economics, among which agriculture currently takes the greatest part

(Stankevica et al., 2016). Besides the investigation of sapropel's composition, HS content in sapropel has not been studied widely. N. Braks in his research mentioned HS as a component that increase a binding property of sapropel which was experimentally tested in production of sapropel concrete and a binder for production of wood chipboard (Braks et al., 1960; Braks, 1971). Another direction of sapropel application has been studied by Russian and Byelorussian scientists who investigated HS of sapropel with the aim to apply sapropel in balneology and for production of new medication and food or feed supplements (Kosyanova et al., 1993; Kurzo, 2005; Kitapova & Ziganshin, 2015) as sapropel contains smaller amount of HS in comparison to other sediments (soil, peat, biohumus etc.) but biological activity of sapropel's HS comparably is higher. HS of sapropel has high ability of biogenic stimulation, i.e., they stimulate macrophagial protection reactions, promote tissue repair processes, cause anti-inflammatory effect in cases of burns and corneal disease. They also stimulate breathing and inhibits activity of free radicals (Kurzo, 2005; Makarov et al., 2017). Therefore, nowadays the interest increases to produce preparations from sapropel that can be applied as biostimulants in various spheres, including human and veterinary healthcare, as well as agricultural use.

Previously performed studies (Bunere & Stankeviča, 2013; Bunere et al., 2014) revealed that humic acids derived from organic sapropel applied together with mineral fertilizers positively influence plant growth at hydroponic conditions. The optimum concentration of purified humic acids that were applied on plants was 5 mg L^{-1}; such applications resulted in longer leaves, greater dry mass of roots and leaves as well as higher concentration of chlorophyll in leaves. However, the concentration that exceeded the optimum was acting oppositely, i.e., plant development was inhibited. It can be supposed that optimum concentrations of purified HS and humates that can positively affect plants and soil organisms in soil will be higher than for applications in hydroponics, and may vary depending on soil type because in soil they actively react with mineral components resulting in lower activity (Orlov, 1993).

Results of freshwater lake sapropel analyses revealed that total content of humic substances varied from 9 mg g^{-1} up to 106 mg g^{-1} in sapropel's organic matter, 2–67 mg g^{-1} in sapropel's dry matter, and 0.3–6.0 mg g^{-1} of bulk sapropel mass (Table 4).

Obtained results indicated that the highest total content of HS (80–106 mg g^{-1}) from organic matter and its fraction of humic acids can be found in sediments which genetically are similar to peat (OS_{pla}, OSS_{pla}) and which organic matter mainly consists of higher plants (vascular plants) (Fig. 2A). Such HS contain high content of humic acids (70–95 mg g^{-1}), and HA/FA ratio is greater than 6 (Table 4).

Table 4. Average content and characteristics of humic substances in studied sapropel samples, mg g^{-1} (BS – bulk sediments, DM – dry matter, OM – organic matter, TOC – total organic carbon, HA/FA – humic acids/fulvic acids)

Sediment type	Humic substances			Humic acids			Fulvic acids			HA/FA	TOC
	BS	DM	OM	BS	DM	OM	BS	DM	OM		
OS_{alg}	1	26	34	1	21	27	0.4	6	7	4	2,417
OS_{pla}	5	69	81	4	61	72	0.6	8	10	9	622
OSS_{alg}	2	25	42	2	20	34	0.4	5	8	4	5 461
OSS_{pla}	6	63	106	5	56	95	0.6	7	11	10	871
CS_{alg}	0.3	2	9	0.2	1	5	0.2	1	4	1	1,820
SS_{alg}	2	12	43	2	10	36	0.4	2	7	5	9,512

On the contrary, in sapropel's HS which organic matter consists only of algae and animal remains humic acids can be detectable at low levels, and HA/FA ratio is below 5 (Kurzo, 2005; Shtin, 2005).

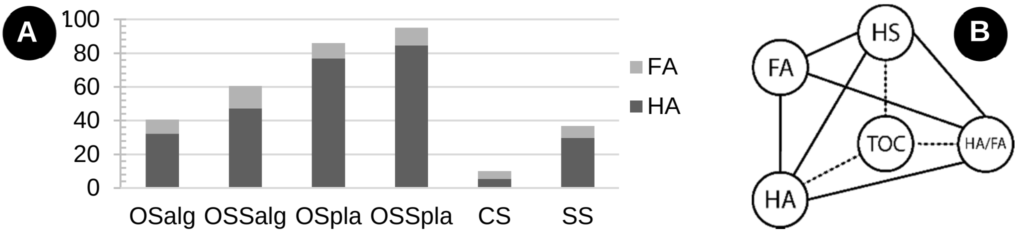

Figure 2. a) Content of humic substances and their fractions in different types of sapropel; b) Statistically significant correlation (P < 0.05, N = 178) of humic substances (HS), total content of humic acids (HA), fulvic acids (FA) and quantity of total organic carbon (TOC) in humic substances: (line) positive correlation, (dots) negative correlation.

In general, content of humic acids in sapropel's organic matter from algae decreased by 70 times (in comparison to sapropel's organic matter from vascular plants), while content of fulvic acids decreased by 3 times, and varied in all tested sediment samples in comparatively constant range from 4 mg g^{-1} to 12 mg g^{-1}, but total organic carbon concentration was assessed as high (1820–9512 mg g^{-1} HS).

Significant correlation (P < 0.05, N = 178) was determined regarding total organic carbon, i.e., for samples of sediments with higher total content of humic substances and humic acids, as well as HA/FA ratio and total organic carbon content was lower (Fig. 2, B). Poor correlation was detected for humic substances or their fractions and organic matter content.

CONCLUSIONS

Investigation of HS content in sapropel is significant for the Baltic States and Northern Europe due to wide distribution and availability of sapropel in freshwater bodies. That promotes a search for new ways of extraction methods and bioeconomically effective utilization of this natural resource, obtainable in economically significant amounts, with high opportunities of its use especially in agriculture.

Content of HS in organic rich lake sediments such as freshwater sapropel varies from 9 mg g^{-1} to 106 mg g^{-1}, humic acids: 5–95 mg g^{-1} and fulvic acids 4–11 mg g^{-1}. Sediments more rich in HS are those which consist from peat forming plants, but total organic carbon concentration is higher in HS which are formed from algae and animal remains.

Scientific literature reveals the evidence that HS of sapropel has higher biological activity than other HS (e.g., derived from peat), thus, sapropel's HS can become as a valuable raw material for balneology, human and veterinary healthcare, but in case of agriculture their extraction can be too expensive and uneconomical. For agricultural purposes application of HS derived from biohumus and compost would be more reasonable and efficient. Contemporary agriculture strongly desiderates in new products of high effectivity enhancing soil and crop productivity and quality hand in hand with sustainable development and careful attitude to the nature and surrounding environment, thus, one of the ways how it can be achieved is understanding how, where and how much HS preparations can be applied, but these studies need to be continued.

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Hydrothermal carbonization and torrefaction of cabbage waste

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Abstract. In recent years, waste biomass has been increasingly becoming an energy source. The utilization of biomass includes a number of potential treatments: thermochemical, physicochemical and biochemical. In the food industry, significant amounts of biodegradable wastes are produced which have to be quickly treated to not pose an environmental problem. In this work cabbage waste (*Brassica oleracea var. capitata*) was treated by hydrothermal carbonization and torrefaction.

Hydrothermal carbonization experiments were carried out in a pressure reactor vessel Berghof BR-300 (inner volume 400 mL, temperature regulation by Berghof BTC 3000). The carbonization took place at target temperatures 180 °C and 225 °C. Torrefaction tests were carried out in a thermogravimetric programmable oven LECO TGA701 under nitrogen atmosphere at temperatures 225 °C, 250 °C and 275 °C. The residence time was 30 min for both processes. Proximate and elemental composition, as well as calorific value was analysed in all samples. To express the influence of the treatments on combustion behaviour, stoichiometric combustion calculations were performed.

The analyses show a positive effect of both torrefaction and hydrothermal carbonization on fuel properties in the samples. Most obvious is the reduction in oxygen content which depends on the process temperature. After hydrothermal carbonization at 225 °C the oxygen content was lowered by 46.7%. The net calorific value increased proportionally with temperature in both processes. After hydrothermal carbonization at 225 °C the net calorific value increased on average by 3 MJ kg^{-1} to 20.89 MJ kg^{-1}. Both tested processes significantly increased the fuel value of this biodegradable waste.

Key words: biomass, biochar, elemental analysis, energy properties.

INTRODUCTION

In recent years, waste biomass has become an important part in renewable energy production. The use of waste biomass involves a wide range of potential thermochemical, physico-chemical and bio-chemical processes (Hamelinck et al., 2005).

Brassica varieties are grown today for food everywhere in the world. Cruciferous vegetables are one of the most important dietary vegetables consumed in Europe due to their availability on local markets, affordability and consumer preference (Šamec et al., 2011). Headed cabbage (*Brassica oleracea var. capitata*) and Chinese cabbage (*Brassica rapa cv. pekinensis*) are one of the most widely grown vegetables grown for human consumption (Liu et al., 2014). The cabbage head generally develops during the first year in the plant's life cycle, flowering and seed production usually occur in the second year (Šamec et al., 2017). The weight of the white cabbage head generally ranges from 0.5 to 4 kg and can be green, light green or white in colour. In most cases, up to 40% of the outer leaves and the cabbage cores are discarded and treated as waste, often used as livestock feed, for composting or for biogas production (Nilnakara et al., 2009).

One of the ways to further utilize waste biomass is the technology of hydrothermal carbonization and torrefaction.

Hydrothermal carbonization (HTC), often referred to as wet torrefaction, is the process of transforming biomass into carbonaceous material at a relatively low temperature (150–250 °C), elevated pressure, and in water environment (Kannan et al., 2017). Biomass is completely immersed in water during the process with an overpressure of up to 4.6 MPa (Lynam et al., 2011). The HTC reaction time is in the range of 5–240 min (Chen et al., 2012). The mechanisms of hydrothermal carbonization are associated with a series of hydrolysis, condensation, decarboxylation, and dehydration reactions (Pala et al., 2014). The reaction products include gases (mainly carbon dioxide, carbon monoxide, hydrogen, methane, ethane and propene), and a mechanically easily separable mixture of solids, referred to as hydrochar, and liquid, which contains the solvent used in the HTC reaction as well as solubilized organic products (Berge et al., 2011; Benavente et al., 2015). Compared to torrefaction, HTC has the advantage of not requiring an energy-intensive drying process for wet materials (Pala et al., 2014).

The main product of the HTC is ‘hydrochar’ (hydrothermal biochar), a hydrophobic solid fuel with much better grindability, lower moisture content and higher calorific value compared with the untreated biomass (Bach et al., 2013) The amount and quality of the hydrochar are dependent on a number of parameters, especially on the treatment temperature, the original material and the residence time (Lu & Berge, 2014).

Torrefaction is a process of biomass thermal treatment where the biomass is heated in the temperature range of 200–300 °C in an inert atmosphere. The torrefaction temperature provides the activation energy for the destruction of chemical bonds in organic matter, i.e. cellulose, hemicelluloses and lignine. The effect is a change in material structure and release of gases, volatile liquids and tars (Toscano et al., 2015). During torrefaction, the moisture content decreases, increasing the energy density of torrefied biomass (Couhert et al., 2009). Further, the oxygen content is reduced, the torrefied biomass has a lower O/C ratio than the original biomass (Bridgeman et al., 2008; Van der Stelt et al., 2011). The final solid product from torrefaction is dry, blackened material, which is described as torrefied biomass or biochar (Baskar et al., 2012).

In terms of physical properties, the colour of the torrefied biomass element changes to brown and even to black with increasing torrefaction temperature, the volume decreases and particles change shape (Chen et al., 2014). Literature shows that torrefaction process generally improves the fuel properties of biomass (Chen & Kuo 2010; Tamelová et al., 2018).

Many authors have studied torrefaction and hydrothermal carbonization of lignocellulosic biomass (Prins et al., 2006; Couhert et al., 2009; Chen et al., 2011; Phanphanich & Mani 2011; Bach et al., 2014). However, fewer studies have focused on wastes from agriculture and food industry (Benavente at al., 2015; Tamelová et al., 2018; Wang et al., 2018).

Since these materials tend to be more heterogeneous than woody biomass and often not suitable for a direct energy valorisation, torrefaction process could be a useful solution to overcome this issue (Toscano et al., 2015).

The aim of this article is to assess the fuel value of white cabbage before and after hydrothermal carbonization and torrefaction.

For these samples, elemental analysis, calorific value and combustion heat have been be determined. Stoichiometric combustion parameters such as the theoretical amount of air for perfect combustion or the amount of dry flue gas are also determined and the calorific value of the treated samples will be determined depending on the water content.

MATERIALS AND METHODS

Sample preparation

The waste from the cleaning of white cabbage (*Brassica oleracea var. capitata*) was obtained from an agricultural company processing white cabbage. The material contained waste cabbage leaves and cores. Three 100 g samples were used for moisture determination. For subsequent tests, the material was left to dry in forced flow of ambient air. Then, the material was milled with a RETSCH SM100 cutting mill to size under 1 mm.

Experimental procedure of hydrothermal carbonization

Hydrothermal carbonization of white cabbage was carried out in a Berghof BR-300 reaction vessel with an internal volume of 400 mL paired with a Berghof BTC 3000 temperature controller. The reactor vessel is made of stainless steel. For each test run, 50 g of cabbage sample was put in the reactor and 200 mL of water was added. Target temperatures for hydrothermal treatment were 180 °C and 215 °C with residence time 30 minutes. Subsequently, the vessel was cooled to about 50 °C. During the measurement, the reaction temperature and pressure were recorded. Reaching the target temperature and cooldown both took ca. 40 min. When the reactor was cooled, the remaining overpressure was released, the reactor was opened, and the pH of the resulting process liquid was measured. The solid residue in reactor was filtered and dried in a Memmert UN 30 oven at 60 °C for 24 .

Experimental procedure of torrefaction

Torrefaction process was simulated using a LECO TGA 701 thermogravimetric analyser in which the samples undergo a thermal programme in periodically weighed crucibles. First the samples were dried for 2 h at 105 °C, then nitrogen atmosphere was introduced, and the samples were heated to a target temperature and held at this temperature for 30 min. In total, three measurements were made at each target temperature of 225 °C, 250 °C and 275 °C. During the torrefaction treatment of the samples, the weight loss was monitored as a function of time.

Moisture, ash, elemental composition and calorific value determination

The LECO TGA 701 thermogravimetric analyser also determined the total moisture and ash. Determination of the elemental composition of carbon (C), hydrogen (H), nitrogen (N) and sulphur (S) contents was performed on the LECO CHN628 + S analyser. Gross calorific value was determined in an isoperibolic calorimeter

LECO AC-600. All measurements were repeated at least three times to obtain reliable results. Net calorific value was determined by calculation using the results of calorimetry, elemental and proximate analysis. Based on these measured parameters, stoichiometric calculations were determined.

Stoichiometric combustion calculations

The theoretical amount of oxygen for complete combustion $O_{2,min}$ (m^3 kg^{-1}) is based on the equation:

$$O_{2,\min} = V_m(O_2)\left(\frac{C}{M(C)} + \frac{H}{M(2 \cdot H_2)} + \frac{S}{M(S)} - \frac{O}{M(O_2)}\right) \tag{1}$$

Where C, H, S, and O are the contents of carbon, hydrogen, sulphur and oxygen in the sample (% wt.); $V_m(O_2)$ = 22.39 m^3 $kmol^{-1}$ is the molar volume of oxygen gas at normal conditions and $M(\ )$ (kg $kmol^{-1}$) are molar masses of theoretical species that combine with O_2.

Where the theoretical amount of dry air L_{min} (m^3_N kg^{-1}) is determined from the equation:

$$L_{\min} = O_{2,\min} \cdot \frac{100}{C_{atm}(O_2)} \tag{2}$$

Where $C_{atm}(O_2)$ = 20.95% vol. is volumetric concentration of oxygen in air.

The theoretical amount of dry flue gases $v_{fg,min}$ (m^3 kg^{-1}) is based on the equation:

$$v_{fg,\min} = \frac{V_m(CO_2)}{M(C)} \cdot C + \frac{V_m(SO_2)}{M(S)} \cdot S + \frac{V_m(N_2)}{M(N_2)} \cdot N + \frac{C_{atm}(N_2)}{100} \cdot L_{\min} \tag{3}$$

Where $V_m(\ )$ (m^3 $kmol^{-1}$) are the molar volumes of flue gas components; $C_{atm}(N_2)$ = 78.05% vol. is the concentration of N_2 in air.

The theoretical amount of emission concentrations of $CO_{2,max}$ (m^3_N kg^{-1}) is based on the equation:

$$CO_{2\max} = \frac{M(C) \cdot C}{V_m(CO_2) \cdot v_{fg,\min}} \cdot 100 \tag{4}$$

Volumetric amounts of combustion products:

$$v(CO_2) = \frac{V_m(CO_2)}{M(C)} \cdot C + \frac{C_{atm}(CO_2)}{100} \cdot L \tag{5}$$

$$v(SO_2) = \frac{2 \cdot V_m(SO_2)}{2 \cdot M(S)} \cdot \tag{6}$$

$$v_{N_2} = \frac{V_m(N_2)}{M(N_2)} \cdot v(N_2) + O_{2,\min} \cdot \frac{C_{atm}(N_2)}{C_{atm}(O_2)} \tag{7}$$

Conversion of the calorific value of Q_i^r at an arbitrary water content W to a different water content Wt is made according to the formula:

$$Q_{in}^r = \frac{100 - Wt}{100 - W} \cdot \left(Q_i^r + 0.02442 \cdot W\right) - 0,02442 \cdot Wt \tag{8}$$

Where Wt (% wt.), the total water content in the original sample; W the net calorific value of the original sample (MJ kg^{-1}) and Q_i^r is the net calorific value at the target water content.

RESULTS AND DISCUSSION

Table 1 shows the results of the proximate and elemental analysis of white cabbage samples before and after hydrothermal carbonization and torrefaction treatment.

Table 1. Composition and calorific values of white cabbage before and after hydrothermal carbonization and torrefaction treatment at varying temperatures and 30 minute residence time

Sample	Water Content (% wt.)	Ash (% wt.)	Carbon (% wt.)	Hydrogen (% wt.)	Nitrogen (% wt.)	Sulphur (% wt.)	Oxygen (% wt.)	Gross Calorific Value (MJ kg^{-1})	Net Calorific Value
	W	*A*	*C*	*H*	*N*	*S*	*O*	Q_s	Q_i
Original sample	75.12	3.88	10.08	1.30	0.72	0.26	8.64	3.98	1.86
Dry basis		15.61	40.50	5.21	2.91	1.03	34.74	15.98	14.84
H-180-30		21.56	46.32	4.92	3.40	1.43	20.97	18.88	17.81
H-225-30		21.16	52.08	4.98	4.13	1.44	16.22	21.97	20.89
T-225-30		19.31	46.44	4.90	3.78	1.04	24.52	18.76	17.69
T-250-30		21.17	48.43	4.77	4.03	1.11	20.49	19.55	18.51
T-275-30		24.60	50.53	4.48	4.35	1.19	14.85	20.42	19.45

H – Hydrothermal carbonization, 180, 225 – temperature (°C), 30 – residence time (min.); T – torrefaction, 225,250,275 – temperature (°C), 30 – residence time (min.)

The results of the proximate and elemental analysis show a positive effect of HTC and torrefaction on the examined white cabbage sample. The original material had high water content 75.12% wt. as well as ash content at 15.61% wt. on dry basis. Abdul Samad et al., (2017) determined a comparable value of dry ash in a food waste sample to 16.89% wt. This can be contrasted with wood biomass where Van der Stelt et al., (2011) reported only 1.3% wt of ash in dry wood. With increasing torrefaction temperature, the ash content in the cabbage sample rose. At 250 °C the ash content increased to 21.17% wt. and at temperature 275 °C, the ash went up to 24.60% wt. Van der Stelt et al., (2011) reported the value of ash in wood after torrefaction at 250 °C for 30 minutes at 1.5% wt.

The carbon content increases during both processes with increasing temperature at the expense of oxygen and hydrogen, which leads to the reduction of H/C and O/C ratios (Pentananunt et al., 1990). During carbonization, dehydration and decarboxylation reactions of aromatic structures occur and subsequently the sample becomes more hydrophobic (Berge et al., 2011). The carbon content in dry original sample was 40.50% wt. and it rose with treatment temperature in both processes. During the HTC process, the carbon content increased by almost 6% wt. to a final value of 52.08% wt. at HTC 225 °C. With increasing torrefaction temperature, the increase in carbon is not as significant as that of HTC. The carbon value increases by about 2% wt. with an increasing temperature to a final value of 50.53% wt. In comparison, spruce torrefied at 270 °C for 16.5 min. had 52.50% wt. carbon content (Larsson et al., 2013), cotton stalk torrefied at 250 °C for 30 min. had 56.18% wt. (Chen et al., 2015) and orange peel torrefied at 275 °C for 30 min. achieved 67.05% wt. (Tamelová et al., 2018).

Oxygen content decreases during both processes. Its value decreased by 57.25% in the dry state during torrefaction to a final value of 14.85% wt. at a process temperature of 275 °C. During HTC, oxygen is reduced by 53.57% compared to the original sample in the dry state to 16.22% wt. at temperature 225 °C.

When increasing the process temperatures of HTC and torrefaction, hydrogen content is being reduced compared to the original sample, albeit by a small degree.

Nitrogen content increased with increasing temperature in both processes. The original sample contained 2.91% wt. nitrogen in dry state. After HTC at 180 °C for 30 min. this increased to 3.40% wt. After 30 min HTC at 225 °C it rose to 4.13% wt. Nitrogen content in torrefied samples was similar. After 30 min. torrefaction at 225 °C the value rose to 3.78% wt. and after 30 min. at 275 °C it reached 4.35% wt.

White cabbage has a relatively high proportion of sulphur. The greater proportion of sulphur is due to the fact that *Brassica* family species tend to show high concentrations of amino acids and other organic compounds derived from sulphur metabolism when accumulating other elements and heavy metals (Mazzafera, 1998). Sulphur in reduced form plays an important role in plant growth and plant growth regulation (Moreno et al., 2005). In dry sample, the sulphur content is 1.03% wt. This content increased with growing treatment temperature. The highest value (1.44% wt.) was reached after HTC at 225 °C. Comparing sulphur values with other biomass samples, for example Abdul Samad et al., (2017) reported the sulphur content of dry food waste sample at 0.16% wt. and, after torrefaction at a temperature of 330 °C and a residence time of 30 minutes, this increased to 0.26% wt. Miranda et al. (2009) determined the dry sulphur value for orange peel at 0.60% wt.

Gross calorific value increased with temperature after both process types. The gross calorific value of the white cabbage sample was 15.98 MJ kg^{-1} in dry state. Compared to the original dry sample, it is increased by 5.99% wt. during the HTC process at 225 °C to value 21.97 MJ kg^{-1}. HTC increases the calorific value by approximately 3 MJ kg^{-1} to 20.89 MJ kg^{-1} at process temperature 225 °C. Similar heating value values (21.17 MJ kg^{-1}) were reported by Wang et al. (2018), who carbonized by HTC corn stalk at temperature 220 °C and 30 minute residence time.

Bach et al., (2014) reported net calorific value of spruce 22.97 MJ kg^{-1}after HTC at 225 °C for 30 minutes. Benavente et al. (2015) showed net calorific value of orange waste 27.73 MJ kg^{-1} after HTC at temperature of 225 °C and residence time 2 hours. Pala et al., (2014) hydrothermally carbonized grape pomace and reported net calorific value 25.65 MJ kg^{-1} after 30 min at 225 °C.

During the torrefaction process, the net calorific value increased compared to the original dry sample by 2.85 MJ kg^{-1} at 225 °C and further by another 1 MJ kg^{-1} to the final value of 19.45 MJ kg^{-1} at 275 °C. Pala et al., (2014) reported net calorific value 23.12 MJ kg^{-1} in grape pomace torrefied at 275 °C for 30 min. When compared to wood biomass, Larsson et al., (2013) reported the Net calorific value of spruce of 21.1 MJ kg^{-1} after torrefaction at 270 °C with residence time 16.5 minutes.

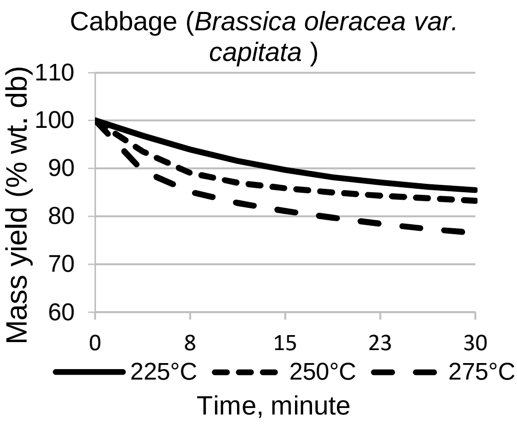

Figure 1. Mass loss curves during torrefaction of white cabbage.

Fig. 1 shows the weight loss over time during torrefaction temperatures of 225 °C, 250 °C and 275 °C. The greatest weight loss was recorded at 275 °C at almost 25%. The curves at 225 °C and 275 °C are offset by about 10%. Similar results were published by Meng et al., (2015) who pyrolyzed Chinese cabbage in the temperature range of 200-1,000 °C.

Tables 2 and 3 show the results of stoichiometric analysis. The tables show the difference between the treatment degree. Increasing temperature in HTC and torrefaction treatment changes the proportional representation of elements having the effect to increase specific theoretical volume of air for complete combustion and flue gas production, as well as the emission concentrations of individual combustion products. Very similar effects were reported by Tamelová et al. al., (2018) for citrus specimens. The effect was most pronounced in sample treated hydrothermally at 225 °C. In this case, the specific air consumption is 1.4 times that of the original sample. Similar results were determined for the torrefaction treatment, where the difference is up to 1.35 times the original sample.

Table 2. Stoichiometric combustion of white cabbage and hydrothermally carbonized samples

			Original sample	H-180-30	H-225-30
L_{min}	Theoretical air consumption	(m^3 kg^{-1})	3.85	4.76	5.45
$v_{fg,min}$	Theoretical flue gas production	(m^3 kg^{-1})	3.79	4.62	5.26
$v(CO_2)$	CO_2 production	(m^3 kg^{-1})	0.75	0.86	0.97
$v(SO_2)$	SO_2 production	(m^3 kg^{-1})	0.01	0.01	0.01
$v(H_2O)$	H_2O production	(m^3 kg^{-1})	0.73	0.74	0.77
$v(N_2)$	N_2 volume in flue gas	(m^3 kg^{-1})	3.03	3.76	4.28
CO_2max	Maximum CO_2 concentration in dry flue gas	(%)	19.84	18.58	18.36

Table 3. Stoichiometric combustion of torrefied white cabbage

			T-225-30	T-250-30	T-275-30
L_{min}	Theoretical air consumption	(m^3 kg^{-1})	4.64	4.91	5.22
$v_{fg,min}$	Theoretical flue gas production	(m^3 kg^{-1})	4.52	4.77	5.05
$v(CO_2)$	CO_2 production	(m^3 kg^{-1})	0.86	0.90	0.94
$v(SO_2)$	SO_2 production	(m^3 kg^{-1})	0.01	0.01	0.01
$v(H_2O)$	H_2O production	(m^3 kg^{-1})	0.73	0.73	0.71
$v(N_2)$	N_2 volume in flue gas	(m^3 kg^{-1})	3.65	3.87	4.11
CO_2max	Maximum CO_2 concentration in dry flue gas	(%)	19.06	18.81	18.55

Fig. 2 shows calculated net calorific value for all studied samples against variable moisture content up to 30% wt. The amount of water in the fuel will determine the efficiency in energy utilization (Esteban et al., 2014) as well as the emission concentrations of the combustion plant (Johansson et al., 2004; Malaťák & Passian, 2011). In hydrothermal carbonization, the difference in net calorific value between the original sample and the H-225-30 sample is 27.73% and for the T-275-30 sample it is 21.44%. From the graph in Fig. 2, the net calorific value can be deducted for arbitrary moisture content in the fuel. For example, as shown in Fig. 2 for sample H-225-30, 10% wt. moisture content decreases the net calorific value by 10.2%.

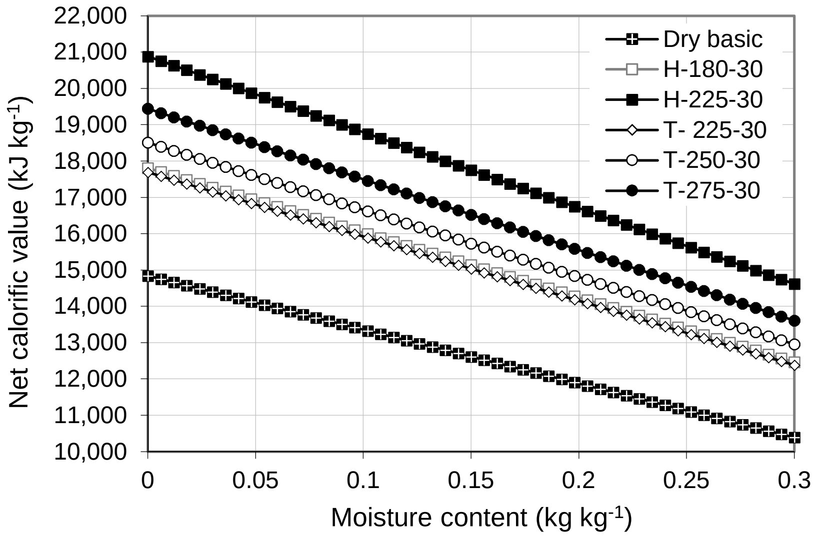

Figure 2. Net calorific value of all samples at variable moisture content.

CONCLUSIONS

Torrefaction and hydrothermal carbonization are thermochemical treatments that can be used for a wide range of waste biomasses. As a suitable representative waste, white cabbage which is an important by-products in the food industry was chosen for this study. The main product of these processes is a biochar.

The fuel parameters of white cabbage before and after treatment by torrefaction and hydrothermal carbonization processes showed significant changes. Torrefaction is generally capable of producing better fuel compared to the original biomass, primarily by increasing the calorific value and reducing the oxygen content. For the samples examined, the highest net calorific value 20.89 MJ kg^{-1} was obtained after hydrothermal carbonization at 225 °C with a residence time of 30 minutes. With increasing process temperature, the calorific value increased. The highest increase between two treatment temperatures in net calorific value occurred with HTC between temperatures 180 °C and 225 °C, rising by 3.08 MJ kg^{-1}. The net calorific value after torrefaction increased by approximately 1 MJ kg^{-1} between both temperature steps.

However, both processes had an undesirable effect in increasing the ash content. In the dry state, the ash content was 15.61% wt. After torrefaction at 275 °C and reaction time of 30 minutes, it increased to 24.60% wt. Such ash content limits the use of torrefied fuel in some areas, e.g. in small domestic appliances. The sample of white cabbage was found to have an unusually high amount of sulphur compared to, for example, wood biomass. In the dry state, the sulphur content was 1.03% wt. The sulphur content after both processes increased with increasing the temperature. The highest value of 1.44% wt. was measured after HTC at 225 °C.

The stoichiometric combustion characteristics of the treated white cabbage samples showed a positive effect of the treatments when compared to the original material.

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A software to estimate heat stress impact on dairy cattle productive performance

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Abstract. The aim of this study is to develop a computational tool, based on the Temperature and Humidity Index value, to characterize the thermal environment in dairy cattle barns and to evaluate the impact of thermal stress on productive performance. The software for the thermal environment prediction, and determination of the influence of heat stress on dairy cow productivity (Ambi + Leite) was developed using the C# programming language in the Microsoft Visual C# 2010 Express Integrated Development Environment. The following scenario was considered for the program test: air temperature 32°C, relative air humidity 70% and milk production potential in thermoneutrality condition 20 kg cow^{-1} day^{-1}. The prediction of the thermal environment based on the simulated situations indicates that the animals are submitted to a moderate heat stress condition with THI equal to 82.81. In this condition a decrease of approximately 26% in milk production and a reduction of 4 kg cow^{-1} day^{-1} in food intake was calculated. In conclusion, the developed software can be a practical tool to assist the producer in making-decision processes.

Key words: thermal environment, THI, dairy cows, software.

INTRODUCTION

Dairy cattle farming is an activity present in all the regions of Brazil, constituting an important source of income and employment (Lopes et al., 2011). However farmers have to pay attention on the microclimatic conditions related to the production environment, particularly air temperature and relative humidity, which can have a negative influence on the welfare and consequently on the animal performance. A proper management of the thermal environment for the animals is of paramount importance, in order to reduce the influence of climatic conditions on the comfort and the performance of the animals. Dairy cows are highly productive animals, which produce heat in large amount. The excess of heat must be removed to the environment (Nóbrega et al., 2011; Radon et al., 2014; Herbut et al., 2015).

The occurrence of high temperatures throughout the day, especially during the summer, causes changes in the physiological mechanisms of the animals, with raise of body temperature and increase of respiratory rate and sweating. In addition some behavioural changes indicate that the animals are in conditions of thermal discomfort (Pinheiro et al., 2015; Heinicke et al., 2018; Herbut & Angrecka, 2018). Beyond physiological and behaviuoral changes, when subjected to thermal discomfort caused by heat, the cows reduce feed consumption and present a consequent decrease in milk yield (Rodrigues et al., 2010; Herbut et al., 2015).

According to Baêta & Souza (2010), the comfort of the animals inside a barn is expressed by several indexes, which generally consider two or more climatic variables. The most common index is the Temperature-Humidity Index (THI), which uses the dry-bulb temperature (Tdb) and the wet bulb temperature (Twb) to estimate the magnitude of heat stress (Thom, 1959). The THI was studied by several researchers, which defined formulas to calculate the index in relation to different conditions (Ingraham et al., 1979; Buffington et al., 1981; Mader et al., 2006; Gaughan et al., 2008; Herbut et al., 2018a). THI is commonly used to estimate the effects of climatic conditions on the dairy cows' thermal comfort (Heinicke et al., 2018), also by means of computer tools available on web.

Knowing how these environmental factors influence animal welfare and performance is crucial to obtain a successful production. Therefore, the use of some computer tools can help in the fast and accurate diagnosis of animal-environment interaction. Some of these tools can be found in the literature (Teles Junior et al., 2016; Teles Junior et al., 2018). The present work aims to develop a computational tool based on the Temperature and Humidity Index value, able to characterize the thermal environment in dairy cattle barns and to evaluate the impact of heat stress on the productive performance of the animals.

MATERIALS AND METHODS

The software for the prediction of thermal environment in dairy cows barns and for the determination of the heat stress influence on the performance (Ambi + Leite) was developed using the C # programming language in the Microsoft Visual C # 2010 Integrated Development Environment (IDE).

The thermal environment was classified on the basis of the Temperature and Humidity Index value (THI), calculated from input data of air temperature and relative humidity, by means of Eq. (1) proposed by Buffington et al. (1982):

$$THI = 0.8 \times T_{air} + \frac{RH \times \left(T_{air} - 14.3\right)}{100} + 46.3 \qquad (1)$$

where THI = Temperature-Humidity Index; T_{air} = Air Temperature (°C); RH = Relative Humidity (%).

The thermal environment was classified according to the calculated THI value, following the guidance of Armstrong (1994), as shown in Table 1.

After characterization and evaluation of the thermal environment based on the THI value, if the animals are in a heat stress condition, the next step is to evaluate the heat stress influence on their productive performance. For this purpose, we estimated the decline in milk production and food intake as a function of the calculated THI value, based on Hahn (1993) and Hahn & Osburn (1969) equations (2) and (3).

Table 1. Dairy cows thermal environment classification based on the value of the Temperature-Humidity Index (THI)

Thermal environment classification	THI values range
Thermal Comfort	≤ 72
Mild Stress	72–78
Moderate Stress	79–88
Severe Stress	> 88

$$DMP = -1.075 - 1.736 \times SMP + 0.02474 \times THI \times SMP \qquad (2)$$

where DMP = Decline in milk production (kg cow^{-1} day^{-1}); SMP = Standard Milk Production (kg cow^{-1} day^{-1}); THI = Temperature-Humidity Index.

$$RFI = -28.23 + 0.391 \times THI \qquad (3)$$

where RFI = Reduction in feed intake (kg cow^{-1} day^{-1}).

For testing the program, a simulation was performed considering a critical scenario related to the thermal comfort of animals, kept under the following conditions: average air temperature 32°C; average relative humidity 70%. The animals considered in the simulation were Holstein cows with milk production potential in thermoneutrality condition of 20 kg cow^{-1}. day^{-1}.

The results of the simulation were compared with the data searched in the literature, that depict the real production conditions in dairy cows facilities, in order to verify the reliability of the proposed software.

RESULTS AND DISCUSSION

The algorithm for the prediction of thermal environment and evaluation of the heat stress influence on the productive performance of the cows follows the steps outlined in Fig. 1.

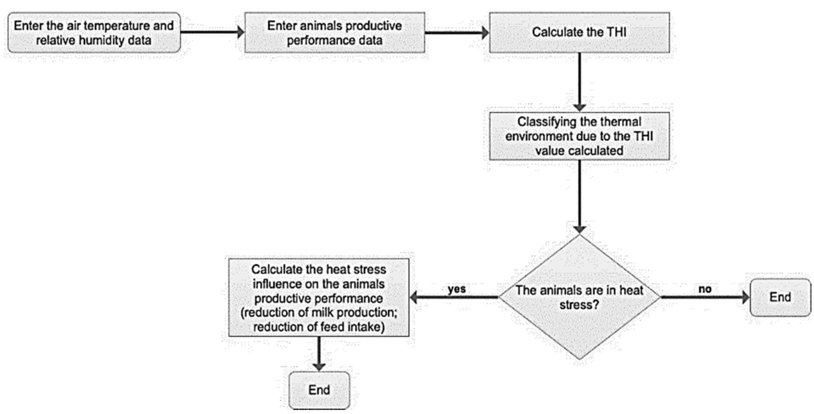

Figure 1. Algorithm execution steps flowchart.

The first stage of algorithm execution consists of data entry, where data are entered referring to the climatic variables and the animals standard productive performance. After entering the input data, the next step is to calculate the Temperature-Humidity Index. From the THI value the thermal environment for the cows is calculated and classified. If the animals' thermal environment is classified as stressful, based on the calculated THI value, the next step is to evaluate the impact of this stress on the productive performance of the cows, based on the calculation of the reduction in milk production and the reduction of food intake.

The developed software is compatible with operational system Windows XP or up. The software graphical user interface is basically divided into three windows, the first of which is shown in Fig. 2. This is a first window (splash screen) for program initialization, from which the main data entry window is opened (Fig. 3). In this window the input data are inserted and processed for THI calculation, for the thermal environment classification and for the evaluation of the heat stress influence on the productive performance of the animals.

Figure 2. Program initialization window (splash screen).

The main window (Fig. 3) is divided into three parts. The first is for data entry (climate data and animals' standard performance data) (A), the second for climate data processing to calculate THI and classify the animal thermal environment based on THI (B), and the third for calculation of the heat stress influence on the performance of the animals (C).

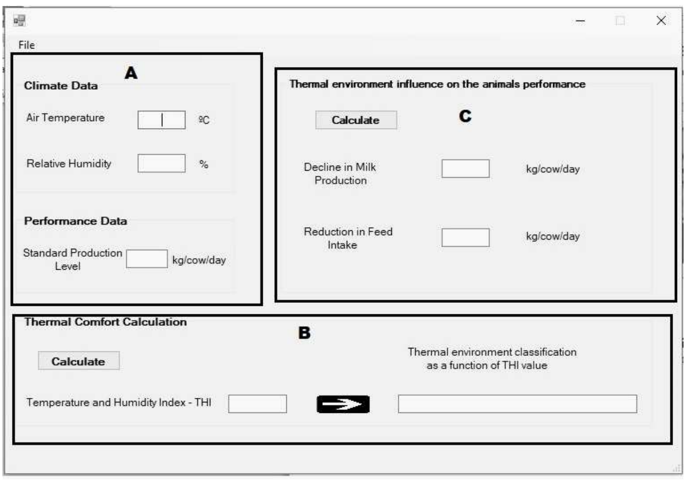

Figure 3. Software main data entry window. A: Data entry field; B: Data processing field to calculate THI and classify the thermal environment; C: Data processing field to calculate the heat stress influence on the animals.

The results of simulation carried out following the program test scenario (average air temperature 32 °C, average relative humidity 70%, Holstein cows with milk production potential in thermoneutrality condition 20 kg cow^{-1} day^{-1}) are shown in Fig. 4.

The prediction of the thermal environment, performed considering the entry conditions reported in the program (air temperature and relative humidity), indicates that the cows are subjected to a moderate heat stress condition with THI equal to 82.81.

Taking into account that the animals considered in the simulation present a milk production potential in thermoneutrality condition of 20 kg cow^{-1} day^{-1}, it is calculated that in the simulated thermal condition a reduction of approximately 26% in milk production potential occurs. This result is consistent with what was verified by Oliveira et al. (2013), which observed a 15% reduction in milk production in dairy cows with potential production of 20 kg day^{-1} submitted to mild heat stress. In the simulated thermal stress condition, the animals show a reduction of food intake of about 4 kg day^{-1}. Porcionatto et al. (2009) argue that this reduction in food intake is the main cause of the reduction in milk production of cows on heat stress.

It is important to note that this decrease in milk production by the cows does not occur immediately after the beginning of stress conditions. There is a delay in this process that can take about 2 to 3 days after the occurrence of heat stress (West et al., 2003; Spiers et al., 2004). In addition, Herbut et al. (2018b) affirm that the reduction in the productive performance of dairy cows also depends on the severity of the heat wave and the duration of heat during the previous periods.

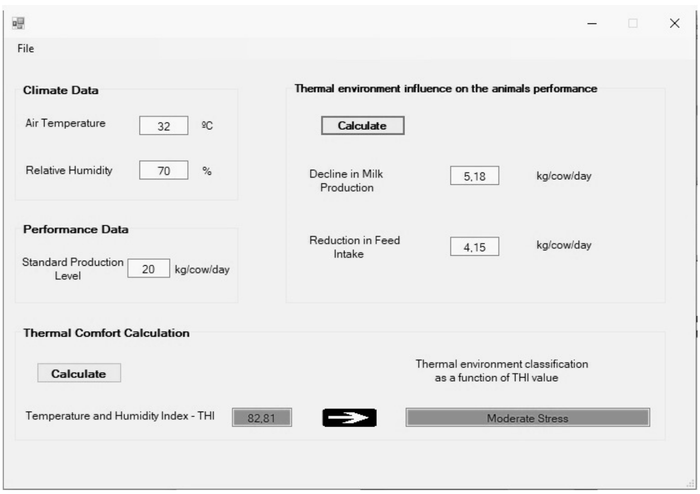

Figure 4. Simulation results.

CONCLUSIONS

The computational program developed is a practical tool to help producers in decision-making, helping to evaluate the thermal environment and the effect of thermal stress on the productive performance of the cows, in order to improve the farming management.

After the first version of the software, presented in this paper, the developers are working on new updates. In particular, the goal is to realize a software able to communicate with a data acquisition system (temperature and relative humidity sensors), for the real-time evaluation of thermal conditions in the barn, and to affect the decision-making process for control of the heating, ventilation and cooling systems.

Other improvement of the software has to consider new input variables, such as dairy cattle breeds, length of stress conditions, lactating phase and animal age.

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Assessment of selected parameters of automatic and conventional equipment used in cattle feeding

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Abstract. A cattle farming is a very important sector of agriculture. In the Czech Republic, both breeds with 'combined useful' as well as 'meat cattle' are breeding, but especially 'dairy cattle' breeds. Providing feed at the right time, in required quantity and quality is the basis of successful breeding, especially in breeding dairy cows. Automatic systems are present in almost all sectors of human activity, and livestock production is no exception. Fully automatic feeding systems for pigs or poultry are already in use. The process of milking cattle using automated milking systems is also sufficiently mastered. An interesting trend is the installation of automated feeding systems for cattle feeding. They are stationary lines that perform the following operations: they dose the individual components of the feed mixture, mix the feed mixture and distribute it to the relevant feed places. All these activities are usually done without the presence of a person. The automated feeding system Lely Vector and the conventional feeding system using feeding wagon Cernin were compared. The number of automated feed wagon runs has been monitored and then the feed consumption was compared while using automatic and conventional equipment. The aim of this paper is to evaluate the benefits of an automatic feed system with regard to the conventional feed system through a mobile feed car.

Key words: cattle, feed, silage, feeding, conventional feeding system, automated feeding system.

INTRODUCTION

The current speed of automation and robotization is a phenomenon that will lead to a rethinking of the understanding and implementation of a huge amount of human activities in the near future. While voice automates on customer lines or robots in industrial production have long since gained their place, and for example, automotive production cannot be imagined without modern technical solutions, the penetration of modern technology in the form of automatic systems into agricultural production is slower. For this reason, the first stationary automated feed lines for cattle on the Czech farms were launched only in the first half of 2014. Increased interest in automated systems can also be expected in this area (Reger et al., 2018).

All technologies used in livestock farming must meet the conditions of so-called welfare (Pšenka et al., 2016; Šematoviča et al., 2017; Ruska et al., 2017). This requirement must, of course, also be met by automatic technology (Přikryl et al., 1997; Hromasova et al., 2018; Vaculik et al., 2018).

Methods of feeding

Hand feeding is the oldest way to feed cattle, which primarily uses human manual labour with minimal use of mechanization. It is still used in a small extent on some small farms. The feed is brought to the stable where either slowly passes the car from which the feed is thrown into the troughs by workers, or it can be unload into the centre of the stable and then manually re-moved into the troughs.

Today, however, the vast majority of farms use some type of machinery or equipment to feed cattle. These can be divided mainly according to the way of transport and delivery of feed into stationary feeding equipment and mobile feeding equipment (Přikryl et al., 1997; Jehlička & Sander, 2015; Sander & Jehlička, 2016; Vaculik et al., 2018).

Mobile feeding equipment (feeding wagons) are attached behind the towing machine and, when passing stables, they lay the feed on one or both sides, or they can also lay it underneath. Their main advantage over stationary equipment is simple implementtation of replacement operation in the event of a fault. The disadvantage is the disturbed microclimate when passing the stable.

Feed mixing wagons represent an improved special variant of feeding wagons. It is not only used to put the feed into the troughs, but can also form a homogeneous feed mixture. Feeding wagons, that are more modern, also include a strain gauge weight that allows precise weighing of added feed components (Přikryl et al., 1997).

Stationary feeding equipment is firmly built into a stable, where they are used for one or two rows of animals. They can connect to a stationary line for feed transport or to mobile devices that transport feed from the warehouse or directly from the field. According to their location in the stable, it is possible to divide them into these main groups:

- belt feeders (trough conveyers, conveyers above trough),
- electric feeding wagons,
- automatic (robotic) feeding systems.

Since these devices are firmly built into the stable, it is more problematic transition to a different or more modern type of technology than for feed devices that is simply replaced. In the case of a fault, it is necessary to have a prepared alternative feeding solution, which is often solved using a feeding wagon (Přikryl et al., 1997).

The main effort in introducing automated systems is to save people's work, reduce time-consuming and allow more time flexibility. In livestock farming, efforts are also made to improve the conditions of breeding, to better adapt the environment of the stable to the natural behaviour of the animals. The feed is automatically continuously replenished according to the needs of the animals. Accurate dosing of individual feed components independent of human factor and control of feed intake during the day allows an increase in feed intake and thus an increase in livestock performance (Přikryl et al., 1997; Vegricht & Šimon, 2016).

It is important to pay attention to the preparation of feed in cattle breeding (Vaculík et al, 2013), their appropriate analysis (Chládek et al., 2013, Chladek et al., 2018), optimal utilization of raw materials (Smejtková et al., 2016; Smejtkova & Vaculik, 2018) and appropriate energy-efficient transport and storage (Hromasová et al., 2018).

MATERIAL AND METHODS

Basic data on the dairy cattle bred on the evaluated farm and basic data on the characteristics of used feed are given in the table (Table 1).

Table 1. The basic characteristic of Fleckvieh Breed and Feed

Breed		
Basic information		
Breed	(-)	Fleckvieh Breed
Country of origin	(-)	Czech Republic
Degree of breeding	(-)	noble breed
Performance direction	(-)	meat-dairy
Physical characteristics		
Male weight	(kg)	1,200.0–1,300.0
Female weight	(kg)	650.0–750.0
Male height at withers	(cm)	152.0–160.0
Female height at withers	(cm)	140.0–144.0
Body framework	(-)	medium to large
Colour	(-)	red mottled
Classification and standard		
Breeding group	(-)	group of mountain cattle
Milk performance (adult cow for lactation)	(-)	6,500.0
Protein content in milk	(-)	3.6
Feed (daily ration - dairy cows)		
Maize silage	(kg)	22.0
Clover grass silage	(kg)	12.0
Hay	(kg)	5.0
Straw	(kg)	2.5
Grain scrap	(kg)	4.0
Soybean meal	(kg)	1.2
Rapeseed meal	(kg)	1.2
Vitamin-mineral supplement, molasses, grains, sugar beet pulp, glycerol and others	(kg)	about 0.1
Total	(kg)	about 48.0
Physical characteristics		
Bulk density	(kg m^{-3})	900.0

This article deals with the assessment of automatic feeding system Lely Vector and the conventional feeding system using the feeding wagon Cernin C13.

Feeding wagon Cernin C13 (Fig. 1) - this type of feeding wagon is suitable for processing square and round bundles of feed, loose and bulk material, the volume of which can reach up to 13 m^3 and the maximum weight of the mixed feed dose can be 4,550 kg (the technical parameters are given in Table 2).

The wagon is equipped with one vertical stirring auger, on which are placed eight knives against which are two mechanical edges. Vertical mixing has several advantages over a horizontal one. One of them is the rapid preparation of a mixed feed, the mixing of which usually takes up maximum 3 to 4 minutes. The resultant mixture has retained structuring fibre, it is soft and evenly distributed, which allows for easier digestibility. The mixed feed dose containing micro granules and minerals reaches deviation 2.8% of the mixed material. The revolution speed of the stirring auger is set to 27 rpm. A two-speed gearbox can be supplied as an option accessories, by which can be reduced the speed. The mixing wagon is connected to a tractor with a power of 64 kW (47 kW in the case of a reduction gear tractor). The advantage is its own hydraulic system, which allows independence of tractor hydraulics. The uniform distribution of feed on the feed table is solved by a stainless steel double-sided drag conveyer. The mixing wagon is also equipped with a four-point strain gauge weighing system.

Figure 1. Tractor and feeding wagon Cernin C13 (Source: http://www.cernin.cz/p/model-c-i-6-13-m3).

Table 2. Technical parameters of feeding wagon Cernin C13

Mixing equipment	(-)	vertical system
Volume	(m^3)	13.0
Length with conveyer	(m)	5.72
Length without conveyer	(m)	4.21
High	(m)	3.04
Width	(m)	2.40
Total weight without conveyer	(t)	4.40
Total weight witch conveyer	(t)	4.89
Outside width of wheels	(m)	2.15
Input power without two speed gearbox	(kW/hp)	66/90
Input power with two speed gearbox	(kW/hp)	47/64
Auger/knives	(pcs)	1/8

Automatic (robotic) feeding system Lely Vector (Fig. 2) - the entire system consists of two main parts, which are feed preparation and feed wagon (the technical parameters are shown in Table 3).

At the beginning of the whole process, it is necessary to place the straight-cut blocks of roughage at a predetermined location. This placement is usually done every 2–3 days. When using concentrates and feed supplements it

Figure 2. Automatic feeding system Lely Vector (Source: https://www.agropartner.cz/automaticky-system-krmeni-lely-vector-p255.html).

is also necessary to check their stock. The ratios of the individual feed components, ride route and frequency of repetitions are by simple way set into the feed wagon system. The wagon goes through the stables at specified times and feeds the feed. At the same time, it measures its height. If its average quantity is below the set level, the wagon returns to the feed preparation and it is filled by next feed ration. It is picked up by an electronic grab and weighed in a feed wagon. At the same time, individual components are mixed thoroughly. When the feed mixture is ready, the feed wagon returns to the stable and evenly feeds the missing feed. This is repeated 24 hours a day. The main principle is the constant replenishment of fresh feed after small rations, which animals are able to feed.

Table 3. Technical parameters of feeding wagon of automatic feeding system Lely Vector

Mixing equipment	(-)	vertical system
Volume	(t)	0.15–0.60
Length	(m)	2.46
Width	(m)	1.62
Weight	(t)	1.285
Height	(m)	2.00
Height at feeding	(m)	2.90
Minimum passage width in transit	(m)	2.75
Rotation Diameter	(m)	3.10
Maximum number of groups	(-)	16.00
Volume of one feeding wagon	(number of cattle)	250–300
Volume of two feeding wagons	(number of cattle)	300–600
Maximum floor slope	(%)	5.00
Maximum stair height	(m)	0.02
Diameter of the roll	(m)	1.50
Maximum feed height	(m)	0.60
Max breadth of feed	(m)	0.72
Max transfer speed	($km.h^{-1}$)	2.00
Min Rate of Movement	($cm.s^{-1}$)	3.50
Feeding speed	($cm.s^{-1}$)	3.50–4.50
Power supply	(Ah)	55.00
Engine for mixing	(kW)	3.00
Feed distributor engine	(kW)	0.55

Measurement of selected parameters

Measurement was carried out at a family farm located in West Bohemia, which has an average of 191 dairy cows.

The data for the feeding wagon are from 31.12.2016 to 28.6.2017. These data were obtained from company documents. Values measurement when using the automatic system ran from 31 December 2017 to 28 June 2018. The following parameters were evaluated, when assessing automated feeding system Lely Vector: power consumption, regularity of the feeding wagon ride and their number and amount of feed consumed.

The three-phase, one-way DTS 353 electricity meter (Fig. 3) with LCD display is used to measure power consumption and is designed for secondary, informational or workshop measurements (the technical parameters are shown in Table 4).

The electricity meter was connected to the distribution box of the Lely Vector feeding system. Measurement of power consumption covered the entire system, i.e. the feed wagon, together with the crane and the grab. Additional data related to both system operation at the time of measurement and for a longer period of time were obtained from the Management Program T4C. This program is supplied by the firm Lely and is used to configure system Vector.

Figure 3. Electricity meter DTS 353 (Source: https://www.moje-elektro.cz/merice-spotreby/21651-elektromer-na-din-listu-dts-353-l-100a-7m-trifazovy-3f.html?gclid=EAIaIQobChMI472bhdK13wIVCOJ3Ch0kRA4wEAQYBCABEgIOI_D_BwE)

The data related to the feeding system operation include the amount of unloaded feed, the number of rides, and the number of cattle pieces served by the feeding wagon. The value readings were performed according to the order at approximately weekly intervals.

Table 4. Technical parameters of electricity meter DTS 353

Reference voltage	(V)	3x230 / 400
Standard	IEC62052-11, IEC62053-21	
Frequency	(Hz)	50.0–60.0
Reference current	(A)	10.0
Maximum current	(A)	100.0
Accuracy class	(-)	1.0
Impulse constant	(kWh)	800.0
LCD display mode	(-)	6 + 2
Own consumption	(VA)	< 10.0
Own consumption	(W)	≤ 2.0
Working temperature	(°C)	-20.0–55.0
Pulse output	(-)	open collector
Pulse indication	(-)	red LED
Pulse voltage	(V)	< 30.0
Pulse current	(mA)	≤ 27.0
Mounting DIN rail TS	(mm)	35.0
Connection of screw terminal	(mm^2)	25.0
Degree of protection IP	(-)	20.0
Dimensions (7 modules)	(mm)	122.0 x 100.0 x 65.0

Table 5 shows the detected data, both deducted from the electricity meter DTS 353 and then taken from the management program T4C.

Experimental measured values have been evaluated statistically using program in computer.

Table 5. The measured values when used automatic feeding system Lely Vector in period 31. 12. 2017 to 28. 6. 2018

Number	Date	Measurement time	Hours of measurements	Electricity consumption	Average daily el. consumption	Wagon rides	Wagon rides per day	Average amount of feed per day	Average feed	Average feed per dairy cows per day	Dairy cows
(-)	(-)	(-)	(hours)	(kWh)	(kWh day^{-1})	(-)	(rides day^{-1})	(kg day^{-1})	(kg)	(kg pcs.$^{-1}$ · day^{-1})	(heads)
2017											
0	31. 12.	23:59	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	191.0
2018											
1	01. 01.	18:00	25	32.9	31.6	17.5	16.8	8,325.4	8,672.3	43.6	191.0
2	07. 01.	14:00	140	149.8	25.7	85.2	14.6	7,956.7	46,414.1	41.9	190.0
3	14. 01.	16:00	170	198.4	28.0	110.5	15.6	8,495.2	60,174.3	44.8	189.5
4	21. 01.	13:00	165	186.3	27.1	118.3	17.2	7,883.0	54,195.6	41.8	188.5
5	28. 01.	18:00	173	208.6	28.9	115.3	16.0	8,657.5	62,406.1	45.1	192.0
6	01. 02.	18:00	96	115.6	28.9	63.2	15.8	8,426.1	33,704.4	43.9	192.0
7	07. 02.	12:00	138	139.2	24.2	81.7	14.2	8,431.3	48,480.0	44.4	190.0
8	14. 02.	15:00	171	200.5	28.1	126.8	17.8	8,009.6	57,068.4	42.4	189.0
9	21. 02.	17:00	170	195.6	27.6	135.3	19.1	8,302.0	58,805.8	43.8	189.5
10	28. 02.	17:00	168	183.7	26.2	111.3	15.9	7,867.4	55,071.8	41.8	188.0
11	01. 03.	15:00	22	26.5	28.9	13.6	14.8	8,421.5	7,719.7	45.0	187.0
12	07. 03.	16:00	145	178.6	29.6	83.4	13.8	7,988.0	48,260.8	42.3	189.0
13	14. 03.	14:00	166	211.3	30.5	125.9	18.2	7,831.4	54,167.2	41.0	191.0
14	21. 03.	18:00	172	207.4	28.9	111.8	15.6	8,736.5	62,611.6	45.9	190.5
15	28. 03.	20:00	170	222.3	31.4	120.4	17.0	8,726.0	61,809.2	45.4	192.0
16	01. 04.	19:00	95	100.8	25.5	53.8	13.6	8,387.1	33,198.9	43.5	193.0
17	07. 04.	20:00	145	153.9	25.5	102.1	16.9	8,125.9	49,094.0	42.3	192.0
18	14. 04.	21:00	169	194.2	27.6	121.8	17.3	8,364.8	58,902.1	43.5	192.5
19	21. 04.	18:00	165	169.0	24.6	95.6	13.9	7,531.6	51,779.8	39.6	190.0
20	28. 04.	19:00	169	201.3	28.6	101.4	14.4	8,435.8	59,402.1	44.4	190.0
21	01. 05.	17:00	70	87.4	30.0	49.0	16.8	8,325.9	24,283.9	43.7	190.5
22	07. 05.	16:00	143	151.7	25.5	94.1	15.8	8,211.7	48,928.0	42.8	192.0
23	14. 05.	15:00	167	172.4	24.8	114.8	16.5	7,965.2	55,424.5	41.3	193.0
24	21. 05.	18:00	171	194.7	27.3	127.5	17.9	8,002.4	57,017.1	41.6	192.5
25	28. 05.	19:00	169	186.3	26.5	121.1	17.2	8,481.1	59,721.1	44.6	190.0
26	01. 06.	16:00	93	94.3	24.3	64.3	16.6	8,285.3	32,105.5	43.8	189.0
27	07. 06.	17:00	145	139.1	23.0	91.2	15.1	8,165.9	49,335.6	43.0	190.0
28	14. 06.	15:00	166	187.3	27.1	95.5	13.8	8,332.8	57,635.2	43.5	191.5
29	21. 06.	16:00	169	178.5	25.3	104.9	14.9	8,534.1	60,094.3	44.2	193.0
30	28. 06.	17:00	169	190.8	27.1	114.8	16.3	8,244.6	58,055.7	43.1	191.5

The arithmetic average was used for evaluation of the measurement. The arithmetic average is defined as being equal to the sum of the numerical values of each and every observation divided by the total number of observations. Symbolically, if we have a data set containing the values $a_1,..., a_n$. The arithmetic average is defined as:

$$\phi = \frac{1}{n}\sum_{i=1}^{n} a_i \; (-) \qquad (1)$$

where $Ø$ – arithmetic average (–); $a_1,..., a_n$ – the values of data set (Feynman et al., 2011).

RESULTS AND DISCUSSION

From the data obtained, it was possible to determine the indicators that are related to the distribution of feed by the feed wagon Cernin (Table 6) and automatic system Lely Vector (Table 7).

Table 6. Average resulting values for the period – feeding wagon Cernin C13

Feeding wagon Cernin C13 Period 31. 1. 2016 to 28. 6. 2017					
Daily electricity consumption	Wagon rides per day	Feed per day	Total amount of feed per period	Feed per dairy cows per day	Dairy cows
E_d (kWh.day^{-1})	R_{pd} (rides day^{-1})	F_{pd} (kg day^{-1})	F_{pp} (kg)	F_{cpd} (kg cs^{-1} day^{-1})	C (heads)
-	2.0	8,900.0	1,645,560.0	46.6 *	191.0

Note: * the value 'Feed per dairy cows per day' is calculated by the formula number 2.

$$F_{cpd} = \frac{F_{pd}}{C} \;\; (\text{kg cs}^{-1}\ \text{day}^{-1}) \qquad (2)$$

where F_{cpd} – feed per dairy cows per day (kg pcs^{-1} day^{-1}); F_{pd} – feed per day (kg day^{-1}); C – dairy cows (pcs).

By evaluating the data, it can be state that the following values were achieved when using the conventional feeding system using the mobile feed wagon Cernin C13. In the monitored season, on average, 191.0 dairy cows were reared and a total of 1,645,560.0 kg of feed was delivered, which means 46.6 kg of feed per day per one cow. The amount of fuel consumed could not be determined because the towing device was also used for purposes other than the distribution of feed.

Table 7. Average resulting values for the period – automatic feeding system Lely Vector

Automatic feeding system Lely Vector Period 31. 12. 2017 to 28. 6. 2018					
Daily electricity consumption	Wagon rides per day	Feed per day	Total amount of feed per period	Feed per dairy cows per day	Dairy cows
E_d (kWh.day^{-1})	R_{pd} (rides day^{-1})	F_{pd} (kg day^{-1})	F_{pp} (kg)	F_{cpd} (kg pcs^{-1} day^{-1})	C (heads)
27.3	16.0	8,248.4	1,523,691.6	43.2 *	191.0

Note: * the value 'Feed per dairy cows per day' is calculated by the formula number 2.

When using the Lely Vector automatic feeding system, it can be seen a uniform distribution of rides in one day, averaging 16.0 rides per day. In the monitored season, there were on average 191.0 dairy cows and a total of 1,523,691.6 kg of feed was delivered by the automatic feeding system. Of this, 43.2 kg of feed per one cow per day.

Although the total feed consumption, when using the system Lely Vector, was lower than when using feeding wagon Cernin, the actual feed intake for one cow increased. This was due to lower feed losses when using system Lely Vector. According to the owner of the farm, the feed losses are about 5% when using the system Lely Vector, while losses when using the feeding wagon Cernin are greater than 10%. Milk yields of dairy cows were the same or higher with this whole lower feed consumption.

Energy saving in livestock farming is a very topical issue, with regard to dairy cow farming and milking it is fundamental issue (Smejtková & Chládek, 2012; Unal et al., 2017; Vaculik et al., 2018). An effort to save energy is also at least partially solved for example by the use of biomass (Kažimírová & Čerešňa, 2015; Skanderová et al., 2015), but with regard to the environmental impacts (Kažimírová & Opáth, 2016, Malaťák & Bradna, 2017). When using the automatic feeding system Lely Vector energy saving has occured. Pezzuolo et al., 2016 reports a reduction in energy consumption when using an automatic feeding system 2.74 kWh per day per 1 cow to 0.76 kWh per day per 1 cow. The average consumption at the farm under review was 0.14 kWh per day per 1 cow. Similar electricity consumption is also reported by Oberschätzl-Kopp, 2018. This energy consumption is low compared to the feed wagon also by Oberschätzl-Kopp et al., 2018. Consideration must also be given to fuel savings for the feed wagon towing equipment.

Reduced labor demand is also a significant saving. According to Pezzuolo et al., 2016 labour was reduced from 2.5 h per day related to the conventional feeding system to 1.02 h per day needed for the management of the automatic feeding system.

Obtaining feeding data and conducting their analysis is important also for further research (Xiong et al., 2017).

CONCLUSION

Automatic systems are increasingly used in livestock farming. They have also begun to be used for feeding dairy cows, they replaced feeding wagons or trough conveyors.

The main benefit of the automatic feeding system is a significant saving in staff time, a reduction in the cost of feeding, improving the microclimate in the stable. After the automatic feeding system was installed, the time required to prepare and distribute the feed for the herd was reduced by about 60%. The system is highly reliable, provides statistical data usable for further work, and allows the more natural all day provision of feed supply.

The need for higher initial investment may discourage from the introduction of automatic feeding systems. Also, employees must be able to operate this system. Problems can be with providing a substitute feeding system in the event of an automatic system failure. The return on investment in the automated system depends on a number of factors. Account must be taken of the purchase price of the system and the need for construction adjustments for the installation of the system, next for example the size of the herd or milk performance and the savings that the system will bring.

According to the farm owner, the benefits of the automatic feeding system will compensate for this investment and there were no major complications during the automatic system operation in terms of its failure.

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Computational fluids dynamics (CFD) in the spatial distribution of air velocity in prototype designed for animal experimentation in controlled environments

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Abstract. Maintaining a comfortable and productive thermal environment is one of the major challenges of poultry farming in tropical and hot climates. The thermal environment encompasses a number of factors that interact with each other and reflect the actual thermal sensation of the animals. These factors characterize the microclimate inside the facilities and influence the behaviour, performance and well-being of the birds. Thus, the objective of this study is to propose and validate a computational model of fluid dynamics to evaluate the spatial distribution of air velocity and the performance of a system designed to control air velocity variation for use in experiments with birds in controlled environment. The performance of the experimental ventilation prototype was evaluated based on air velocity distribution profiles in cages. Each prototype consisted of two fans coupled to a PVC pipe 25 cm in diameter, one at each end of the pipe, with airflow directed along the entire feeder installed in front of the cages. The contour conditions considered for the simulation of airflow inside the cage were air temperature of 35 °C at the entrance and exit of the cage; air velocity equal to 2.3 m s^{-1} at the entrance of the cage; pressure of 0 Pa. The model proposed in this study was representative when compared to the experimental measurements, and it can be used in the study of air flow behaviour and distribution for the improvement of the prototype design for later studies.

Key words: Computational Fluids Dynamics, air velocity, ventilation, poultry farming.

INTRODUCTION

In the last decades, the Brazilian poultry industry has presented great advances and expressive numbers within the animal protein production complex. In view of all the modernization of the sector, quail breeding in Brazil is considered a very profitable activity for the producer who wishes to invest professionally in the exploitation of eggs and meat (Albino & Barreto, 2012).

One of the major challenges of poultry farming in tropical and hot climates is the maintenance of a comfortable and productive thermal environment for birds (Coelho et al., 2018), since, under unfavourable thermal conditions, animals need to adjust their behavioural and physiological patterns in order to perform the heat balance (Farag & Alagawany, 2018). Climatic elements such as temperature and relative humidity of the air, wind and solar radiation are preponderant factors as they directly affect the productive, reproductive and survival capacity of quails (Baêta & Souza, 2010; Leinonen et al., 2014; Nawab et al., 2018).

One of the most commonly used tools for the characterization of the animal breeding thermal environment is the development of mathematical models and the application of numerical simulations based on Computational Fluid Dynamics (CFD) (Curi et al., 2017; Saraz et al., 2017; Rojano et al., 2019). This methodology is an efficient way to predict the distribution of climatic variables inside a facility, because it reduces the time and the experimental costs and, consequently, it assists in the decision-making regarding the optimization of the installation design. Several thermal packaging configurations can be readily reproduced and evaluated in CFD simulations, as performed by Rojano et al. (2015), which evaluated the dynamics of a broiler facility analysing sensible and latent heat, mass transport and radiant energy transfer from the poultry rearing environment. Damasceno et al. (2014) adapted and validated a model for predicting temperature and air velocity of a heated air distribution system in chicken broiler houses. The authors verified that the validated model can be used to test different design configurations, different construction materials and other conditions of temperature and velocity of the incoming air. Osório Saraz (2010) also used the CFD to develop and validate a model to determine the distribution of ammonia concentrations in a broiler installation equipped with natural ventilation and without thermal insulation. The author states that the proposed model presented a good statistical correlation with the experimental data, and it can be used to predict the behaviour of the ammonia concentration within the house in real time.

Air velocity in animal facilities is one of the main factors to be considered, especially in Brazil, where the constructive typology of aviaries is largely open. Thus, it is of paramount importance to plan the design of animal facility projects according to the environmental needs of the species, the type of management and the climatic characteristics of each region (Biaggioni et al., 2008; Coelho et al., 2015), including the direction and speed of the air, so that it can be controlled as required. In view of the relevance of more studies relating the influence of air velocity on the well-being and performance of farmed animals, and considering the practical difficulty often encountered to perform this type of experiment under field conditions, it is of paramount importance the development of control prototypes of this variable, which can be used in experiments with animals in controlled environments. An example of this is the system developed by Yanagi et al. (2002) for the control and measurement of dry bulb temperature, relative humidity and air velocity in a research evaluating the effect of heat stress on birds.

Thus, the present work aims to propose and validate a model using computational fluid dynamics (CFD) to be used in the study of the spatial distribution of air velocity and in the evaluation of the performance of a system designed to control the variation of air velocity for use in experiments with birds in a controlled environment.

MATERIALS AND METHODS

Experimental Design

The present research was carried out in a climatic chamber located in the Experimental Area of the Center for Research in Ambience and Engineering of Agroindustrial Systems (AMBIAGRO) in the Agricultural Engineering Department of the Federal University of Viçosa. The climatic chamber has dimensions of 3.2 m in length, 2.44 m in width and 2.38 m in height and is equipped with heating, humidification and cooling system. Setpoints of temperature and relative humidity were established by electronic micro controllers (Model MT-513R plus, Full Gauge Controls, Canoas, RS, BR), installed inside the climatic chambers, with temperature control in the range of -10 to 70 °C and resolution of 1 °C, and relative humidity control from 20 to 85%, with resolution of 0.1%.

The designed air velocity control system consists of Micro Motor fans (Elgin 1/25 MM-20B Bivolt, 60 Hz frequency, 11.93 W and 25 cm diameter). The set consists of two fans coupled in a PVC pipe, one at each end, with the outflow of air directed to the cages. The maximum volumetric flow rate of the system, according to the manufacturer's specifications, is 950 $m^3 h^{-1}$. Thus, by adjusting the power frequency, the air velocities of the fans could be manipulated and adjusted at different levels, according to what was predetermined for the experiment.

The experimental ventilation prototype was installed in front of the cage (Fig. 1), with possibility to adjust different air velocities at the level of the birds.

Figure 1. Inside view of the climatic chambers, where 1: air conditioning; 2: air humidifier; 3: electronic temperature and relative humidity controller (MT-531R plus); 4 and 5: ventilation tubes; 6: air heater; 7 and 8: cages; 9 and 10: feeders; 11 and 12: water tanks.

To validate the simulation, air velocity data were collected at 275 points uniformly arranged along the three dimensions (width, length and height) of the whole cage. The thermoanemometer Testo 425, used for the trials, has the following specifications: probe head 7.5 mm in diameter, measuring range 0.0 to 20.0 m s^{-1}, resolution of 0.01 m s^{-1} and range for the 2-second moving average. The data were collected during the period of 1 minute, totalling 30 samples per point, and finally the average was recorded in the display.

Computational Model

The geometry (Fig. 2) was developed in software ANSYS S® Workbench™ 18.2 Academic using the DesignModeler™ and the mesh was developed in Meshing. The three-dimensional geometry was conceived in the actual dimensions of the cage used in the experiment, the area being modelled 0.38 x 0.33 m, considering only half-length in order to reduce the computational domain.

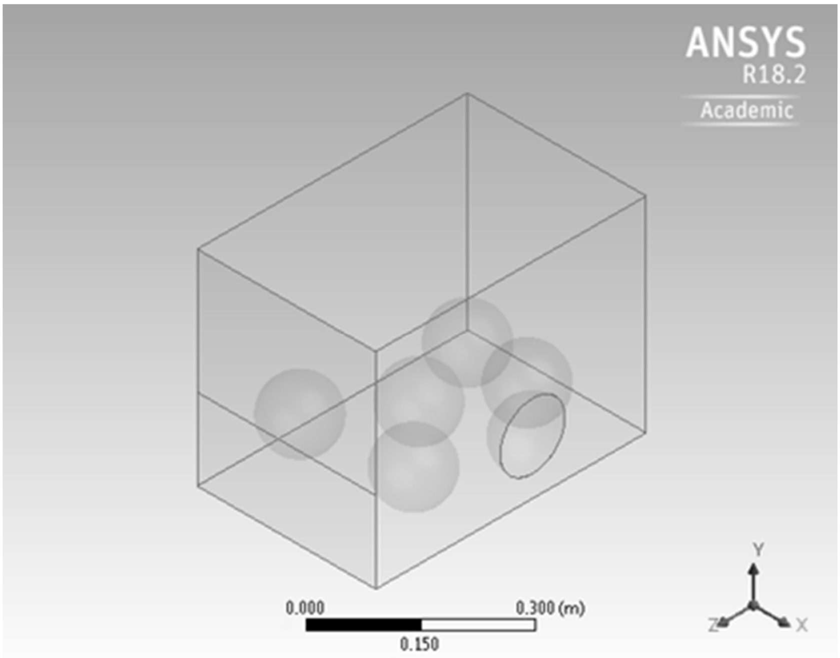

Figure 2. Cage's geometry in ANSYS software 18.2.

The CFD technique was used to solve the Navier-Stokes equations and energy equation, discretizing the fields of velocity, temperature and pressure by the finite volume method. The set of governing equations is given by the equations of continuity, conservation of momentum and energy.

The considerations assumed were: permanent regime, incompressible and turbulent flow. The model of turbulence adopted was the Shear Stress Transport model, where the High Resolution option in Turbulence Numerics was selected.

Quail was considered as a source of heat, and its estimate of heat production (q) was calculated by Eq. 1, proposed by International Commission of Agricultural and Biosystems Engineering - CIGR (2002).

$$q = (6.28m^{0.75} + 1.25) \cdot (1 + \frac{20(20 - T)}{1,000}) \quad (1)$$

where m = bird weight (approximately 0.15 kg); T = environment temperature (°C).

Spheres distributed randomly in the cage represented the birds, in order to evaluate the airflow distribution and the influence of the animals in the heat transfer process. The boundary conditions of the domain are shown in Table 1.

Table 1. Boundary conditions adopted for the simulation of the airflow inside the cage

	Boundary condition	Type	Properties
Cage	Inlet	Inlet	External air temperature = 35 °C
			Air velocity = 2.3 m s^{-1}
	Outlet	Outlet	Pressure = 0 Pa
			External air temperature = 35 °C
	Opening	Opening	Pressure = 0 Pa
			External air temperature = 35 °C
	Wall	Wall	No slip wall
Quail			Heat source = 2144.4 W m^{-3}

The thermophysical properties considered for quails in this study were: a) thermal conductivity: 0.45 W m^{-1} K^{-1} (Pereira et al., 2013); b) specific heat: 3,340 J kg^{-1} K^{-1} (Neves Filho, 1978); c) density: 1,075 g cm^{-3} (Pereira et al., 2013).

The mesh independence test was performed with different levels of refinement. Nine different mesh sizes were tested, ranging from 0.005 to 0.015 m. As convergence criterion, the mean square error type was adopted, with a value less than 10^{-5}, maximum number of iterations equal to 500 and Physical Timescale of 1s. The selected advection scheme was Specified Blend Factor, with Blend Factor of 0.8.

Model validation

The results obtained by the CFD model were compared with the real corresponding experimental data by means of the normalized mean square error (NMSE) (Eq. 2).

$$NMSE = \frac{(V_{CFD} - V_m)^2}{(V_{CFD} \cdot V_m)} \quad (2)$$

RESULTS AND DISCUSSION

Several types of tetrahedral meshes were used, and after the previous evaluation of different levels of refinement, a mesh with 170,502 nodes and 891,715 elements was selected. The result of the mesh test is presented in Table 2 and Fig. 4. The test was performed from the data obtained at the measurement points located near the air outlet of the cage (Fig. 3), 8 cm in height of the floor. Line 1 refers to the location of the points used in the mesh independence test.

A reduction in the difference of the values of air velocity between the meshes was observed and, therefore, mesh independence from the mesh size 0.006 m was verified.

Table 2. Air velocity at the positions of the X-axis (m) at the air outlet of the cage

Mesh size (m)	Number of nodes	Elements	X-axis position (m)			
			0.05	0.10	0.20	0.30
0.005	265,558	1,404,140	2.63	0.69	1.31	2.00
0.006	170,502	891,715	2.62	0.69	1.19	2.00
0.007	117,205	607,156	2.54	0.68	1.13	1.94
0.008	85,055	436,239	2.44	0.71	0.95	1.87
0.009	67,592	346,822	2.36	0.70	0.84	1.83
0.010	52,405	267,013	2.26	0.68	0.75	1.77
0.013	27,709	137,899	1.97	0.66	0.61	1.59
0.015	19,622	95,867	1.70	0.63	0.51	1.43

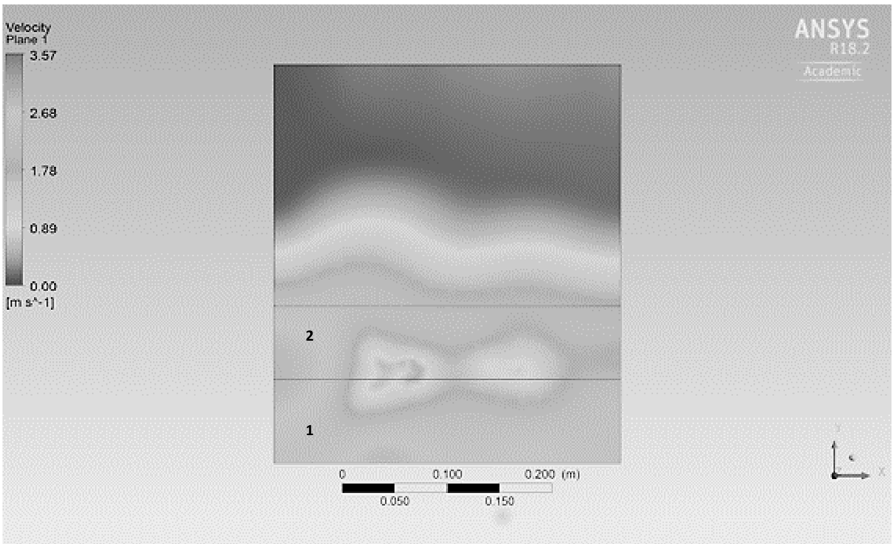

Figure 3. Air velocity profile in cross section of cage.

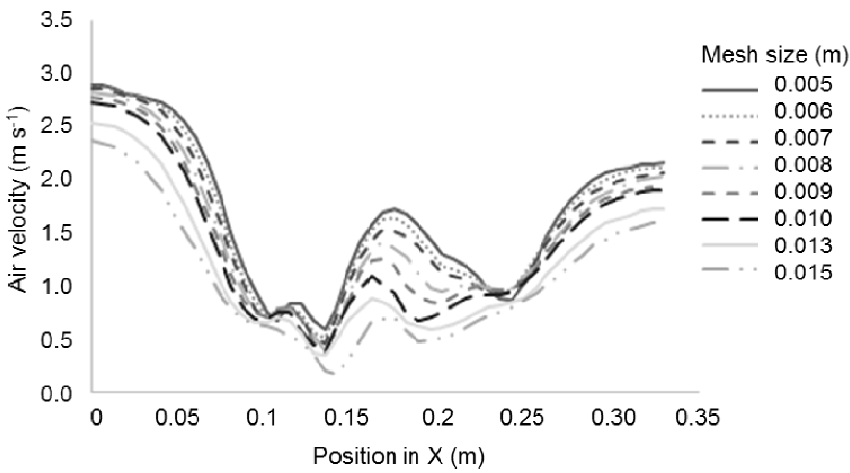

Figure 4. Mesh independence test, with mesh size ranging from 0.005 to 0.015m.

To validate the simulation, air velocity values obtained by CFD at different positions (A: 0.05 m; B: 0.10 m; C: 0.20 m; D: 0.30 m) were compared with the real values measured by means of NMSE. The NMSE was calculated at the entrance Z = 45 cm) and air outlet of the cage (Z = 3 cm). The results found are shown in Table 3.

It is observed that in position A, both in the entrance and in the air outlet of the cage, the NMSE found was superior to the level considered ideal to indicate the agreement between the values simulated and measured experimentally. However, in the other positions, the values found indicated good agreement between the measured and simulated data.

Table 3. Normalized Mean Square Error (NMSE) between the air velocity values obtained in the simulation and experimentally

	Position (m)	NMSE
Air Inlet	A	1.532
	B	0.001
	C	0.000
	D	0.019
Air Outlet	A	5.619
	B	0.051
	C	0.070
	D	0.026

Mostafa et al. (2012) state that NMSE values below 0.25 are considered good indicator of agreement between simulated and field values. Corroborating with our findings, Padavagod Shivkumar et al. (2016) evaluated the performance of a poultry engineering chamber complex by direct flow testing and CFD, and they found NMSE of 0.007, indicating a good agreement of simulated results with measurements. Saraz et al. (2016) evaluated the environmental conditions in a natural ventilation system in broiler chickens by means of the computational fluid dynamics and verified NMSE values of 0.024 to 0.099 between the ammonia concentration obtained in the simulation and the experimental measurements. The values considered in the study indicate that the model is able to predict the concentration of ammonia inside the aviary. Similarly, Mostafa et al. (2012), studying different configurations of ventilation systems of broiler chickens by means of CFD, obtained NMSE values of 0.2 between the simulated and measured values for ammonia concentration, being considered satisfactory for the prediction of the concentration of gas.

After validation of the model, the behaviour of airflow and velocity distribution was observed. Fig. 5 shows the airflow behaviour from the streamlines in the three dimensions of the cage (x, y and z). Fig. 6 shows that air velocity decreases as affected by the presence of the quails but increases on the sides of the birds due to the principle of mass conservation, which leads to air velocities greater than the velocity of entry, which is 2.3 m s^{-1}.

The importance of studying the intensity and distribution of airflow, especially in the area near the feeder, is associated with its influence on the ingestive behaviour of the animals. Thus, Yahav et al. (2001) studying the effect of air velocity on the performance of broilers subjected to heat stress (35 °C), concluded that birds exposed to higher air velocities (2.5 and 3 m s^{-1}) obtained better results in terms of weight gain, feed intake and feed conversion when compared to birds submitted to air velocity of 0.5 m s^{-1}. At air velocities of 2.3 m s^{-1}, there are very low values, generally less than 1 m s^{-1}, and the highest values are very close to 3 m s^{-1}, which implies averages always below the nominal speed expected for the treatment. Such amplitude can be explained due to the effect of the turbulence present in this flow.

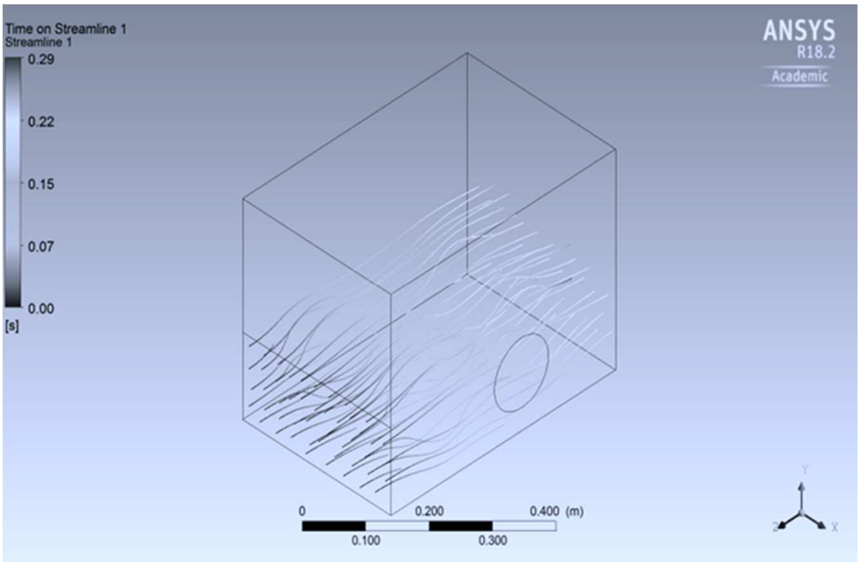

Figure 5. Behaviour of airflow demonstrated by streamlines.

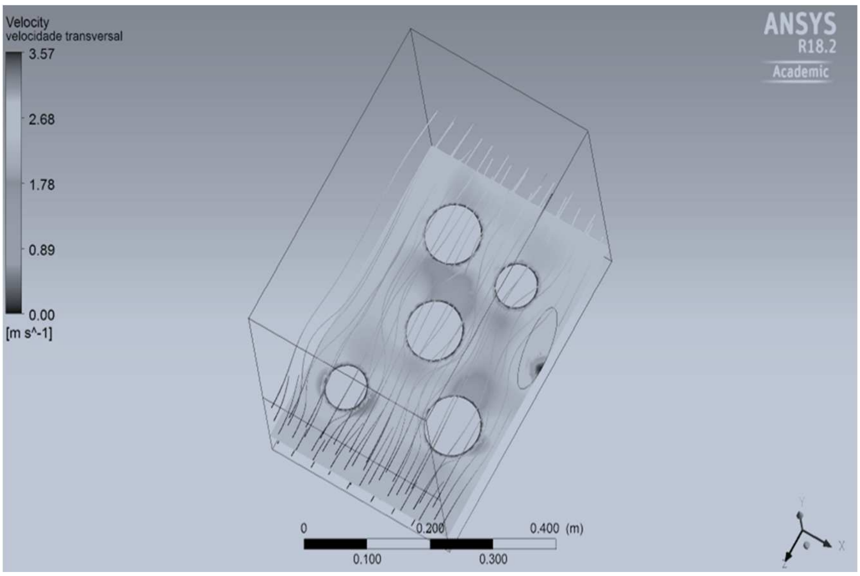

Figure 6. Simulated results visualization for the air velocity in the XZ plane.

According to Bustamante et al. (2013), CFD technique gives a more general view of indoor climate conditions of poultry farms through the graphics than direct measurements, making it a more complete and informative tool. Saraz et al. (2012) affirm that the studies carried out in recent years demonstrate the CFD technique advantages to deepen the studies of the heat and mass transfer phenomena, as well as to improve and optimize the structures designs seeking to obtain a better animal thermal comfort.

CONCLUSIONS

The proposed CFD model presented a good agreement with the real air velocity data obtained by the anemometer, i.e., the air velocity was not influenced by the methodology (real measurements or CFD). Thus, it can be a good tool to help researchers in creation, development and analyses of a system designed to control and adjust the air velocity, for the study of air velocity in controlled environments, as in climatic chambers.

The variation of air velocity observed inside the cage was substantially due to the opening design, since part of the incoming airflow is lost along the way through side and upper openings. In spite of this, higher velocities in the entrance of air were reached at the feeder zone, showing that the constructed prototype can be used in studies related to environment and ingestive behaviour of birds.

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Alternative form to obtain the black globe temperature from environmental variables

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Abstract. Reaching thermal comfort conditions of animals is essential to improve well-being and to obtain good productive performance. For that reason, farmers require tools to monitor the microclimatic situation inside the barn. Black Globe-Humidity Index (BGHI) acts as a producer management tool, assisting in the management of the thermal environment and in decision making how protect animals from heat stress. The objective of this work was to develop a mathematical model to estimate the black globe temperature starting from air temperature, relative humidity and air velocity. To reach this goal, data of air temperature and humidity were collected, with the aid of recording sensors. The black globe temperature was measured with a black copper globe thermometer and the air velocity was monitored with a hot wire anemometer. Data were analysed using a regression model to predict the black globe temperature as a function of the other variables monitored. The model was evaluated, based on the significance of the regression and the regression parameters, and the coefficient of determination (R^2). The model proved to be adequate for the estimation of the black globe temperature with $R^2 = 0.9166$ and the regression and its parameters being significant ($p < 0.05$). The percentage error of the model was low (approximately 2.2%). In conclusion, a high relation between the data estimated by the model with the data obtained by the standard black globe thermometer was demonstrated.

Key words: thermal comfort, black globe temperature, black globe-humidity index, animal housing.

INTRODUCTION

The animal breeding system in the intensive form is increasing, because the food demand of the world population has grown significantly. Therefore, this breeding system stands out and attracts investments, since it presents high productivity when well operated (FAOSTAT, 2015). The climatic variations influence the animal metabolism and consequently can compromise the performance, affecting the profitability of the productive activity. In a breeding system, the animals should remain within their range of thermoneutrality and environmental thermal comfort conditions should be reached (Baêta & Souza, 2010), to avoid that climatic conditions can negatively influence production and well-being.

The four major environmental factors that influence effective temperature are: dry-bulb temperature, humidity, radiation and air movement.

Thermal comfort can be evaluated by means of thermal comfort indexes that integrate two or more microclimatic elements. A variety of indexes are used to predict comfort or discomfort of environmental conditions and then estimate the degree of heat stress affecting the animals (Herbut et al., 2018). Generally, the two environmental parameters considered have been air temperature and relative humidity. The most common index is the Temperature-Humidity Index (THI), which uses the dry-bulb temperature (Tdb) and the wet bulb temperature (Twb) to estimate the magnitude of heat stress (Thom, 1959).

The THI was studied by several researchers (Ingraham et al., 1979; Buffington et al., 1981; Gaughan et al., 2008) and used to evaluate the thermal comfort of animals of different species (Campos et al., 2001; Klosowski et al., 2002; Turco et al., 2008; Gantner et al., 2011; Herbut & Angrecka 2012). Because of the differences in sensitivity to ambient temperature and amount of moisture in the air among species, a range of equations for calculation of THI with different weightings of dry-bulb temperature (Tdb) and air moisture have been proposed.

The general equation to calculate THI can be expressed by the following equation (CIGR, 2006):

$$THI = aTdb + bTwb + c \tag{1}$$

where Tdb is the dry-bulb temperature, Twb is the wet-bulb temperature, a, b, c are constants depending on species.

Dikmen & Hansen (2009) compared eight different THI indices to verify if rectal temperature of Holstein cows is related to THI and other environmental parameters. In particular two of the eight indexes showed a very high correlation with Tdb. As conclusion, for the authors, at a practical level, the predictive value of THI is only slightly better than Tdb alone and Tdb is nearly as good a predictor of rectal temperature of lactating Holsteins in a subtropical environment as THI.

Oliveira et al. (2017) argue that the evaluation of thermal comfort through the indexes is an important tool to help producers in the choice of thermal solutions inside a building.

Another important index used to evaluate the thermal environment and the stress conditions of the animals is based on the black globe temperature. In literature the index based on the black globe temperature is called black globe and humidity (BGHI) or wet-bulb globe temperature (WBGT). In any case, the index requires measuring the black globe temperature, using a black globe thermometer, a device consisting of a thin copper sphere (usually 0.15 m diameter), black painted with a temperature sensor in the centre. The black metal ball absorbs radiant heat, and raises the temperature inside. It gives indirect information about the contribution of radiation and wind speed (°C).

The WBGT is very popular due to its simplicity and ease of use in industry, sports and other areas to indicate the heat stress level for humans and animals (Brake & Bates, 2002; Dimiceli e al., 2011; Golbabaei et al., 2014; Vatani et al., 2015).

The Black Globe Humidity Index (BGHI) integrates dry-bulb temperature, humidity, net radiation, and air movement into a single value. BGHI is created by inserting the black globe temperature (instead of the dry-bulb temperature) in the THI equation.

The BGHI is a very precise indicator of the thermal comfort of the animal in comparison to the THI, in conditions of the external environment presenting high solar radiation or air velocity (Buffington et al., 1981). Consequently, BGHI is a more accurate indicator of animal comfort and production than the THI under heat-stressing environmental conditions when animals are exposed to incident solar radiation. Under conditions of little or moderate thermal radiation levels, BGHI and THI are about equally as effective as indicators of animal comfort.

The BGHI has some limitations. To calculate the index it is necessary to have the black globe temperature. However, the black globe temperature sensor can be costly and, to obtain an appropriate value of black globe temperature, it could be necessary to get measurements in different locations (Yanagi, 2006). So, a long time is required to measure the black globe temperature.

The BGHI can find several applications in animal housing. Collier et al. (2011) found that the effects of radiant heat load can be evaluated using the BGHI, developed by Buffington et al. (1981). Oliveira (1980) developed a model to estimate BGHI using data referred to edification (dimensions and thermal conductivity of the buildings materials) and climate (temperature, relative humidity, wind velocity, atmospheric pressure, and solar radiation). In this model, the incident overall solar radiation on the surface of the roof was estimated by the overall solar radiation measured by instruments and corrected to the surface of the roof.

Yanagi et al. (2011) developed a computer model to predict the black globe humidity index (BGHI) to simulate different resultant conditions in designing poultry buildings. The simulated BGHI values were compared to experimental measurements, obtained in a poultry facility at Viçosa (MG, Brazil), giving a mean deviation of 1.31%. The model was then used to predict BGHI values as affected by roof slopes and column heights.

Some studies have been carried out to solve the problem related to the acquisition of data concerning the black globe temperature. Although this temperature is one of the most common variables used for assessing heat stress, usually it is not reported in meteorological data. Turco et al. (2008) derived equations to estimate the black globe temperature based on meteorological data creating a statistical model.

Dimiceli et al. (2011) obtained a formula to estimate the black globe temperature using readily available data collected by the Weather Service. Recently Hajizadeh et al. (2017) carried out a study in Iran to develop a model to estimate the black globe temperature based on meteorological measurements, in order to calculate the occupational heat stress index in outdoor workplaces.

The aim of this work was to develop a mathematical model to estimate the black globe temperature (T_{gn}) starting from air temperature (T_{ar}), relative humidity (RH) and air velocity (V_{ar}), which are easier to obtain.

MATERIALS AND METHODS

Data Acquisition

The climatic data for the development of the mathematical model of black globe temperature estimation were collected in the experimental area of the Centre for Research in Ambience and Engineering of Agroindustrial Systems (AMBIAGRO, lat 20°46’15” long 42°52’21”) belonging to the Federal University of Viçosa.

Data were collected for three consecutive days at one hour intervals. The air temperature and relative humidity data were collected with the aid of recording sensors (Onset Computer Corp, model Hobo, U12-013; temperature range: -20 °C to 70 °C, accuracy ± 0.35 °C; humidity range: 5% to 95% RH, accuracy: ± 2.5%, USA). The black globe temperature was measured by a temperature probe housed inside a black copper globe (Homis Control and Instrumentation, model TGD – 1,000; temperature range: 0 °C to 50 °C with accuracy ± 0.6 °C, Brazil) and the air velocity was monitored with a hot wire anemometer (SKILL-TEC, model sktafq-01; air velocity 0.4 a 30 m s^{-1}, accuracy 0.1 m s^{-1}, Brazil).

Statistical analysis

The data collected were analysed using a multiple linear regression model:

$$Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \beta_3 X_{i3} + \varepsilon_i \quad (2)$$

where Y_i – response in the ith test; β_0, β_1, β_2 and β_3 – parameters of the model; X_{i1}, X_{i2} and X_{i3} – values of predictor variables in the ith test; ε_i – error term.

The black globe temperature was then estimated as a function of the variables collected (air temperature – Tar, relative humidity – RH, air velocity – Var) and their interaction. The evaluation of the model was performed, based on the significance of the regression and its parameters, as well as the coefficient of determination (R^2).

Validation of the model

To validate the proposed model of black globe temperature prediction, the estimated data were compared through correlation analysis with black globe temperature data measured with the help of a standard black globe thermometer.

RESULTS AND DISCUSSION

The resulting equation, which allows to estimate the black globe temperature from the monitored environmental variables and their respective interactions, corresponds to:

$$\text{Tgn} = 4{,}068 + 0.993 \times \text{Tar} - 0.754 \times \text{UR} - 0.0737 \times \text{Var} \quad (3)$$

The model presented in Eq. 3 is satisfactory for estimating the black globe temperature in the study environment, based on the variables monitored, presenting a coefficient of determination $R^2 = 0.9166$, showing that 91.66% of the dependent variable (Tgn) can be explained by the generated model.

Turco et al. (2008) defined a model to estimate the black globe temperature for outdoor workplaces based on meteorological data and to be able to measure heat stress indices. However, they found serious problems in calculating the index based on meteorological data, due to the lack of measurements of the black globe temperature by weather stations in most countries.

Abreu et al. (2011), proposed an equation to estimate the black globe temperature in protected environments taking into account only the air velocity, and obtained results similar to results of the present study.

Hajizadeh et al. (2017) carried out a study giving similar results. The authors found a significant relationship between the black globe temperature and air temperature, solar radiation and relative humidity. The model obtained was proposed to estimate the black globe temperature in a hot and dry environment and considered useful in assessing occupational heat stress in outdoor workplaces.

In present study, during the validation of the model, we observed a strong correlation between the data collected with the black globe thermometer and the data estimated by equation 3, as shown in Fig. 1.

The correlation coefficient between measured values and values estimated by the generated model is 0.9730.

The model presented an average error of 0.02%, which shows reliability in the given data. This result corroborates with Coelho et al., 2013, who studied the prediction with the use of alternative materials and found high reliability.

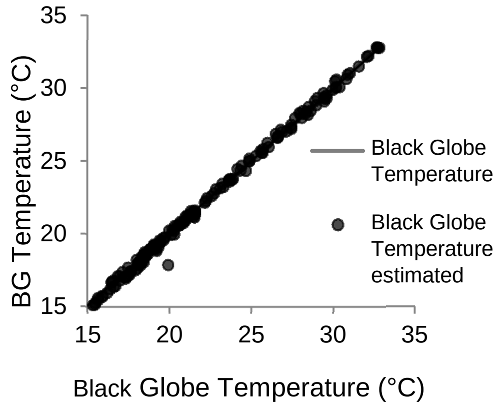

Figure 1. Correlation between the data collected and estimated by the proposed model.

CONCLUSIONS

Thermal comfort conditions of animals inside a barn are essential to improve well-being and to obtain good productive performance. Black Globe-Humidity Index (BGHI) acts as a producer management tool for farmers to monitor the microclimatic situation inside the barn, assisting them in the management of the thermal environment and in decision making how to protect animals from heat stress.

In the present study, a high relation between the data estimated by the model with the data obtained by the standard black globe thermometer was demonstrated.

The mathematical model, based on air temperature, relative humidity and air velocity as environmental variables, is satisfactory for estimating the temperature value of the black globe thermometer, and it becomes an aid tool in the decision-making of the producers to identify and ensure animal thermal comfort.

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