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Determination of silage density in bunker silos using a radiometric method

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Abstract. Wilted grass and chopped maize have to be compressed in bunker silos in order to achieve storability for high quality silage. High losses can occur if the compaction is too low. The aim of the project was to develop a measuring device to determine the density of the ensiled material during the compaction drives. The measuring method is based on the radiometric density determination by backscattered gamma-photons. Cesium Cs-137 is used as photon source. The cesium source and the detector were located in a measuring wheel, which is trailed by the compaction vehicle over the silo. In conjunction with data from a Differential Global Positioning System (DGPS), the density values can be related to certain positions in the silo. An assessment of the costs and benefits showed that the radiometric measurement method is cost-effective if the number of dairy cows exceeds 135 cows.

Key word: Silage, compression, radiometry, bunker silo, costs, benefits.

INTRODUCTION

When storing wilted grass or chopped maize in bunker silos, the ensiled material has to be compacted in order to avoid losses. At present, in order to measure the density of silage, samples are taken out of the silo using special drills or silage blocks are cut out with a silo block cutter. The density is calculated from the volume withdrawn and the associated mass. However, both these methods can only be applied after the storage period when the silage is removed.

For a relatively long time radiometric methods have been used for measuring densities of natural materials such as wood (Malan & Marais, 1992; Macedo et al., 2002); tobacco (Okumoto, 1987), ice cream (Badr, 2012), starch suspensions (Kempf et al., 1976), grain (DLG, 2001), straw and silage bales (Mumme & Katzameyer, 2007; Gläser et al., 2007; Sun et al., 2012) and silages (Kuhn, 1976; Gläser & Kuhn, 1997).

On the bases of the experiences of Gläser & Kuhn (1997) and Fürll (2008), the radiometric measuring method was chosen as the most promising measuring principle to determine the density of the ensiled material during the compaction drives.

MATERIAL AND METHODS

The measuring principle is based on the interaction of gamma photons with the electrons of the scattering material.

The used measuring unit consists of a cesium radiator with an activity of 37 MBq and a sodium iodide scintillation detector. The measuring system detects the gamma photons radiated back from the material. That means the higher the density of electrons, the higher is the material density.

First of all preliminary experiments were done to find out the optimal geometric arrangement of source and detector. Afterwards the radiometric measuring device was calibrated. For this, natural raw materials of known density were placed beneath the measuring wheel and the impulses of the radiation backscattering were measured. This method is based on the principle that organic materials are similar in their stochiometric composition and thus also display similar mass absorption coefficients (Gläser, 1992; Macedo et al., 2002). The materials used were hemp shives (woody fragments of the hemp stem), balsa, spruce and oak, as well as oats and rye grains. In addition, the impulse rates for air and water were measured. One spruce sample was measured in the natural density state with 430 kg m^{-3}, the other after a mechanical compression with 880 kg m^{-3}.

For each sample the backscattered photons were counted for 1 second with 100 repetitions. This means every measurement series consists of 100 values. A quadratic regression was done with all values of all series by using the statistical software SAS 9.3.

Based on these examinations, a wheel-like measuring device with optimized arrangement of source and detector was developed (Fig. 1) and tested while driving over the silo (Fig. 2). The measuring wheel is connected with the tractor by the three point linkage at the rear. The design is suitable for road transportation as well. The measuring wheel has a diameter of 1 m and a design width of 0.4 m.

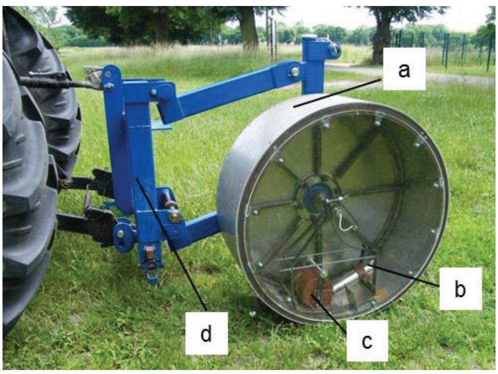

Figure 1. Measuring wheel with cesium source and detector (a – measuring wheel, b – detector, c – cesium source with lead casing, d – frame for three-point linkage).

Figure 2. Measuring pass on a bunker silo with chopped maize.

The necessary number of dairy cattle for a profitable application of a radiometric measuring device was calculated based on a cost-benefit calculation. Cost criteria were silage losses, compaction work, employment of veterinarian, and costs for insemination. Revenues are gained from milk and calves sale. No coherent information were available in literature for every stage from the storage of the ensiled material to the milk sale or cow health. Data for assessing the measurement system were therefore collected from different publications with differing backgrounds. For each criterion a standard value and, in addition, a value with an assumed improved level was determined. Often an improvement of 5% was assumed.

RESULTS

The calibration by various organic materials and water shows a quadratic connection between the given material density and the impulse rate (Eq. 1, Fig. 3). After transformation of Eq. 1, the density can be calculated by using the minus sign in front of the root (Eq. 2).

$$I = -0.222268 \cdot \rho^2 + 6.87148 \cdot \rho + 6517.57751 \quad (1)$$

$$r^2 = 0.99$$

$$\rho_{1,2} = 15.87654 \pm \sqrt{1514.87654^2 - \frac{I - 6517.57751}{0.002268}} \quad (2)$$

with: I – impulse rate, (s^{-1}); ρ – density, (kg m^{-3}); r^2 – coefficient of determination, (-). As expected, the calibration curve (Fig. 3) shows a higher impulse rate with increased density.

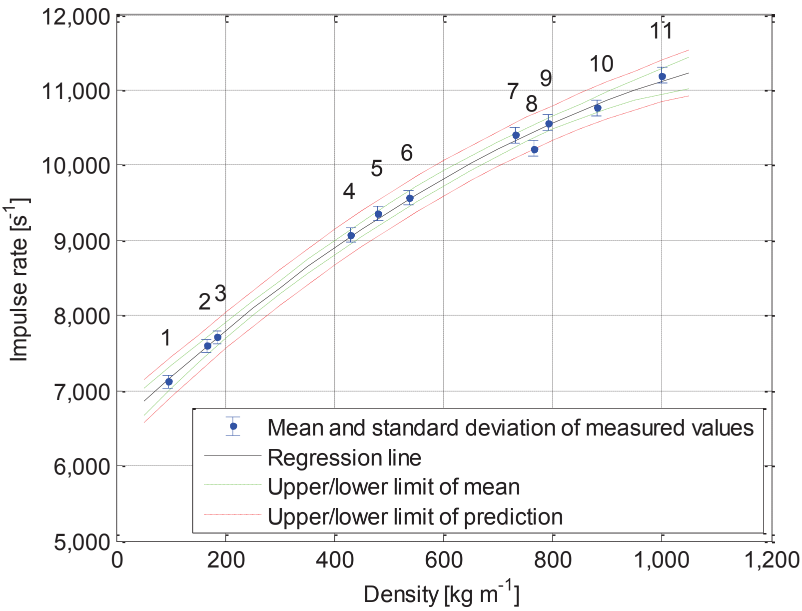

Figure 3. Calibration curve with confidence areas for the radiometric measuring device: 1 balsa, low density; 2 hemp shives; 3 balsa, high density; 4 spruce, natural; 5 oats, loosely poured; 6 oats, firmly tapped; 7 rye, loosely poured; 8 oak; 9 rye, firmly tapped; 10 spruce, compressed; 11 water.

The measuring wheel was tested eight times on bunker silos with maize and wilted grass (Fig. 2). In conjunction with data from a Differential Global Positioning System (GPS), the density values can be related to certain positions in the silo (Fig. 4).

For displaying to the driver of the compaction vehicle the current density on a monitor inside of the cabin of the compaction vehicle a software program was developed. The current density is graduated using a color scale. The colour 'red' represents low densities and 'green' indicates high densities.

The measuring wheel gives the density for one site of the compaction vehicle. No values are available for the second site and for the area between the wheels. The software menu option 'Associated width of a measured value' allows the selection of whether the displayed line represents only the site of the vehicle measured or it is extrapolated on the entire vehicle width (Fig. 4).

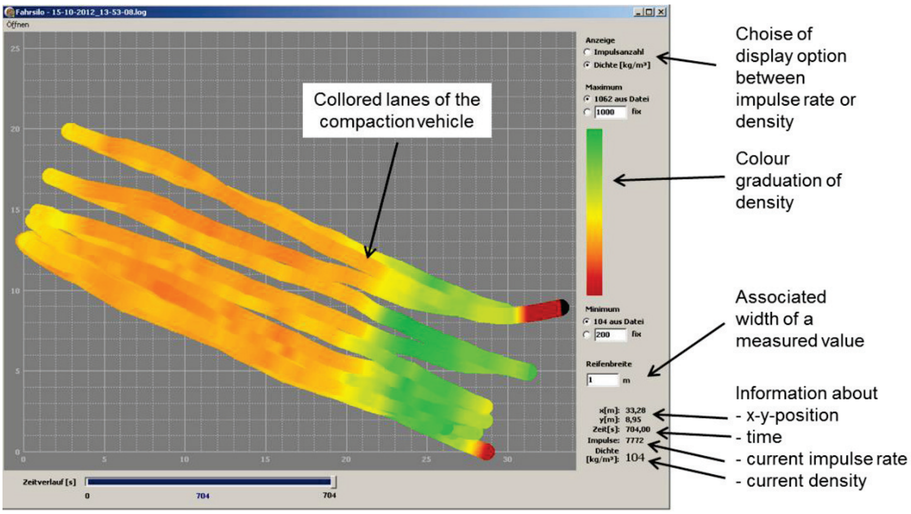

Figure 4. Measured silage density as a function of the position inside a bunker silo with wilted grass (green colour indicates high density, red colour indicates low density).

The acquisition of the measuring system leads to cost. However, financial incentives are to be expected if the ensiled material is compacted properly. The values for the dry matter mass losses given in literature are 7.95% (Ruppel at al., 1995), 9.0% (Köhler et al., 2012), 11.0% (Thaysen, 1993), 11.7% (Böttcher, 1957), 12.0% (Köhler et al., 2012), 13.5% (Hell, 1966), 15.0% (LFL, 2006), 18.0% (DOW, 2012) up to 43.0% (Ruppel et al., 1995).

It is assumed that the losses can be reduced from 13% to 10% (Table 1, row 2) if the ensiled material is compacted as required. For further calculations, a reduction of losses of 3 percentage points is assumed independent of the total level of losses. The calculation results in a cost benefit of 18.05 EUR cow^{-1} a^{-1} (row 6).

The driver of the compaction vehicle controls the next drives based on the current density value. However, because it is not known whether and to what extend compaction time can be saved, no effects due to time losses or savings were applied (row 15).

Table 1. Comparison of the standard cost to the improved costs by using the radiometric density measurement system

Row	Position	Unit	Standard variant	Improved variant
Costs of losses				
1	Need for silage	m³ cow^{-1} a^{-1}	26.72	
2	Losses, relative	%	13.00	10.00
3	Losses, absolute, (OS)	m³ cow^{-1} a^{-1}	3.47	2.67
4	Costs of silage (OS)	EUR m^{-3}	22.52	22.52
5	Costs of losses	m³ cow^{-1} a^{-1}	78.21	60.16
6	Cost advantage	EUR cow^{-1} a^{-1}		18.05
Costs of compaction work				
7	Standard value for maize (OS)	min t^{-1}	1	1
8	Standard value for wilted grass (OS)	min t^{-1}	3	3
9	Relation 1/3 maize, 2/3 grass	min t^{-1}	2.33	2.33
10	Mass of silage (0.65 t/m³)	t cow^{-1} a^{-1}	2.56	2.56
11	Time for compaction	min cow^{-1} a^{-1}	2.48	2.48
12	Time for compaction	h cow^{-1} a^{-1}	2.51	2.51
13	Costs for driver and tractor	EUR h^{-1}	2.50	2.50
14	Costs for compaction	EUR cow^{-1} a^{-1}	6.26	6.26
15	Cost advantage	EUR cow^{-1} a^{-1}		0.00
Costs of veterinarien				
16	Data from literature	m³ cow^{-1} a^{-1}	89.00–02.75	
18	Assumed reduction	%		5
17	Standard value	m³ cow^{-1} a^{-1}	95.88	91.09
18	Cost advantage	EUR cow^{-1} a^{-1}		4.79
Costs of insemination				
19	Data from literature	m³ cow^{-1} a^{-1}	25.00–45.00	
20	Assumend reduction	%		5
21	Standard/reduced value	m³ cow^{-1} a^{-1}	30.00	28.50
22	Cost advantage	EUR cow^{-1} a^{-1}		1.50
Proceeds of milk sale				
23	Number of milk cows in Germany	cows	4,164,789	
24	Amount of milk in Germany	t a^{-1}	29,198,675	
25	Encreased quantity of milk	%		10
26	Quantity of milk	l cow^{-1} a^{-1}	7,010.84	7,711.93
27	Profit	EUR l^{-1}	0.02	
28	Proceeds of milk sale	EUR cow^{-1} a^{-1}	140.22	154.24
29	Cost advantage	EUR cow^{-1} a^{-1}		14.02
Proceeds of calves sale				
30	Improvement	%		5
31	Number of lactations	cow^{-1}	2.50	2.63
32	Average proceeds of calf	EUR a^{-1}	174.00	174.00
33	Proceeds	EUR cow^{-1}	435.00	456.75
34	Age of milk cow	a	5	5
35	Proceeds	EUR cow^{-1} a^{-1}	87.00	91.35
36	Cost advantage	EUR cow^{-1} a^{-1}		4.35

It is assumed that high quality fodder stimulates the health of cows and therefore leads to reduced costs for veterinarian. Averages of costs for animal care are between

89.00 EUR cow^{-1} a^{-1} (Wattendorf-Moser, 2001) and 102.75 EUR cow^{-1} a^{-1} (Dummer, 2010). As standard variant in the calculation 95.88 EUR cow^{-1} a^{-1} (row 18) is used and 91.09 EUR cow^{-1} a^{-1} as improved variant, that is 5% cost reduction. The financial benefit amounts to 4.79 EUR cow^{-1} a^{-1} (row 18).

A good cow health is also reflected in lower insemination costs. The insemination costs are estimated at 25.00 – 45.00 EUR cow^{-1} a^{-1} (LFL, 2006). The evaluation calculates with 30.00 EUR cow^{-1} a^{-1} as standard value (row 21). The assumed benefit amounts to 1.50 EUR cow^{-1} a^{-1} (row 22).

Kressel (2008) reported, that cows give 38.33 kg milk day^{-1} if they were fed with good maize silage and only 33.83 kg day^{-1} if they were fed with molded silage. This means a reduction of approx. 10%. From the point of view of a quality improvement due to the density measurement, an increased milk amount of 10% (row 26) was used in the calculation. The benefit amounts to 14.02 EUR cow^{-1} a^{-1} (row 29).

It can be expected that a healthy cow is more efficient and gets more calves. In average a cow gets 2.5 calves (row 31) (LKV, 2012). If the number of lactations increases to 2.63 calves (plus 5%), a financial benefit of 4.35 EUR cow^{-1} a^{-1} be the result (row 36). The total lifetime of cows is set to 5 years in the calculation.

The compilation of cost advantages shows that the reduction of losses and the increase of milk production deliver the greatest cost benefits (Table 2, rows 37 and 41).

Table 2. Compilation of cost adavantages

Row	Position	Unit	Improved variant
37	Costs of losses	EUR cow^{-1} a^{-1}	18.05
38	Costs of compaction work	EUR cow^{-1} a^{-1}	0.00
39	Costs of veterinarien	EUR cow^{-1} a^{-1}	4.79
40	Costs of insemination	EUR cow^{-1} a^{-1}	1.50
41	Proceeds of milk sale	EUR cow^{-1} a^{-1}	14.02
42	Proceeds of calves sale	EUR cow^{-1} a^{-1}	4.35
43	SUM	EUR cow^{-1} a^{-1}	42.71

A financial benefit of 42.71 EUR is the result underlying these conservative assumptions.

The purchase price of the measuring device is not fixed yet. Presumably, the invest will be between 10,000 EUR and 13,000 EUR (Tab. 3, row 44). Assuming an eight-year-lifetime, the fixed costs will be between 2,997.50 EUR a^{-1} and 3,746.75 EUR a^{-1} (row 54). These costs include training courses regarding the radiological protection of the labour of 500 EUR a^{-1} (row 52). There are also variable costs of 42.72 EUR a^{-1} (row 58). The sum of cost ranges between 3,040.22 EUR a^{-1} and 3,789.47 EUR a^{-1}.

With a financial benefit of 42.71 EUR/cow/a between 71.2 and 88.7 milk cows are necessary for a profitable employment of the radiometric measuring device (Table 3, row 60), considering positive effects only. Due to uncertainties in calculation, an excess charge of 50% on highest value is recommended. Economic viability is given if the stock of dairy cattle is 135 or more.

In Germany, about 3,600 farms have a stock of between 100 and 200 dairy cows (Destatis, 2012). Approximately 1,530 farms keep more than 200 dairy cows. Thus, there are a sufficient number of potential users.

CONCLUSIONS

The radiometric measuring principle by using a cesium radiator is well suited to determine the density of ensiled material. By arranging source and detector in a trailed measuring wheel, the silage density can be measured online during movement. In conjunction with data from a Differential Global Positioning System (DGPS), the density values can be allocated to certain positions in the silo. By that, the driver is enabled to plan the next passes.

A conservative assumption of the costs of the measuring device and the benefit shows that approximately 135 milk cows are necessary to guarantee an economic employment of the measuring system presented here.

Table 3. Calculation of the costs and minimum number of cows

Row	Position	Unit	Variant 1	Variant 2	Variant 3
44	Purchase price	EUR	10,000.00	11,500.00	13,000.00
45	Residual value	EUR	500.00	575.00	650.00
46	Lifetime of device	a	8.00	8.00	8.00
47	Depreciation	EUR a^{-1}	1,187.50	1,365.63	1,543.75
48	Interest rate	%	4.00	4.00	4.00
49	Interest	EUR a^{-1}	210.00	241.50	273.00
50	Assurance	EUR a^{-1}	500.00	575.00	650.00
51	Housing	EUR a^{-1}	100.00	115.50	130.00
52	Education	EUR a^{-1}	500.00	500.00	500.00
53	Maintenance cost	EUR a^{-1}	500.00	575.00	650.00
54	**Sum of fixed costs**	**EUR a^{-1}**	2,997.50	3,372.63	3,746.75
55	Service	h	2.67	2.67	2.67
56	Cost of labor	EUR h^{-1}	15.00	15.00	15.00
57	Allocable labor costs	EUR a^{-1}	40.05	40.05	40.05
58	**Sum of variable costs**	**EUR a^{-1}**	42.72	42.72	42.72
59	**Sum of costs**	**EUR a^{-1}**	3,040.22	3,415.35	3,789.47
60	Minimum number of milk cows		71.2	80.0	88.7

REFERENCES

Badr, H.M. 2012. Improving the microbial safety of ice cream by gamma irradiation. *Food and Public Health* **2**(2), 40–49.

Böttcher, H. 1957. Futterkonservierung durch Silage. Deutscher Bauernverband, Berlin, 132 p.

Destatis. 2012. Land- und Forstwirtschaft, Fischerei. Statistisches Bundesamt, https://www.destatis.de/DE/Publikationen/Thematisch/LandForstwirtschaft/ViehbestandTierischeErzeugung/Viehhaltung2030213109004.pdf?__blob=publicationFile, access: 25.02.2014.

DLG. 2001. Ertragsermittlung im Mähdrescher – Ertragsmessgeräte für die lokale Ertrags-ermittlung. Ergänzte und überarbeitete Neuauflage. Ed.: Deutsche Landwirtschafts-Gesellschaft (DLG), DLG-Merkblatt 303. 19 p.

DOW. 2012. Bewertung der Trockenmasseverluste bei der Silageherstellung. Information material of Dow Chemical Company, http://www.dow.com/silage/, acsess 31.07.2012.

Dummer, C. 2010. Auswertung der Tierarztrechnungen. http://www.aelf-co.bayern.de/tierhaltung/29344/auswertung_mlp_11_11.pdf, access 18.02.2014.

Fürll, C., Schemel, H. & Köppen, D. 2008. Prinziplösungen für die Dichtemessung in Siliergütern. *Landtechnik* **63**(2), S. 94–95.

Gläser, M. & Kuhn, E. 1997. Forschungssonde für die Dichtemessung an landwirtschaftlichen Gütern. *Agrartechnische Forschung* **3**(1), 44–51.

Gläser, M. 1992. Grundlagenuntersuchungen zur radiometrischen Bestimmung der Masse geförderter Güter, insbesondere in der landwirtschaftlichen Forschung und Praxis. Forschungsberichte VDI Reihe 14, Düsseldorf, Germany, VDI-Verlag GmbH.

Gläser, M., Jahnke, W. Pütz, M & Mumme, M. 2007. Zerstörungsfreie radiometrische Bestimmung des Dichteverlaufs an Rund- und Quaderballen. *Landtechnik* **62**(3), 146–147.

Hell, K.W. 1966. Optimale Investitionen in der Silowirtschaft bei Grassilagen als Futtergrundlage in der Rinderhaltung. Arbeitsgemeinschaft landwirtschaftliches Bauen, ALB-Heft-Schriftenreihe 28, Frankfurt am Main.

Kempf, W., Friedrich, I., Hoepke, C.-H., Veldenkamp, J., Vierhuf, J. & Brandtmöller, W. 1976. Kontinuierliche Mengen- und Dichtemessung von Stärkesuspensionen. Die Stärke 28(2), 54–68.

Kressel, U. 2008. Erstellung eines Konzeptes für ein dynamisches Qualitätssicherungssystem für Milcherzeugerbetriebe im Kontrollbereich Stoffwechselgesundheit. Ph.D. thesis, Technical University München, München, 338 p.

Kuhn, E. 1976. Die Aussagefähigkeit radiometrischer Messungen zur Bestimmung der mittleren Gärfutterdichte in Horizontalsilos. *Agrartechnik* **26**(11), 532–533.

Köhler, B., Diepolder, M., Ostertag, J., Thurner, S. & Spiekers, H. 2012, Dry matter losses of grass and maize silages in bunker silos. In: Proceedings of the XVI International Silage Conference, 2-4 July 2012, Hämeenlinna, Finnland, Hrsg.: MTT Agrifood Research Finland und University of Helsinki 2012, 318–319.

LFL. 2006. Materialsammlung Futterwirtschaft. Bayerische Landesanstalt für Landwirtschaft (Ed.), Freising-Weihenstephan, 143 p. www.lfl.bayern.de/mam/cms07/publikationen/daten/informationen/p_22478.pdf, access 20.02.2014.

LKV. 2012. Jahresbericht 2012. Landeskontrollverband Brandenburg e.V., Waldsieversdorf, 76 p.

Macedo, A., Vaz, C. M. P., Pereira, J. C. D., Naime, J.M., Cruvinel, P.E. & Crestna, S. 2002. Wood density determination by X- and Gamma-ray Tomography. *Holzforschung* **56**(5), 535–540.

Malan, F.S. & Marais, P.G. 1992. Some Notes on the direct gamma ray densitometry of wood. *Holzforschung* **46**(2), 91–97.

Mumme, M. & Katzameyer, J. 2008. Mobiler Prüfstand zur radiometrischen Messung der Dichteverteilung in Ballen. *Landtechnik* **63**(6), 341–343.

Okumoto, Y. 1987. Device for controlling contents of tobacco on cigarette manufacturing machine. European Patent EP 0268124 A1.

Ruppel, K.A., Pitt, R.E., Chase, L.E. & Galton, D.M. 1995. Bunker silo management and its relationship to forage preservation on dairy farms. J. Dairy Sci. **78**, 141–153.

Sun, Y., Cheng, Q., Meng, F., Buescher, W., Maack, C. & Lin, J. 2012. Image-based comparison between a γ-ray scanner and a dual-sensor technique for visual assessment of bale density distribution. *Computer and Electronics in Agriculture* **82**, 1–7.

Taysen, J. 1993. Silagebereitung II. Sonderdruck aus der Kartei für Rationalisierung. Rationalisierungs-Kuratorium für Landwirtschaft (RKL), Rendsburg-Osterronfeld, 678–792.

Wattendorf-Moser, F. 2001: Betriebszweigauswertung. http://milchgeld.de/, access 20.02.2014.