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Exploring the economic viability and agronomic effects of green manure mixtures on winter wheat yields in organic farming in Latvia: a multi-location study

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Abstract. This study explores the adaptation of green manure practices to Latvia's climatic and soil conditions to enhance soil productivity and economic returns in organic farming systems. The study aims to identify the most suitable green manure mixture by evaluating economic factors, dry matter yield, nutrient amount, and its impact on winter wheat yields in organic fields across different locations in Latvia, considering variations in meteorological conditions. Field trials compared three mixtures: oats-mustard-oilseed rape–buckwheat (non-legume), oats-buckwheat-peas (legumes < 50%), and oats-lupin-vetch (legumes > 50%) against a control (black fallow). Data were collected on dry matter production, nutrient accumulation (N, P, K amount), winter wheat yields, and economic performance. The results revealed a significant variation in dry matter yield depending on year and location. Mixture with non-legumes at the farms 'Gaikeni' and 'Geidas', as well as mixture with legumes below 50% at 'Gaikeni', Ltd. 'Mazbungas', and 'IRGK serviss', produced significantly higher dry matter yields ($P < 0.05$). Despite lower biomass yield in certain years, mixture with legumes above 50%, through the follow-up effect, significantly increased winter wheat yields under optimal conditions at Ltd. 'Mazbungas' and farm 'Gaikeni' being higher by 96.05% and 93.59%, respectively, compared to the control. Economic analysis revealed significant gross margin advantages for green manure cultivation, demonstrating its financial viability. This study underscores the potential of green manure practices in enhancing the sustainability of organic farming, improving yields, and increasing profitability, while highlighting the importance of selecting region-specific mixtures to account for climatic variability.

Key words: legume and non-legume mixtures, yield potential, nutrient amount, gross margin.

INTRODUCTION

Stockless farming systems often struggle with limited rotation options and increasing the risk of soil nutrient depletion. Green manure crops offer a valuable rotational break, helping to reduce soil fatigue and sustain productivity in long-term organic farming systems (Bedoussac et al., 2015; Baddeley et al., 2017). As livestock farming declines, stockless organic cropping systems are gaining traction in many intensive agricultural regions across Europe, highlighting the growing need for sustainable farming solutions (Toleikiene et al., 2024). The importance of green manure practices in organic farming is becoming increasingly relevant as many countries in recent years have begun exploring ways to reduce soil nutrient loss during the plant-free period (Talgre, 2013; Wang et al., 2021; Toleikiene et al., 2024; Zhao et al., 2024). In recent decades, the expansion of organic farming in Latvia has highlighted a growing interest in sustainable agricultural practices. Non-legume and legume-based cover crop mixtures have emerged as a promising strategy to enhance ecosystem services within cropping systems, utilizing agroecological principles to maximize these benefits (Daryanto et al., 2018; Couëdel et al., 2019; Auzins et al., 2023). The green manure market is projected to grow to €2.86 billion by 2028 at an annual growth rate of 7.1%, driven by climate change adaptation, regenerative agriculture, and increasing demand for sustainability. Key trends include the integration of leguminous and cruciferous cover crops, the adoption of no-till farming, and innovations in cover cropping (Tsytsiura, 2024).

Latvia is characterised by regionally variable climatic conditions and diverse soil-related nutritional challenges, making organic farming particularly demanding. Frequent fluctuations between periods of rainfall and moisture deficiency create challenges in maintaining soil moisture. Green manure crops significantly improve soil structure, enhance its water retention capacity, and reduce soil desiccation (Daryanto et al., 2018; Melander et al., 2020; Hu et al., 2023), which is especially important during dry summer periods. Additionally, they promote microbial activity, which is crucial for organic matter decomposition and soil fertility maintenance (Talgre et al., 2010; Couëdel et al., 2019; Hu et al., 2023). In Latvian regions with sloping terrain or frequent rainfall, green manure helps mitigate nutrient runoff and soil erosion by providing vegetative cover during non-cropping periods. This also contributes to enhancing the yield of main crops, ultimately increasing economic returns for farmers.

Selecting an appropriate crop rotation scheme that incorporates green manure can be particularly challenging, as it requires managing trade-offs between crop yields and yield stability, all while ensuring the maintenance of profitability and long-term sustainability. Studies have demonstrated that integrating green manure into crop rotations can improve wheat yields by enhancing soil conditions (Nawaz et al., 2017; Zhao et al., 2024). Despite the long-term benefits, the adoption of green manure crops by farmers remains limited due to the additional costs and labour requirements. Green manure practices offer substantial advantages, such as enhancing soil fertility, increasing yields, and promoting sustainable agricultural methods (Nawaz et al., 2017; Ma et al., 2021). However, the implementation of green manure practices presents considerable financial and operational challenges. Additionally, the land allocated for green manure cultivation may lead to temporary reductions in cash crop yields, which can negatively impact overall farm profitability. Furthermore, the rising costs of agrotechnical operations, fuel, and labour have become significant factors driving up agricultural product prices, which, in turn, affect farmers' incomes (Chen, 2020). These combined challenges highlight the need for careful consideration of the economic feasibility of adopting green manure practices. Moreover, the effectiveness of green manure crops in terms of productivity, crop nutrition, and weed control can vary depending on factors such as crop species, soil type, climate, and the complexity of the cropping system (Wittwer et al., 2017; Wang et al., 2021; Zhao et al., 2022).

This variability highlights the need for more specific experimental studies to determine the precise effects of green manure cropping across different agricultural contexts. Therefore, field trials with the most suitable green manure mixtures were established on larger plots in various regions of Latvia on organic farming systems. Previous data and experience from other studies conducted in Latvia were also utilised (Auzins et al., 2023). The study aims to identify the most suitable green manure mixture by evaluating economic factors, dry matter yield, nutrient amount, and its impact on winter wheat yields in organic fields across different locations in Latvia, considering variations in meteorological conditions. This complex scenario necessitates more long-term and region-specific experimental research to better understanding of the trade-offs and benefits of green manure in diverse agricultural systems.

MATERIALS AND METHODS

Field trials of green manure mixtures were established in four organic farming enterprises: farms 'Gaikeni' (Ga), 'Geidas' (Ge), Ltds. 'Mazbungas' (M) and 'IRGK Serviss' (I), located in different regions of Latvia – Vidzeme, Kurzeme, Zemgale, and Latgale, respectively (Table 1). The trials were conducted from 2022 to 2024, with plot sizes of 0.3 ha. The study evaluated three green manure mixtures against a control (black fallow). The first mixture consisted of oats (*Avena sativa*) (50%), mustard (*Sinapis alba*) (20%), oilseed radish (*Raphanus sativus* ssp. *oleiferus*) (10%), and buckwheat (*Fagopyrum esculentum*) (20%) (non-legume). The second mixture included oats (50%), buckwheat (30%), and peas (*Pisum sativum*) (20%) (legumes below 50%). The third mixture comprised oats (45%), lupin (*Lupinus angustifolius*) (20%), and vetch (*Vicia sativa*) (35%) (legumes above 50%).

Table 1. Data on green manure and winter wheat growing practices and soil properties for farm or Ltd., 2022–2024

Farm/Ltd.	Year	Sowing date of green manure	Soil incorporation date of green manure	Sowing date winter wheat	Harvesting date of winter wheat	The granulometric composition of the soil
Ga	2022	09.06.	25.07.	24.09.2022	13.08.2023	Sandy loam
	2023	01.07.	11.09.	22.09.2023	12.08.2024	Sandy loam
	2024	16.06.	03.08.	-	-	Sandy loam
Ge	2022	19.05	19.07.	09.09.2022	05.08.2023	Sandy loam
	2023	14.06.	19.07.	11.09.2023	12.08.2024	Loamy sand
	2024	04.06.	01.08.	-	-	Loamy sand
M	2022	27.05.	20.07.	26.09.2022	17.08.2023	Loamy sand
	2023	06.06.	26.07.	27.10.2023	07.08.2024	Sandy loam
	2024	11.06.	14.08.	-	-	Sandy loam
I	2022	20.05.	22.07.	14.09.2022	08.08.2023	Loamy sand
	2023	23.05.	23.08.	18.10.2023	12.08.2024	Loamy sand
	2024	27.05.	14.07.	-	-	Loamy sand

Sowing was carried out on an unfertilized background. Soil characteristics, including soil type, organic matter amount, pH, etc., were recorded (Tables 1, 2). The green biomass yield of green manure mixtures at the time of soil incorporation was determined (t ha⁻¹) (Table 1). Aboveground and belowground plant biomass was measured at the full flowering stage (BBCH 64-67) in four randomised plots of 0.125 m². In each plot, shoots were cut, and roots were excavated to a depth of 20 cm in the topsoil. The shoots were subsequently weighed, and the roots were washed, air-dried, and then weighed using a laboratory scale with a precision of 0.01 g. Both shoots and roots were air-dried to completion before being weighed using the laboratory scale.

All laboratory chemical analyses were conducted in quadruplicate, with the determination of the basic biochemical components expressed on an absolutely dry weight basis (Undersander et al., 1993). Dry matter content was measured by drying the samples in an oven at 105 °C, followed by ashing at 550 °C. The dried samples were subsequently re-weighed and ground using an electrostatic laboratory mill. Nitrogen amount in shoots and roots was determined in accordance with LVS EN ISO 20483:2014, while phosphorus and potassium amount were determined using the methods specified in ISO 6491:1998 and LVS EN ISO 6869:2002, respectively.

Table 2. Basic soil characteristics in locations, 2022–2024

Farm /Ltd.	Year	pH_{KCl}	Organic matter, %	N_{tot}, mg g^{-1}	P, mg kg^{-1}	K, mg kg^{-1}
M	2022	5.75	1.29	1.34	105.35	65.12
	2023	6.57	1.76	1.16	57.64	77.50
	2024	5.66	2.33	1.37	121.25	190.90
Ge	2022	6.70	2.36	1.53	5.19	82.67
	2023	7.08	2.57	2.57	4.48	73.73
	2024	6.93	2.62	2.40	18.31	127.99
I	2022	5.48	1.56	1.40	19.20	101.26
	2023	6.13	1.97	1.97	4.70	114.65
	2024	5.31	1.62	0.88	14.76	87.57
Ga	2022	5.63	3.97	1.67	108.69	142.25
	2023	6.28	3.36	3.36	99.60	139.23
	2024	5.75	4.46	2.41	189.09	180.94

Green manure mixtures were incorporated into the soil from late July to August to allow adequate time for decomposition and nutrient release before cash crop sowing in September. In the crop rotation following green manure, the subsequent cash crop was winter wheat (*Triticum aestivum*), where grain yield being assessed. The evaluation focused on the impact of the specie, not on the specific variety. Data were collected on activities performed on individual fields for each green manure variant.

For the study, economic indicators were evaluated as gross margin (1), which corresponds to revenue minus variable costs. The following equations were used for the calculation of the economic results:

$$Gross\ margin = gross\ income - variable\ costs \quad (1)$$

Gross margin was expressed in EUR per hectare (EUR ha⁻¹). The average annual gross margin for the two-year period (2022–2023 and 2023–2024), including wheat yields for each farm, is presented.

The agricultural practices employed by each farm or company were distinct, with each utilising its own specific equipment, including specialised agricultural machinery. The assessment of the economic indicators for the farms was based on the agrotechnical operations collected throughout the study (Fig. 1). Annual costs for each farm were calculated by summing the variable costs associated with agrotechnical operations (ploughing, harrowing, disking, cultivating, combined soil preparation, sowing combined with or without soil tillage of green manure mixtures and winter wheat, green mass shredding, harvesting, and transportation of the harvested yield from the field) as well as raw materials. Constant prices were used in the study to eliminate the impact of market fluctuations and the individual organizational characteristics of each farm.

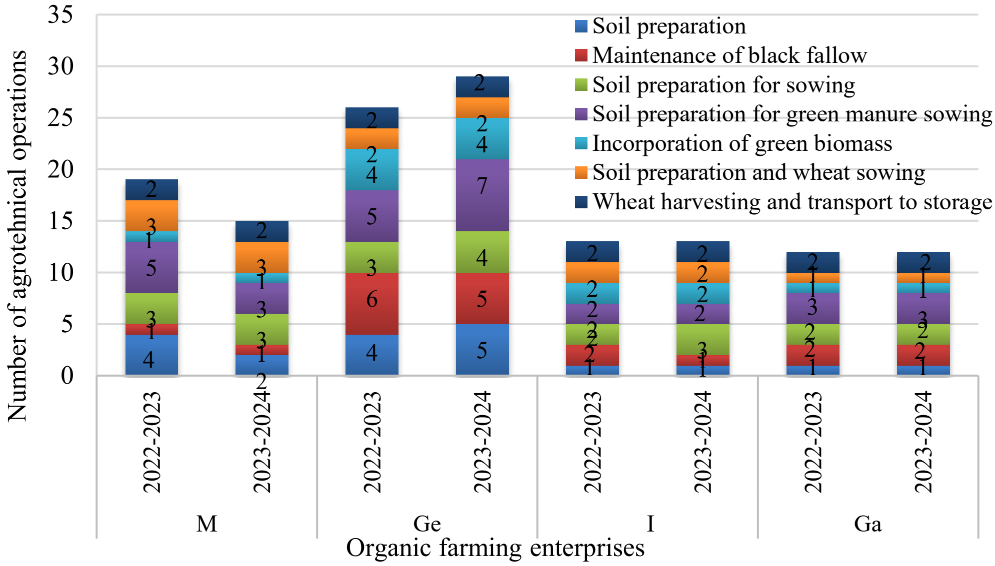

Figure 1. Field operations at Farms or Ltd. for the 2022–2023 and 2023–2024 growing cycles.

The seeding rate and price for winter wheat and green mass were identical across all farms. The price of organic winter wheat seeds was 0.4 EUR kg^{-1}, while the selling price was 230.0 EUR t^{-1}. The wheat prices were determined based on calculations by the Latvian Rural Advisory and Training Centre. The prices of green manure mixture seeds ranged from 0.8 to 1.4 EUR kg^{-1} (Table 3).

Table 3. Seeding rate and seed price for field trials

	Seeding rate, kg ha^{-1}	Price, EUR kg^{-1}	Cost, EUR ha^{-1}
L.0%	64	1.4	89.6
L.< 50%	104	0.8	86.3
L.> 50%	80	1.3	105.6
Winter wheat	230	0.4	92.0

Meteorological data were obtained from the nearest meteorological station of the Latvian Environment, Geology, and Meteorology Centre, which represented the regional conditions of the demonstration sites. The De Martonne Aridity Index (IDM) (Moral et al., 2016) was employed to characterise the arid/humid conditions of the territory over a month, according to Eq. (2):

$$I_{DM} = \frac{12P_m}{T_m + 10} \quad (2)$$

where P_m and T_m are the precipitation volume and mean air temperature in corresponding month, respectively.

According to the I_{DM} values calculated using the equation above, the climate of a region can be classified (type of climate according to the De Martonne aridity index (I_{DM}, adapted after Baltas, 2007) Arid $I_{DM} < 10$; Semi-Arid $10 \leq I_{DM} < 20$; Mediterranean $20 \leq I_{DM} < 24$; Semi-humid $24 \leq I_{DM} < 28$; Humid $28 \leq I_{DM} < 35$; Very Humid $35 \leq I_{DM} \leq 55$; Extremely humid $I_{DM} > 55$.

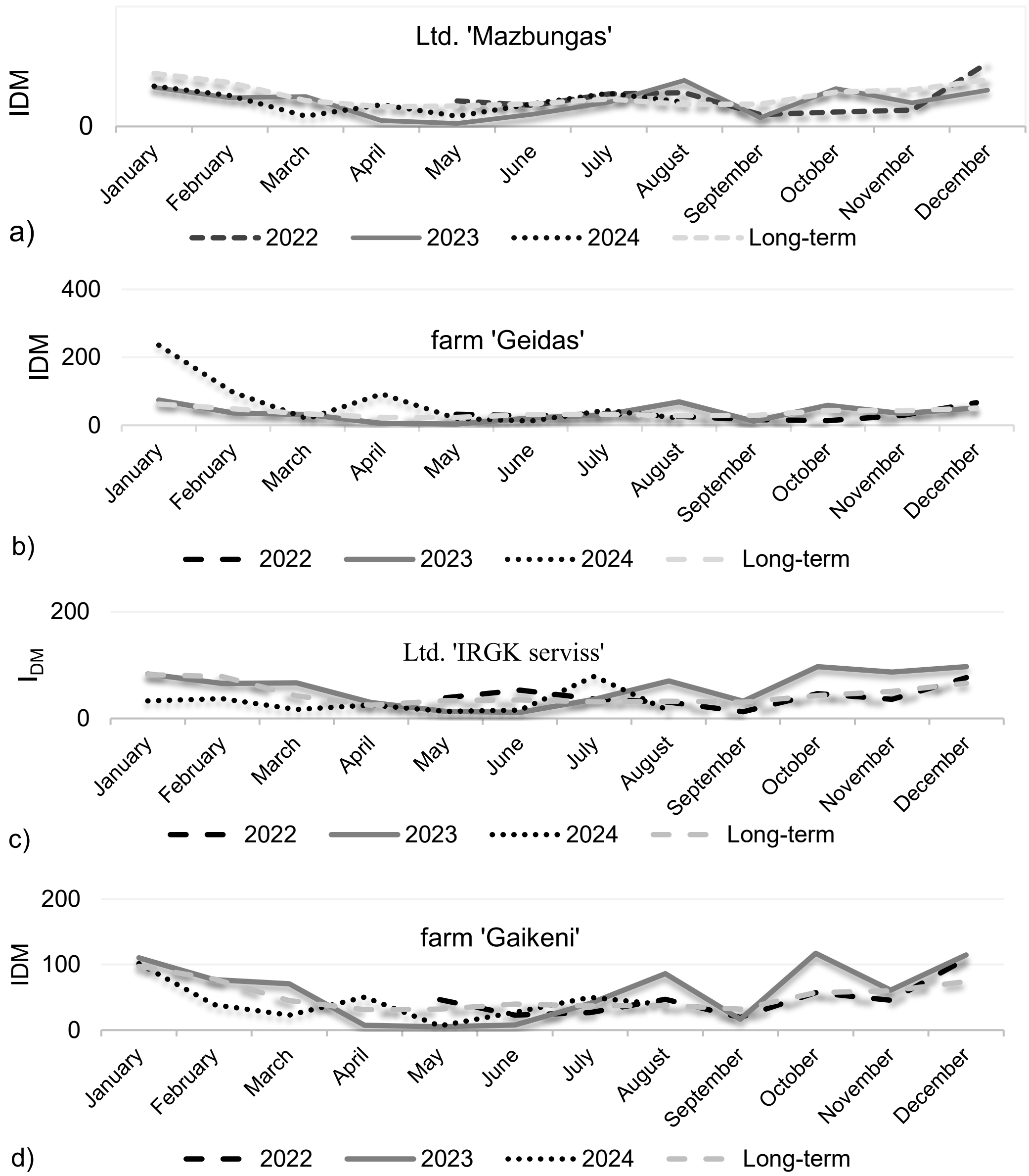

Figure 2. The values of the De Martonne Aridity Index (I_{DM}) for the vegetation periods of the green manure mixtures and winter wheat at the farm or Ltd. locations (a, b, c, d), 2022–2024.

A generalised assessment of the hydrothermal regimes during the vegetation periods of green manure and winter wheat across the research years is presented in Fig. 2. The De Martonne Aridity Index indicated that, under Latvian climatic conditions, May and June represent a critical period for green manure sowing, as these months are characterised by drier conditions across various locations, which may not always be conducive to successful seed establishment. Moreover, July and August are characterised by rapid fluctuations between dry and rainy conditions, which can have both positive and negative effects on green biomass yield.

Dry matter, and nutrient amount data were statistically analysed using Microsoft Excel. Analysis of variance (ANOVA) was employed to assess the significance of differences, with calculations performed at a significance level of $P < 0.05$.

RESULTS AND DISCUSSION

Shoot and root dry matter yield and nutrient amount of green manure mixtures. Field trial results conducted across various locations in Latvia revealed significant variations in green manure yield potential, both across different years and fields, as well as among farms or agricultural enterprises (Ltd.). An analysis of meteorological conditions, in comparison with regional data, highlighted notable differences between locations (Fig. 2). The findings demonstrated that humidity levels play a pivotal role in influencing variations in green manure mixture yield that are specific to particular locations. Teixeira et al. (2016) also emphasised that ensuring optimal cover crop emergence is a significant challenge in regions characterised by hot, dry summers. The optimal vegetation period for the green manure mixture, along with a significantly higher dry matter yield ($P < 0.05$), was observed at Ltd. 'Mazbungas' (M) and farm 'Geidas' (Ge) in 2022, as well as at Ltd. 'IRGK Serviss' (I) and farm 'Gaikeni' (Ga) in 2024. The yield potential of green manure is influenced by multiple interacting factors, including climatic conditions, soil properties, and species composition.

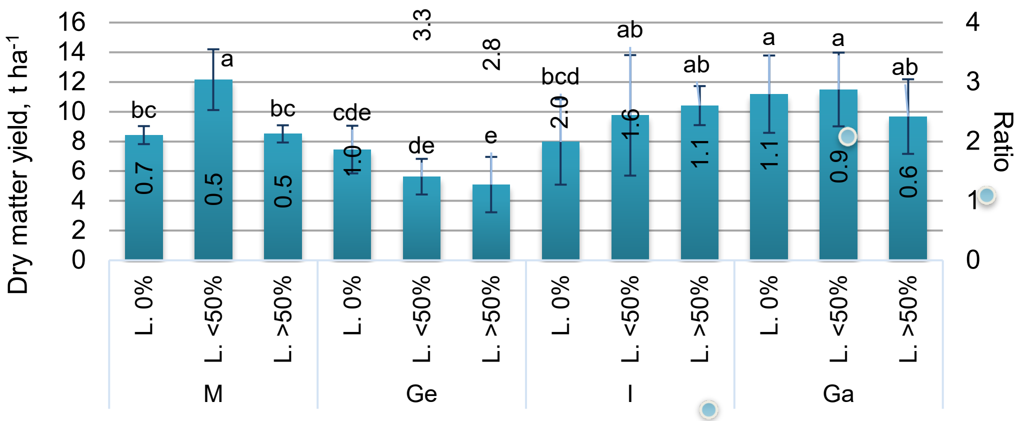

Figure 3. Combined dry matter yield and shoot-to-root ratio of green manure mixtures across different years and locations, 2022–2024.

[abcde] – Different letters indicate significant differences in dry matter yield across locations and years ($P < 0.05$), $LSD_{0.05}$=2.7

The three-year comparison identified that the mixture with legumes below 50% was the most suitable for Ltd. M, achieving a significantly higher dry matter yield (Table 3). The significant dry matter yield at farm Ge depended on the year and whether the mixture with non-legume mixture. The most suitable mixture, either with legumes below 50% or non-legume, for achieving the highest dry matter yield was identified at farm Ga. All mixtures at Ltd. I demonstrate variable yield performance, depending on the year climatic conditions and the adaptability of the mixture more suitable with legumes below and above 50%. At the farm Ge, shoot-to-root ratio comparisons showed that mixtures containing legumes developed a more extensive root system than non-legume mixtures, likely due to improved root-soil interactions, contributing to enhanced soil structure and fertility. The results indicated that, from a practical point of view across all locations, mixture with legumes above 50% was more sensitive to dry periods and required higher humidity for successful biomass development due to the larger seed size of legumes. These findings underscore the importance of selecting an appropriate species composition to optimise productivity and enhance adaptability to local environmental conditions. According to Tribouillois et al. (2016), a laboratory study revealed that the germination of legumes was more sensitive to high temperatures compared to crucifers.

The results indicated that the nitrogen (N) amount, expressed as a percentage, tended to be higher in mixture with legumes above 50% at most locations. However, these findings were not unequivocal, as other mixtures also exhibited elevated nitrogen levels depending on the year and location. Evaluating the total nitrogen amount in the green manure mixture, it does not correlate with higher yield (Fig. 4).

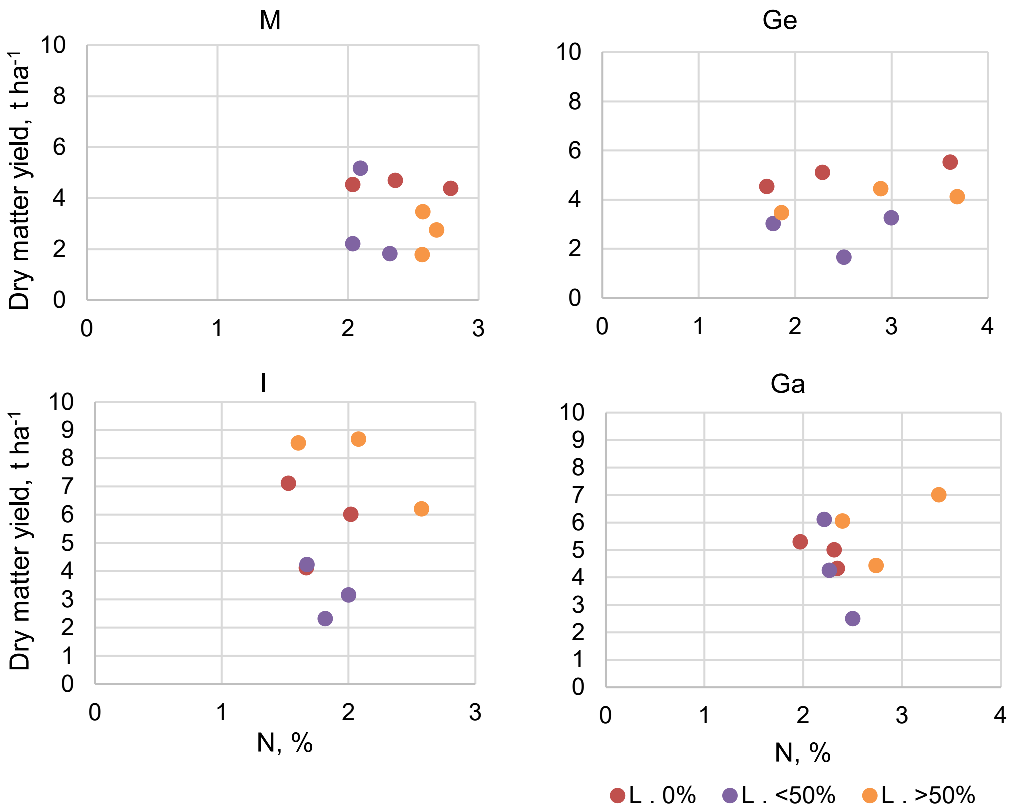

Figure 4. The aboveground nitrogen and dry matter yield of green manure mix in different years and locations, 2022–2024.

Furthermore, the proportion of nitrogen remaining plant-available for the subsequent crop remains uncertain, given that some nitrogen may be lost during residue decomposition. There is a notable lack of research addressing the timing of nitrogen release and its synchronisation with crop uptake, highlighting the need for further investigation.

The nitrogen (N) amount in plant dry matter yield ranged significantly ($P < 0.05$) among the tested green manure mixtures across different years and locations. The average total shoots and roots N amount ranged from 141.2 to 190.1 kg N ha^{-1} for non-legume mixture, 114.8 to 173.9 kg N ha^{-1} for mixture with legumes below 50%, and 112.8 to 205.1 kg N ha^{-1} for mixture with legumes above 50% (Fig. 4). These variations highlight the influence of species composition on nitrogen fixation and uptake efficiency. The average nitrogen amount was not significantly higher in mixtures with legumes above 50%, suggesting that non–legume mixtures can also improve soil nitrogen levels, possibly through mechanisms like nutrient cycling or microbial activity. The higher average nitrogen amount at farm Ga for all green manure mixtures suggests that local factors, such as soil characteristics with higher organic and nitrogen level, climate, and farm-specific cultivation techniques, may have contributed to enhanced nitrogen assimilation in the plants. This highlights the need for site-specific management in selecting green manure mixtures, as species suitability varies by environment, affecting nutrient cycling and soil fertility.

The two-year results potassium (K) and phosphorus (P) amount in plant biomass demonstrated significant difference ($P < 0.05$) across both years and locations for the examined green manure mixtures. The average total shoots and roots K accumulation ranged from 171.5 to 299.9 kg K ha^{-1} for non-legume mixtures, 174.5 to 278.8 kg K ha^{-1} for mixtures with legumes below 50%, and 138.0 to 192.2 kg K ha^{-1} for mixtures with legumes above 50%. The average total shoots and roots phosphorus content ranged from 22.4 to 60.8 kg P ha^{-1} for non–legume mixtures, 14.7 to 58.8 kg P ha^{-1} for mixtures with legumes below 50%, and 16.4 to 53.1 kg P ha^{-1} for mixtures with legumes above 50% (Fig. 5). The range in average K and P amount in green manure shoots and roots across different locations suggests that both environmental conditions and species composition play a significant role in element uptake. Green manure mixtures of non-legumes or with legumes below 50% showed significantly higher K and P accumulation in most cases. This indicates that diverse or balanced species mixtures may be more efficient in K and P uptake under certain conditions. These data indicate that the potential of green manure varies between mixtures. However, field trials are ongoing, and results from the 2023–2024 growing cycle do not yet show any interactions leading to increased winter wheat yield.

The variability in nutrient uptake across locations highlights the significance of location-specific factors, such as soil nitrogen, potassium and phosphorus availability and climate, in determining the effectiveness of green manure mixtures. According Zhao et al. (2024), who demonstrated that different green manure types exhibit varying nutrient effects. Muhammad et al. (2022) noted that bioavailable phosphorus is often the most deficient soil nutrient, while nitrogen and potassium are also essential. Soil fertility is dynamic, relying on nutrient cycling, where microbial decomposition mineralises plant material, releasing nutrients into the soil.

Ha et al. (2008) found that 40–60% of P in crop residues is water-soluble and rapidly released into the soil. Green manure crops, both pure and undersown, could fix up to 153 kg of K and 20 kg of P per hectare, depending on biomass size. Their study emphasized that sustainable management of organic farms is possible through proper manure management, effective use of legumes, and strategic input of phosphorus and potassium. According to study by Talgre et al. (2012), in the tested common green manure legumes sown as pure crops, 114–196 kg of N, 17–24 kg of P, and 89–144 kg of K per hectare were returned to the soil each year.

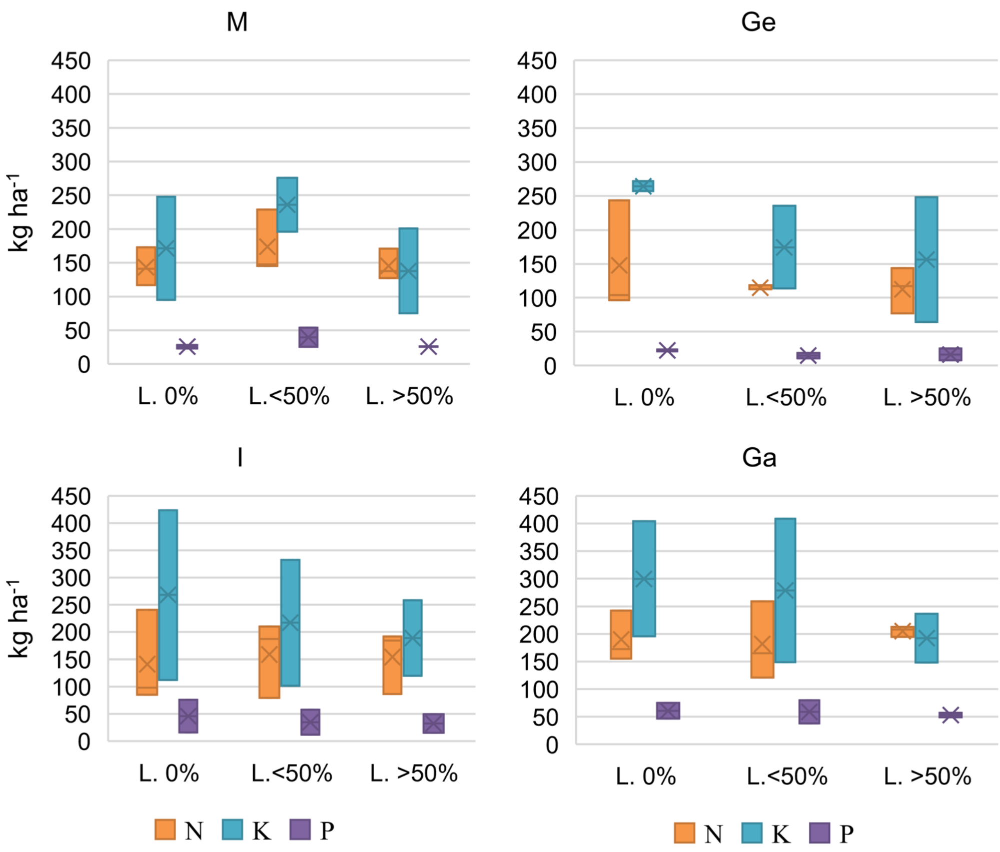

Figure 5. Range of nutrient amount in the total shoot and root dry matter of green manure mixtures across different locations, N kg ha^{-1} 2022–2024 and P, K kg ha^{-1} 2023–2024.

The findings underscore the necessity of tailoring green manure selections to local environmental conditions, as specific species or mixtures may demonstrate enhanced effectiveness in different soil types, thereby optimising nutrient management. Given that the benefits of green manure on crop yields accrue gradually, sustained long-term monitoring is essential to comprehensively assess its enduring impact on soil health and fertility.

Winter wheat grain yield following green manure mixtures was evaluated under varying climatic conditions. Ltd. M and farm Ge experienced lower humidity, whereas Ltd. and farm Ga had higher humidity, with more intense rainfall and pronounced dry periods during the both vegetation periods.

The results suggest that while green manure yield and nutrient amount do not directly correlate with an increase in grain yield, certain green manure mixtures, particularly those with legume above 50%, can positively influence subsequent crop yields most locations under specific conditions. The highest increase in wheat yield compared to the control was observed at Ltd. M in 2024 and at Farm Ga in 2023, with respective increases of 96% and 94% (Fig. 6). Compared to the mixture effect, the impact of fallow on nitrogen availability is more dependent on the management system. In this study, black fallow was periodically kept free from weeds and volunteers by disc cultivation. While such soil disturbance can enhance nitrogen mineralisation, the released nitrogen was likely lost through leaching or volatilisation before the subsequent wheat crop was established, limiting its agronomic benefit.

Winter wheat productivity and economic return on farms

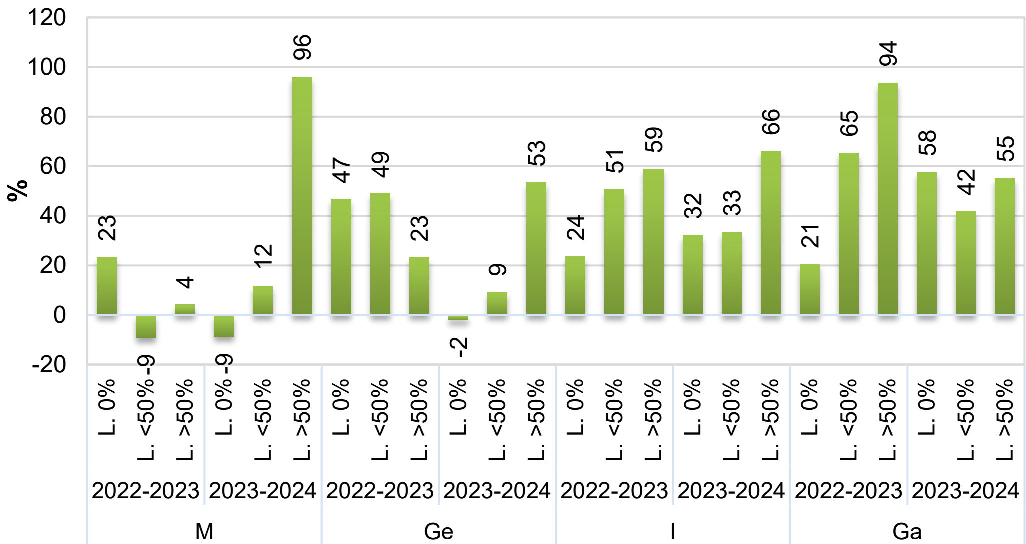

Figure 6. Grain yield increase of winter wheat compared to control across years and locations in the 2022–2023 and 2023–2024 growing cycles.

This highlights the importance of location-specific factors in green manure effectiveness, with significant differences observed between years and location. It emphasises the need to select the most suitable mixture for each year and location to optimise wheat yield. De Notaris et al. (2019) suggests that a well-established legume-based green manure can help stabilise crop yield over time. According to Zhao et al. (2024), a six-year study on green manure incorporation in a diversified crop rotation system found varying soil nutrient responses and cumulative enrichment effects, with significant differences emerging in later years. Crop yields showed inconsistent responses, highlighting the complexity of green manure's agronomic impact.

In 2022–2023, Ltd. I exhibited the highest gross margin, ranging from 81 to 114 EUR ha⁻¹, while Farm Ga recorded the lowest, with values ranging from - 175 to - 309 EUR ha⁻¹. In 2023–2024, several farms experienced improvements in gross margins, particularly Ltd. M, which achieved the highest average gross margin, ranging from 30 to 374 EUR ha⁻¹ (Table 4).

Table 4. Grain yield and gross margin in farms field trials for the 2022–2023 and 2023–2024 growing cycles

Farm/ Ltd. and years		*C, GMM	*GI:		*VC			Gross margin, EUR ha^{-1}
			*GY, t ha^{-1}	GI, EUR ha^{-1}	Seed cost, EUR ha^{-1}	*MO, EUR ha^{-1}	Total VC, EUR ha^{-1}	
M	2022–2023	C	2.15	495	92	356	448	**47**
		L.0%	2.65	610	182	403	585	**25**
		L.< 50%	1.95	449	178	387	565	-117
		L.>5 0%	2.24	515	198	393	590	-76
	2023–2024	C	2.18	501	92	308	400	**101**
		L.0%	1.99	458	182	341	523	-65
		L.< 50%	2.43	559	178	351	529	**30**
		L.> 50%	4.27	982	198	410	608	**374**
Ge	2022–2023	C	2.29	527	92	506	598	-71
		L.0%	3.36	773	182	503	685	**88**
		L.< 50%	3.41	784	178	505	683	**101**
		L.> 50%	2.82	649	198	487	684	-36
	2023–2024	C	2.19	503	92	532	624	-120
		L.0%	2.15	495	182	531	712	-218
		L.< 50%	2.40	552	178	536	714	-162
		L.> 50%	3.36	773	198	563	760	**12**
I	2022–2023	C	1.70	391	92	218	310	**81**
		L.0%	2.10	483	182	307	488	-5
		L.< 50%	2.56	589	178	310	487	**101**
		L.> 50%	2.70	621	198	310	507	**114**
	2023–2024	C	1.51	347	92	254	346	**1**
		L.0%	1.99	458	182	293	475	-17
		L.< 50%	2.01	462	178	293	471	-9
		L.> 50%	2.50	575	198	296	493	**82**
Ga	2022–2023	C	0.78	179	92	306	398	-219
		L.0%	0.94	216	182	344	526	-309
		L.< 50%	1.29	297	178	322	500	-204
		L.>5 0%	1.51	347	198	325	523	-175
	2023–2024	C	1.58	363	92	298	390	-27
		L.0%	2.49	573	182	357	539	**34**
		L.<5 0%	2.24	515	178	327	505	**10**
		L.> 50%	2.45	564	198	331	529	**35**

* C – black fallow; GI – Gross income; GMM – green manure mixtures; GY – grain yield; MO – machinery operations; VC – variable costs.

Farm Ga consistently showed the lowest gross margins across both years, with all trials of green manure mixtures resulting in negative values. This suggests challenging growing conditions and low grain yield at this location.

Farm Ge demonstrated high variability between years. In 2022–2023, it achieved positive gross margins with two green manure mixtures, but in 2023–2024, three trials resulted in losses.

Ltd. M showed the most significant improvement from 2022–2023 to 2023–2024 growing cycles. The mixture with legumes above 50% trial in 2023–2024 yielded the highest gross margin (374 EUR ha^{-1}) among all farms and trials over the two growing cycles. Ltd. I maintained relatively stable gross margins across both growing cycles, with most trials of green manure mixtures yielding positive results.

The green manure mixtures trials showed variable effects across farms and years. In some cases, such as Ltd. M in 2023–2024, the mixture with legumes above 50% trial significantly outperformed the control (black fallow). However, in other instances, green manure mixtures resulted in lower gross margins compared to the control.

The variability in gross margins observed in this study aligns with findings from other research on winter wheat production. For instance, a study by Devkota & Yigezu (2020) reported significant fluctuations in winter wheat gross margins due to yearly weather variations and soil conditions.

The positive impact of green manure mixtures, particularly at mixtures with legumes above 50%, on gross margins in some cases is consistent with research by Ma et al. (2021), who found that green manure can enhance soil fertility and crop yields in certain conditions.

However, the inconsistent results across farms and years suggest that the effectiveness of green manure mixtures may be highly dependent on local factors. The poor performance of Farm Ga across both growing cycles indicates potential site-specific challenges: soil composition, weather conditions, equipment. Similar location-specific variations in winter wheat profitability were noted by Eltazarov et al. (2023) in a multi-site study across diverse agroecological zones. The substantial improvement in Farm M's gross margins in 2023–2024, especially with legumes above 50% mixture, warrants further evaluation. It may be attributed to favourable weather conditions, improved management practices, or a positive interaction between the green manure mixtures and local soil conditions. Kaš et al. (2019) reported comparable year-to-year variations in their long-term study of winter wheat production systems.

CONCLUSIONS

This study highlights the importance of location-specific cropping systems in optimising the potential of green manure within low-input organic growing system. The observed year- and site-specific variations in biomass yield emphasise the necessity of tailored green manure mixtures to enhance nutrient cycling and crop productivity. Mixture with non-legumes at the farms 'Gaikeni' and 'Geidas', as well as mixture with legumes below 50% at 'Gaikeni', Ltd. 'Mazbungas', and 'IRGK serviss', produced significantly higher dry matter yields ($P < 0.05$). Additionally, the results identified a tendency for the highest N in mixture legume above 50% and P, K amount in non-legume mixture or legume below 50%. Despite lower biomass yield in certain years, mixture with legumes above 50%, through the follow-up effect, significantly increased winter wheat yields under optimal conditions at Ltd. 'Mazbungas' and farm 'Gaikeni' being higher by 96.05% and 93.59%, respectively, compared to the control. However, these findings underscore the necessity for long-term research to refine green manure strategies, with the goal of improving soil fertility and nutrient availability for more stable wheat production.

These two growing cycles study reveals significant differences in gross margins across farms. These were influenced by various soil cultivation technologies, their frequency of use, agroclimatic conditions, and the impact of green manure mixtures on winter wheat yields. While some farms and treatments showed promising results, the inconsistency highlights the complex nature of agricultural systems. Further research is needed to understand the factors driving these variations and to develop more reliable recommendations for green manure mixtures use in winter wheat production.

In conclusion, continued policy support and targeted management practices are essential to ensure the long-term viability of organic farming, including winter wheat production, under current conditions at Latvia.

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