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Evaluation of Environmental and Economic Performance of Crop Production in Relation to Crop Rotation, Catch Crops, and Tillage

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Abstract: Crop production constitutes a significant portion of the EU's agricultural output and influences land use decisions. Various elements within the crop production system can significantly impact its outcomes. This paper aims to evaluate the environmental and economic performance of crop rotation, catch crops, and different tillage practices in Latvia by analyzing data from case studies, field trials, and field monitoring to identify the potential for improvement towards a more sustainable utilization of agricultural land. Environmental performance was evaluated by focusing on nitrogen use efficiency (NUE), as it is likely to play a significant role in assessing the environmental suitability of crop production according to the Platform on Sustainable Finance. For economic performance, gross margins were calculated. Crop rotation in Latvia tends to be monotonous, with wheat and oilseed rape dominating over 60% of the cultivated area due to their profitability. The findings of this study indicate that achieving a minimum NUE of 70% is challenging. Crop rotations including oilseed rape, particularly the common wheat–oilseed rape rotation, have an average NUE below the threshold, while proper use of catch crops may increase NUE by 7–9%. The three-year field trials on commercial farms yielded divergent findings about the impact of various tillage practices on NUE and gross margin. However, the field trials conducted on the farm practicing reduced tillage for over ten years show higher NUE compared to ploughing. The advantage of reduced tillage was supported by the obtained results indicating lower costs of agrotechnical operations, including less diesel consumption.

Keywords: crop rotation; catch crops; tillage; nitrogen use efficiency; gross margin; Latvia

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1. Introduction

In an era marked by global challenges related to climate change, resource scarcity, and food security concerns, sustainable agricultural practices have garnered increased attention [1,2], and the interplay between environmental sustainability and economic viability has come into focus in the field of agricultural research [3–6]. To tackle these global challenges, European Union (EU) Member States including Latvia are looking for new solutions to increase the sustainability of food systems, starting with agriculture as a bioresource provider. Ambitious policy initiatives with the aim of sustainability in the agrifood sector are revealed in the European Green Deal strategies: e.g., the From Farm to Fork strategy, the EU Biodiversity Strategy for 2030, the EU Taxonomy for sustainable activities, etc. [7]. The Farm to Fork strategy stipulates a fair, healthy, and environmentally friendly food system while ensuring farmers' livelihoods [8,9]. The strategy aims to ensure that the food chain has a neutral or positive environmental impact; everyone has access to sufficient, nutritious, and sustainable food; and the affordability of food is preserved while generating fairer economic returns in the supply chain [10]. The new paradigm imposes strict requirements for agricultural production. To secure a social license to farm, the role of agricultural producers in the transition to sustainable food systems is no longer only to produce and secure nutritious and high-value raw materials for processing, they also cannot harm the environment and have to consider social impacts. Furthermore, the EU Taxonomy for sustainable activities ("green taxonomy"), as a classification system, is aimed at making finance flows (investment, credits, etc.) consistent with a pathway towards low greenhouse gas (GHG) emissions and climate-resilient development [11]. Therefore, alignment with the Taxonomy will not only reflect the sustainability of farmers but also affect their access to finance (especially bank credit) and, likely, to public support in the future.

Crop production accounts for a significant share (60%) of the agricultural goods output within the EU, corresponding to 66% in Latvia (data from 2021 [12]). It is important to note that crop production systems play a vital role in decisions concerning the utilization of agricultural land. The combination of various elements such as crop rotation, catch crops, and different tillage practices within crop production systems can significantly influence both environmental and economic outcomes. Understanding the performance of each element and the complex interaction among the elements is fundamental for designing sustainable agricultural practices that promote long-term environmental benefits while also ensuring economic resilience for crop farmers.

The aim of this paper is to assess the environmental and economic performance of crop rotation, catch crops, and different tillage practices as elements of the crop production systems in Latvia, using a comprehensive approach that integrates empirical data gathered from case studies, field trials and field monitoring questionnaires, and literature studies to identify the potential areas for improvement with the aim of a more sustainable utilization of agricultural land. To achieve the research aim, several research questions were raised: Q1: What are the nitrogen use efficiency (NUE) and gross margin of typical crop rotations in Latvia? Q2: What is the impact of reduced tillage (min-till, strip-till, and no-till) on the NUE and gross margin compared to conventional tillage (ploughing) in crop-producing farms in Latvia? Q3: How can the composition of catch crop mixtures affect the performance of crop rotations? Q4: What is the impact of catch crop mixtures on the NUE in a medium-term crop rotation? The structure of this paper is organized based on the research questions.

The results of our study contribute to the broader scientific discourse on sustainable development of agricultural practices. By expanding the understanding of the environmental and economic performance of crop production system elements, we contribute to the ongoing efforts to optimize resource utilization, reduce environmental impacts, and enhance the resilience of agricultural systems. Our research findings can support the development of digital tools for farmers and aid in decision making regarding farm management, promoting the ability of farmers to adapt to new regulations and contributing to the implementation of the EU Green Deal strategies.

Crop rotation involves the sequential cultivation of different crops in the same field over a defined period. It is a traditional practice that provides benefits including pest and disease management and nutrient cycling; furthermore, it can enhance soil fertility and contribute to the long-term sustainability of agricultural production [13]. However, the paradigm of input intensification and specialization that has contributed to large yield gains in staple crops has also led to dramatic declines in crop diversity [14]. Approximately 1.2 mill. hectares (data from 2021 [12]) of arable land in Latvia are used for conventional crop production. Wheat, oilseed rape, barley, and oats are the main crops that are cultivated in Latvia, occupying approximately 75% of the total arable land. Structural changes can be observed in the crop production in Latvia since 2015 (Figure 1): the areas for wheat and oilseed rape have increased, mainly at the expense of perennial grass area. The combined area where wheat or oilseed rape were cultivated exceeded 60% of the total in 2019.

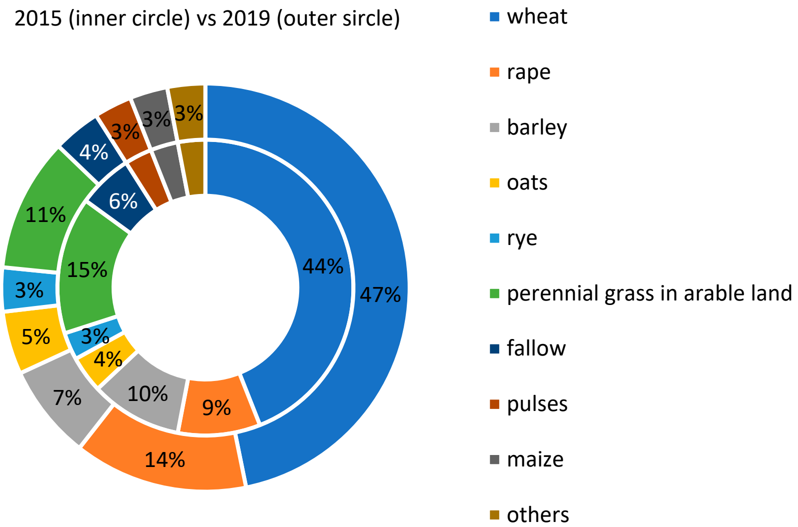


Figure 1. Structure of conventional crop production area in Latvia and its dynamics in 2015 vs. 2019.

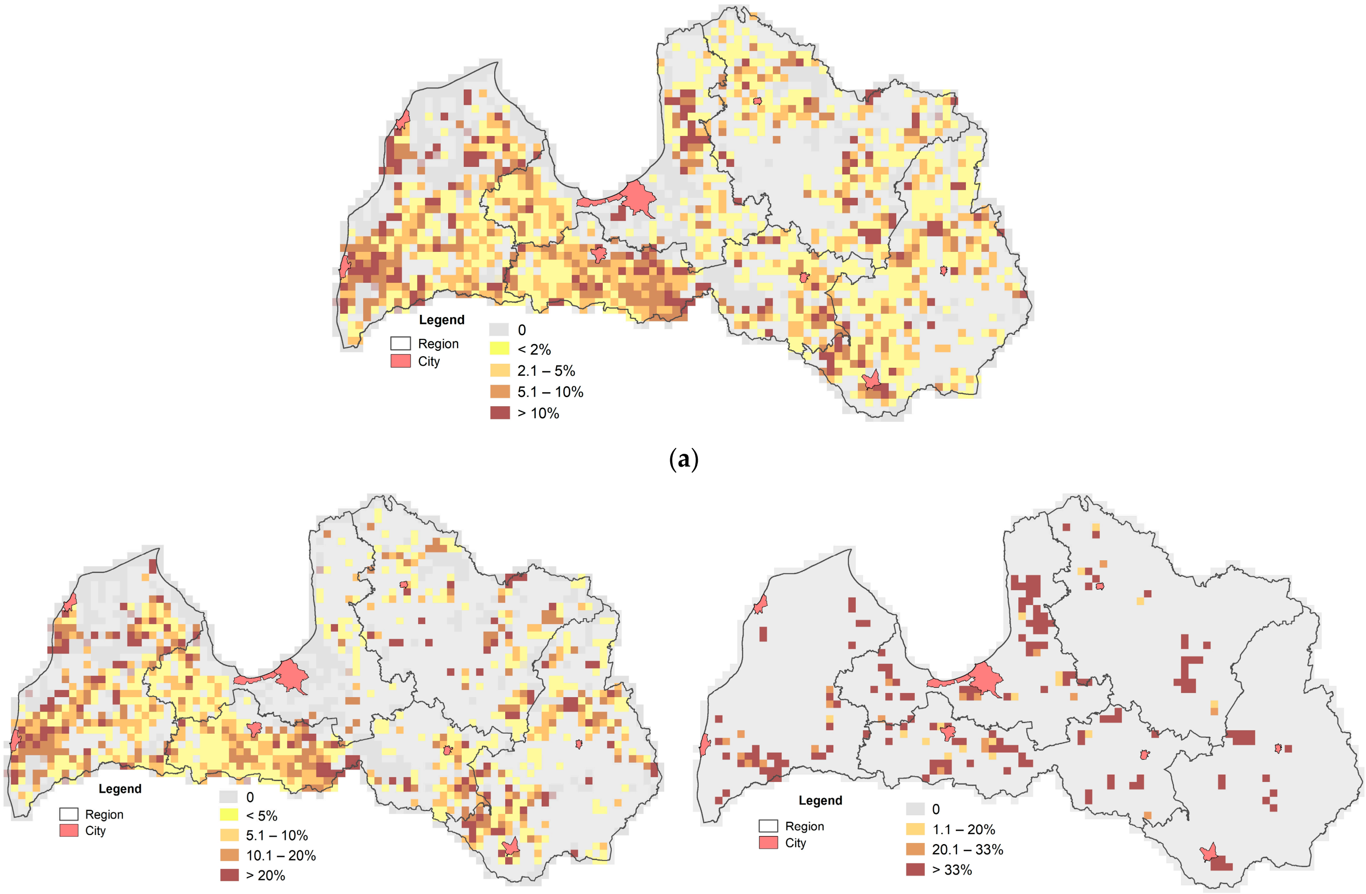
A spatially dynamic analysis conducted using the information on direct payments for declared areas and crops in Latvia between 2015 and 2019 indicates that Latvia's conventional crop production tends to be monotonous. Typically, two or three different crops are included in the rotation. There are fields comprising 3% of the total conventional arable land area where wheat was cultivated as a monoculture continuously for five years within the 2015–2019 period (see Table 1). Only 16% of the total conventional arable land area was not used for wheat cultivation at least once between 2015 and 2019.

Table 1. Crop rotation structure by crop areas in the total area of conventional arable land in Latvia during the period of 2015–2019.

Number of Years of Occurrence in Crop Rotation	Share of Area with Wheat, %	Share of Area with Oilseed Rape, %	Share of Area with Cereals (Wheat Excluded), %	Share of Area with Pulses and/or Legumes, %
0	16	53.6	5	77
1	16	36	9	20
2	21	10	12	2
3	27	0.4	28	1
4	18	0	33	0
5	3	0	13	0

Oilseed rape is cultivated on half of the total conventional arable land in Latvia. Typically, it is included in the crop rotation once within a five-year period; however, there are fields (constituting 10% of the total conventional arable land area) where oilseed rape was included in the crop rotation at least twice during a five-year crop rotation period. It should be mentioned that pulses are not widely cultivated in Latvia. Spatially dynamic analysis reveals that there are fields (encompassing 77% of the total conventional arable land area) where pulses were not cultivated at all between 2015 and 2019.

The practice of monoculture is not commonly employed in Latvia. However, it can be observed in all regions, particularly in the Zemgale region, which is of significant importance for crop production due to its fertile soil, as well as in the Kurzeme region (Figure 2). Wheat is the most common crop cultivated as a monoculture, and maize (both for feed and for energy production) follows as the second most widespread crop cultivated as a monoculture.



(**a**)

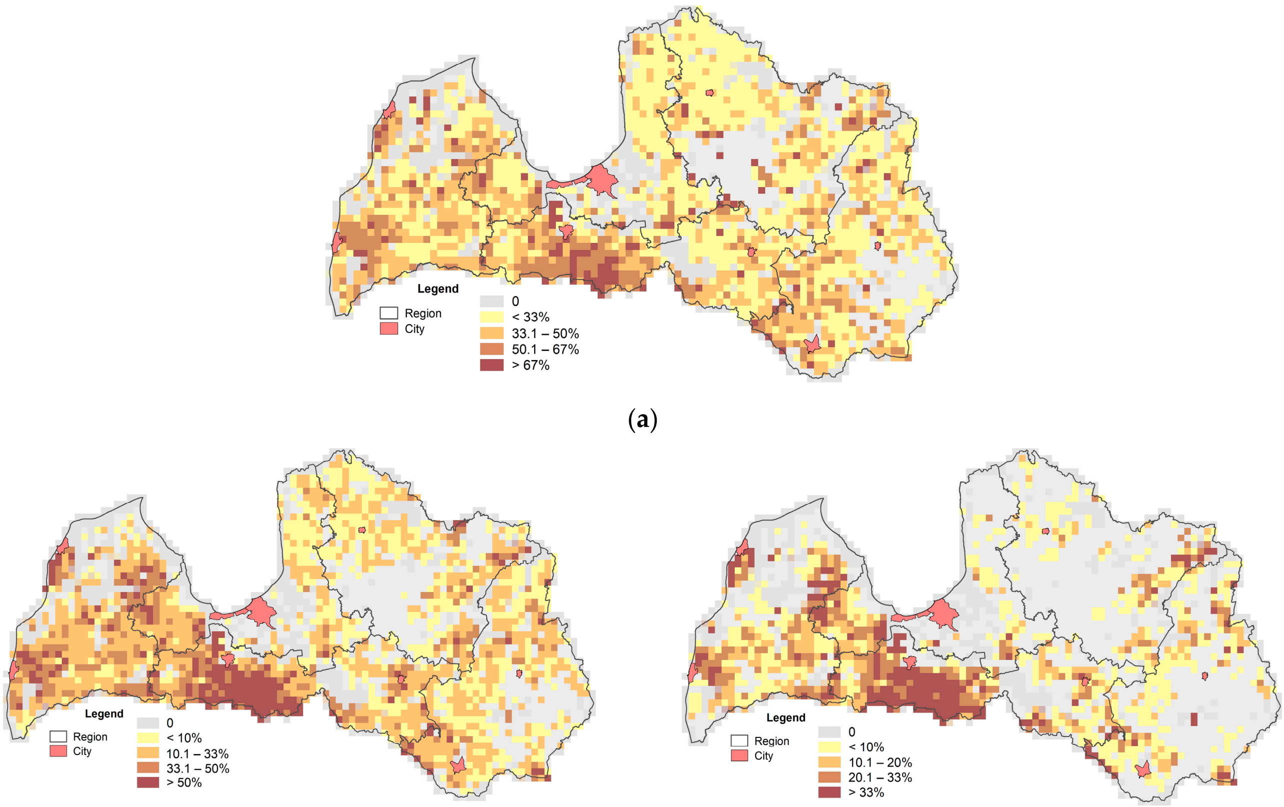
(**b**) (**c**)

Figure 2. Share of monocultures in the average total conventional arable land in Latvia during 2015–2019 (%): (**a**) total area with a monoculture; (**b**) area with wheat as a monoculture; (**c**) area with maize as a monoculture.

Two-crop rotation is a widely adopted practice in the Latvian crop production system, with only a few areas where it is not commonly applied (Figure 3). In the majority of the country, two-crop rotation occupies less than 33% of the total conventional arable land. However, there are certain areas where two-crop rotation is the dominant practice in crop production, encompassing more than 50% of the total conventional arable land.

The selection of a crop rotation practice is influenced by various factors. Assuming that the objective of crop farmers is to establish an optimal solution tailored to local conditions and maximize the productivity potential of their fields, the prevalence of two-crop rotation in Latvian crop production indicates that farmers, whenever possible, choose to cultivate oilseed rape alongside wheat. In cases where this combination is not feasible, farmers typically opt to grow wheat in combination with other cereal crops. The incorporation of pulses and other protein crops into crop rotation is not yet widely adopted, resulting in a missed opportunity to fix nitrogen from the atmosphere and enhance the long-term sustainability of the crop production system.

The inclusion of catch crops as intermediate crops in crop production is a relatively new phenomenon in Latvia. This is primary due to the prevailing practice of cultivating winter crops as the main crops, as revealed by crop rotation analysis. However, considering the crop rotation in the period between 2015 and 2019, the average sowing potential of catch crops in conventional arable lands in Latvia was 272,980 ha per year. It is anticipated that the availability of areas for catch crops will increase with the introduction of more legumes or other spring crops in the crop rotation (Figure 4).



(**a**)

(**b**) (**c**)

Figure 3. Share of two-crop rotations in the average total conventional arable land in Latvia, during 2015–2019 (%): (**a**) total area with a two-crop rotation; (**b**) area with a two-crop rotation including wheat; (**c**) area with a wheat–oilseed rape rotation.

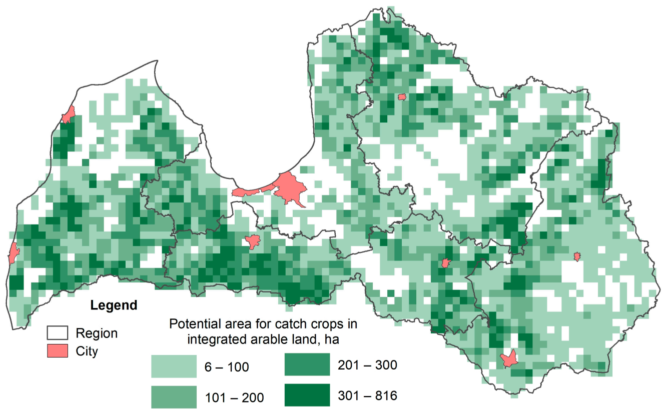


Figure 4. Potential area for catch crops in conventional arable land of Latvia (average ha annually) according to crop rotation during the period of 2015–2019.

Recently, the focus on catch crops, particularly regarding their potential to enhance N balance and NUE in crop rotation, has increased. In some European countries, for, example Denmark, cultivation of catch crops is mandatory to absorb excess soil N during the autumn season [15], following catch crops, a mandatory reduction in the amount of N fertilizer that can be applied to the succeeding crop is imposed [16]. The reduction accounts for the N derived from the mineralization of the catch crop residues and thus compensates for the residual effect of catch crops in the years after their incorporation [17]. There is also a great interest in including leguminous catch crops, as they can, through their biological N fixation, enhance the nitrogen supply to the subsequent crop and thus further reduce N fertilization rates [17]. The use of mixtures of non-leguminous and leguminous catch crops has been promoted to better utilize the N fixed by legumes without the risk of increased N losses via leaching from pure leguminous catch crops [18]. Reducing N input would be vital for improving NUE, with a current loss of 40% of the total N input via leaching, gaseous emissions, and runoff [19].

The choice of tillage type in crop production is also a meaningful decision that farmers face. Conventional tillage involving deep ploughing and soil disruption has traditionally been practiced for weed control and seedbed preparation [20]. However, reduced and no till have gained popularity due to their potential benefits, including improved soil structure, moisture retention, erosion control, and lower fuel consumption [21,22]. The selection of tillage type depends on various factors, such as soil type, climate, crop rotation, weed pressure, equipment availability, and farmers' preferences [21]. Therefore, the development of local knowledge in this field is critically important; especially nowadays, by understanding how different tillage types can influence N balance and NUE, farmers can make informed decisions to enhance NUE, reduce environmental impacts, and maximize crop productivity.

2. Materials and Methods

The main data source for this study is unpublished information and empirical data obtained from Latvian crop farmers within the agricultural European Innovation Partnership (EIP-AGRI) project "Progressive land cultivation system as the basis for environmentally friendly and effective crop production". During the implementation of the project, field monitoring, field case studies, and field trials were carried out.

Field monitoring covered about 150 monitored fields belonging to the farms of the two largest Latvian grain cooperatives (project partners), VAKS and Latraps. For each monitored field, general data such as location, farm size, farm specialization, farming system, and tillage system were collected through questionnaires. Soil characteristics including soil type, soil organic matter, pH, etc., were also recorded. Additionally, data on production activities and results, including crop information, agrotechnical operations, use of synthetic and organic fertilizers, use of plant protection products, and yield parameters, were obtained for four consecutive years (2018, 2019, 2020, and 2021) for the same farm field and reported per 1 hectare (field monitoring questionnaire form provided in Supplementary Material). The cooperatives were entrusted with the selection of farms for field monitoring, and currently, the obtained information constitutes the largest dataset containing information on field histories of the main crop production in Latvia. The dataset was used to analyze and compare the environmental and economic performance of crop rotation, as well as conventional tillage (ploughing) and non-inversion tillage.

Field case studies were carried out on six conventional crop farms to investigate whether different types of tillage (ploughing and non-inversion tillage, including min-till, strip-till, and no-till) result in different economic and environmental outcomes (Table 2). The tillage trials were conducted for three consecutive years (2020–2022), with each farm implementing at least two different types of tillage. Each farm applied its own crop rotation and cultivation technology based on the cultivated main crop. The same agrotechnology (fertilization and plant protection measures) was applied for all trial fields within a given farm in order to assess the potential impact of tillage type on the crop yield. The trial fields were established with a minimum size of 0.5 hectares. The farms involved in the case studies were located in different regions of Latvia, encompassing soil with various granulometric compositions. This included one farm with clay soil, while the remaining farms had varying sandy clay soils. Considering the unique nature of each field case study, an evaluation of environmental and economic performance associated with different types of tillage was conducted individually for each case. However, to facilitate better interpretation of the results, the cases were divided into three groups based on the type of crop rotation implemented during the respective case studies: (1) crop rotation involving only cereals; (2) crop rotation involving cereals, oilseed rape, and faba beans; (3) and crop rotation including maize.

Table 2. Characteristics of field case studies for different tillage types (2020–2022).

Field Case Study	Ploughing	Min-Till	Strip-Till	No-Till
Crop rotation involving only cereals				
Field A	X	X	-	X
Crop rotation including maize				
Field B	-	X	-	X
Field C	X	X	-	-
Crop rotation involving cereals, oilseed rape, and faba beans				
Field D	X	X	-	X
Field E *	-	X	X	-
Field F	X	X	X	-

* Ploughing has not been practiced for more than 10 years. X indicates the application of the respective tillage type.

Field trials were conducted to obtain empirical data for catch crop performance analysis, with the focus on catch crop mixtures. Data for catch crop mixes were collected from the field trials conducted over three years (2019–2021) in two locations—(1) the Institute of Agricultural Resources and Economics Stende Research Center (Stende) in the Kurzeme region and (2) the "Lielvaiceni" (Vitini) agricultural farm in the Zemgale region—both located in the western part of Latvia. According to the Köppen climate classification, Latvia has a mild continental humid climate. The catch crop mixtures were grown in a randomized complete block design what included plots of 36 m^2 (3 m $\times$ 12 m) in four replicates in Stende and 0.1 ha plots in Vitini.

Agrometeorological condition characteristics were obtained from the Stende and Saldus hydrometeorological stations. In the study, the hydrothermal coefficient (HTC) was calculated for each month during the catch crop vegetation period (Figure 5). The calculations were performed using the following formula [23]:

$$\mathrm{HTC} = \Sigma x / \Sigma t \times 10, \quad (1)$$

where Σx is the total precipitation for the period (mm), and Σt is the total temperature for the period in which the average temperature exceeds 10 °C.

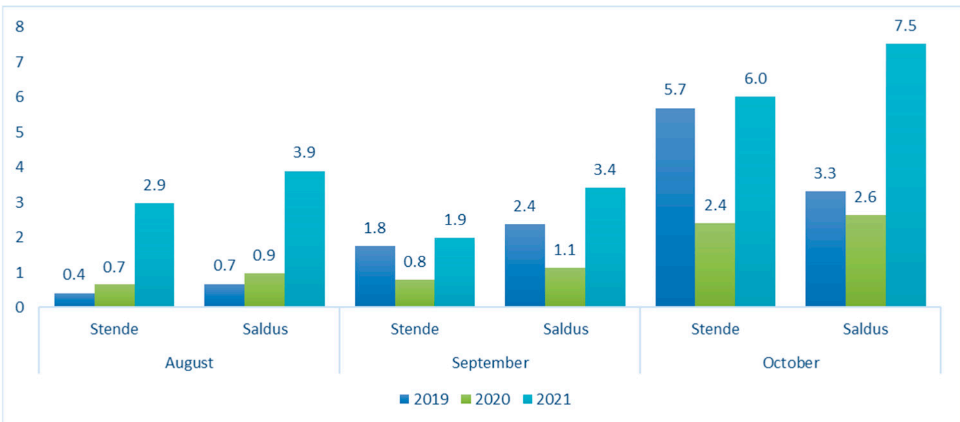


Figure 5. Hydrothermal coefficient (HTC) from August to October 2019–2021.

Ranges of values of this index were classified according to Sielianinov coefficient as modified by Skowera et al. as [24]: extremely dry—HTC $\leq$ 0.4, very dry—0.4 < HTC $\leq$ 0.7, dry—0.7 < HTC $\leq$ 1.0, relatively dry—1.0 < HTC $\leq$ 1.3, optimal—1.3 < HTC $\leq$ 1.6, relatively humid—1.6 < HTC $\leq$ 2.0, humid –2.0 < HTC $\leq$ 2.5, very humid—2.5 < HTC $\leq$ 3, or extremely humid—HTC > 3.0. The meteorological data for each month represent the measurements taken during the growing season, starting from the sowing date and continuing until the catch crop termination date (biomass harvest date).

Catch crop species were selected based on their ability to grow rapidly during the autumn in a short-term fallow period until winter. The following species were included in the mixtures: oats (*Avena sativa* L.), ryegrass (*Lolium multiflorum*), rye (*Secale cereale* L.), mustard (*Sinapis alba* L.), radish (*Raphanus sativus* var. *longipinnatus* L.), oilseed rape (*Brassica napus* L.), buckwheat (*Fagopyrum esculentum* Moench), phacelia (*Phacelia tanacetifolia* Benth.), crimson clover (*Trifolium incarnatum)*, and vetch (*Vicia sativa* L./*Vicia villosa* Roth). There were three non-legume-based mixtures ((1) oats and mustard; (2) mustard and radish; and (3) ryegrass, buckwheat, and phacelia) and three legume-based mixtures ((1) ryegrass, crimson clover, and phacelia (not included in the mixture for all years); (2) oats, vetch, and phacelia; and (3) rye, oilseed rape, and vetch/phacelia). The control was bare fallow in both locations. The field was prepared, and catch crops were sown immediately after the winter wheat harvesting: on 12 August 2019, 26 August 2020, and 6 August 2021 in Stende and on 11 August 2019, 13 August 2020, and 10 August 2021 in Vitini. The granulometric composition comprised sandy clay soils in both locations (Table 3).

Table 3. Soil agrochemical characteristics and preceding crops for catch crop trials (2019–2021).

Location		**Stende**			**Vitini**	
Year	**2019**	**2020**	**2021**	**2019**	**2020**	**2021**
pH_{KCl}	4.9–5.7	6.1	6.8	7.4	7.3–7.6	7
Organic matter, %	2.0–2.5	3.7	3.8–4.3	2.7	3.7–4.7	3
P_2O_5, mg kg^{-1}	158–219	238	42	165	75–201	230–370
K_2O, mg kg^{-1}	169–182	107	128	131	130	
Preceding crop		Winter wheat			Winter wheat	
Following crop		Spring barley		Spring barley	Field pea	Faba beans

Aboveground biomass and belowground biomass were collected from a 0.25 m^2 plot per replicate for four replications. Samples were washed and dried, and the dry matter of shoots and roots was weighed. In 2021, the total nitrogen and carbon contents of dried samples were determined (separately in belowground and aboveground biomass) based on the LVS ISO 13878:1998 [25] and LVS ISO 10694:2006 [26] methods, respectively. Correlation analysis was employed to examine the relationships between the dry matter yield of shoots and roots, as well as between the combined dry matter yield of shoots and roots and HTC for each catch crop mixture by year ($p \leq 0.05$ or $p \leq 0.01$).

To study the performance of catch crop mixtures, a literature analysis was also conducted to review the influence of combining catch crops on various aspects, including providing a source of nitrogen (in the case of legumes), nitrogen scavenging, the availability of free phosphorus and potassium, erosion and weed control, topsoil loosening and subsoiling effects, nematodes and disease suppression, and allelopathic effects on the soil environment. A meta-analysis of the performance and potential advantages of catch crop mixtures covering different scientific sources was conducted, including information from studies conducted in the USA, Germany, Estonia, France, and other countries.

2.1. Measuring Environmental Performance

In this study, environmental performance was evaluated by focusing on nitrogen balance because the nitrogen cycle plays a significant role in the agrifood sector due to its direct impact on crop productivity, soil health, and environmental sustainability. Moreover, the Platform on Sustainable Finance (PSF) has proposed nitrogen use efficiency (NUE) as an indicator of nitrogen balance [27,28]. Thus, the NUE for a field was calculated and used as an indicator of N balance and environmental performance. According to the general methodology, NUE was calculated as the ratio of N output to N input:

$$\text{NUE} = \Sigma\text{N\_output}/\Sigma\text{N\_input}, \tag{2}$$

where ΣN_output is a field's N output (kg N ha^{-1}), and ΣN_input is a field's N input (kg N ha^{-1}).

As the typical practice in Latvia is that straw and other aboveground plant above-ground residues are left in the field, it was assumed that ΣN_output was comprised of N removal by harvest. The N removal by harvest was assessed according to the crude protein content. To calculate N content based on crude protein, the standard nitrogen-to-protein conversion factor (Kjeldahl method; 5.7 in the case of winter wheat and spring wheat, and 6.25 for other crops) specified by ISO 20483:2013(E) [29] was used. If information on the crude protein content was not available from the empirical project data, the nitrogen content in dry matter derived from the values reported by Kārkliņš and Ruža (see Table 4) [30] was used.

Table 4. Nitrogen removal by harvest of different field crops.

Field Crop	Product	Dry Matter, %	N Content, kg·t^{-1} Dry Matter
Winter wheat	Grain	86	22.0
Rye	Grain	86	17.4
Winter barley	Grain	86	20.3
Winter triticale	Grain	86	18.6
Spring wheat	Grain	86	25.3
Spring barley	Grain	86	21.0
Oats	Grain	86	18.1
Field peas and faba beans	Seeds	86	45.7
Winter oilseed rape	Seeds	92	29.1
Spring oilseed rape	Seeds	92	38.3

Source: derived from Kārkliņš and Ruža [30].

ΣN_input was comprised of N inputs from seed, synthetic fertilizers, organic manure (if applied), and biological N fixation (if relevant). If trials involved sowing catch crops (grown as intermediate crops), the N inputs from their seeds were also considered. It was assumed that the N content in seeds was the same as that in the harvested grains or seeds. Biological N fixation was assessed by assuming that, on average, faba beans fix 72.6 kg of N per ton of dry matter (DM) yield, field peas fix 46.7 kg of N per ton of DM yield, and spring vetches fix 73.5 kg of N per ton of DM yield. These assumptions were derived from the research project "Legume-supported cropping systems for Europe (Legume Futures)" [31]. According to the methodology proposed by the PSF, the changes in soil nitrogen content were not considered as N input or output [27,28].

To exclude short-term effects that can affect the result for a single year, NUE was calculated for a multiyear period. Such an approach complies with the recommendations of the PSF, which suggest calculating NUE as a rolling average of three years [27,28]. As the field monitoring involved a four-year period, NUE for crop rotations was calculated as the average for four years (2018–2021). NUE for different tillage types was calculated as a rolling average for a three-year period based on field case studies.

The NUE calculation results for the crop rotation considering the data from the field monitoring dataset were first assessed by Piliksere, Auzins, and Aboltins [32]. However, the analysis at that time was based on preliminary field monitoring data, and the available dataset (particularly for 2021) was considerably smaller. Moreover, the previous research did not consider the actual crude protein content to assess N input (only the values reported by Kārkliņš and Ruža were used).

It should be mentioned that the PSF has proposed that biological N fixation can be excluded from N input to encourage the cultivation of legumes (pulses) [28]. If this proposal is accepted and incorporated in the technical screening criteria of the Taxonomy, crop rotations including pulses will have an advantage over crop rotations without pulses. Therefore, the assessment of the NUE for crop rotations was supplemented with calculations in which biological N fixation was excluded. The laboratory tests conducted by the Institute of Agricultural Resources and Economics within this project revealed that the N content in winter rapeseeds was likely higher than the value reported by Karkliņš and Ruža. According to these tests, the N content was 20% higher (90% confidence interval: 11–28%). Thus, the assessment of the NUE for crop rotations was also supplemented by additional calculations in which adjusted N content of winter rapeseed (by 20% higher) was used.

NUE for catch crop (intermediate crops) trials was calculated for two-year periods (2019–2020, 2020–2021, and 2021–2022). These two-year periods consisted of the year before catch crop cultivation and the year following catch crop cultivation. Such an approach allowed for assessment of the effect of catch crops in reducing N losses (leaching) and transferring N to the next cash crop. The average NUE was calculated as a simple average of NUE for the periods of 2019–2020, 2020–2021, and 2021–2022. The effect of catch crops on NUE was assessed by comparing the average NUE between a catch crop mixture and the control group, calculating the relative difference:

$$RD_{NUEi} = NUE_{cci}/NUE_{con} - 1, \quad (3)$$

where RD_{NUEi} is the relative difference for mixture i of catch crops, NUE_{cci} is the average NUE for the mixture i of catch crops, and NUE_{con} is the average NUE for the control group.

The relative differences in NUE were calculated using both stubble after disc harrowing and ploughing as the control group. Since the trials of 2019–2020 involved only stubble after disc harrowing and did not include ploughing, the assessments and comparisons with ploughing were conducted excluding the period of 2019–2020.

2.2. Measuring Economic Performance

For the study, the economic performance was evaluated as the gross margin, which corresponds to the revenue minus variable costs. The gross margin is expressed in EU per hectare (EUR ha^{-1}). The average annual value of the gross margin is presented for a four-year period (2018–2021).

Evaluation of the economic performance for crop rotation and different tillage types was conducted based on the dataset of monitored fields (field monitoring) compiled during the implementation of the project and the information gathered from the field case studies (see Table 2). The revenue for each field and year (2018, 2019, 2020, and 2021) was calculated based on the crop yield in tonnes per ha (obtained from the farm questionnaires; see the questionnaire form in Supplementary Materials) and the corresponding sales price of the crop. The evaluation was conducted using constant 2020 prices, which were sourced from the official agricultural producer price statistics [33]. Constant prices were used in the evaluation to exclude the effects of market fluctuations and individual organizational characteristics of each farm.

The costs for each field and year were obtained by aggregating the variable costs for the following agrotechnical operations and raw materials from the questionnaires: liming and liming material, ploughing, subsoiling, disc harrowing, levelling, cultivation, combined soil preparation without sowing, sowing/planting of a main crop and a catch crop, seed for the main crop and catch crop, combined soil preparation with sowing, roller pressing, harrowing, application of synthetic fertilizers, application of plant protection products, application of animal manure or digestate, harvesting, straw chopping, straw pressing, crop rolling and chopping, and chemical crop termination (catch crops).

The total costs of agrotechnical operations for each field were determined by considering the number of times the activity was reported to have been performed in the questionnaires and the associated price/cost per executed operation. However, the costs of spreading organic manure were derived from the quantities of distributed organic manure or digestate reported in the questionnaires and the corresponding spreading price/cost per tonne. The evaluation was carried out at constant 2020 prices. Information regarding the price/cost of agrotechnical operations was obtained through direct communication with the expert of the Latvian Rural Advisory and Training Centre (LRATC) [34].

The costs of seeds were calculated based on the sowing rate provided in the questionnaires and the corresponding seed price for the specific crop [35]. The costs of synthetic fertilizers were determined by considering the quantity of nitrogen reported in the questionnaires and the corresponding value of nitrogen. The value of nitrogen was derived from the prices of NPK complex fertilizers, ammonia nitrate, and ammonia sulphate fertilizers [35], considering their respective nitrogen (N), phosphorus (P_2O_5), potassium (K_2O), and sulfur (S) contents. An equation was constructed to calculate the values of N, P_2O_5, K_2O, and S based on these factors. The costs of organic fertilizers and digestate were estimated by considering the amount of organic manure or digestate used on each field and the estimated quantities of N, P_2O_5, and K_2O present in the manure [36] or in digestate (field case studies), as well as the estimated value of the basic plant nutrients. Additionally, costs associated with other fertilizers, as presented in terms of value in the questionnaires, were included in the calculations. The costs of plant protection products (PPPs) were obtained by summing the PPP items presented in the questionnaires, including herbicides, limacides, fungicides, insecticides, retardants, desiccants, and biological PPPs. These costs were provided in monetary terms in the questionnaires. The cost of liming material was estimated by considering the consumption of liming material reported in the questionnaires, as well as the corresponding prices. For each agrotechnical operation, the consumption of diesel was also estimated by the expert of LRATC [34], enabling the determination of the total diesel consumption associated with the agrotechnical operations implemented for crop production in the field.

For the purpose of grouping fields by crop rotations, only those fields from the field monitoring dataset were selected for the subsequent analysis, where production did not occur using organic farming methods and costs and revenue were greater than zero in all four years (excluding the year with fallow land). When analyzing the economic performance of different tillage types using data from field monitoring, a field was selected for the ploughing system if ploughing had been conducted every year during the four-year period. In the case of non-inversion tillage, it was required that the monitored field had not been ploughed for at least three years within the four-year period, allowing for the possibility of ploughing once in any of the four years. Analysis of the collected data was performed using the R programming language (Excel files were provided as an input data source: the total of four Excel files for the years 2018, 2019, 2020, and 2021). R served as a tool for data verification, calculations, and grouping.

3. Results

3.1. Effect of Crop Rotation on NUE

The assessed average NUE and its confidence intervals for crop rotations within field monitoring are presented in Table 5. When applying the assumptions regarding biological nitrogen fixation described in Section 2.1, wheat, various cereals and green maize–other field crop rotations demonstrated the highest average NUE. However, the confidence intervals (CI) for various cereals and green maize–other field crops rotations were very wide (even extremely wide). Thus, only wheat rotation showed a statistically significant difference from the other crop rotations (except various cereals and green maize–other field crop rotations). Rotation of various cereals also demonstrated statistically significantly higher average NUE values than wheat–oilseed rape and wheat–oilseed rape—pulses rotation, although this rotation did not outperform other crop rotations.

Table 5. Average NUE for different crop rotations (for the period of 2018–2021).

Crop Rotation	Number of Farm Fields *	Average NUE, %	CI for Average NUE **, %
Wheat	5	74.3	(71.2, 77.3)
Various species of cereals	11	74.7	(67.4, 81.9)
Wheat–oilseed rape	42	63.9	(60.7, 67.1)
If N content of winter rapeseed is adjusted	42	66.1	(62.9, 69.3)
Wheat–pulses	6	63.4	(58.8, 68.0)
If biological N fixation is excluded	6	81.2	(75.0, 87.3)
Wheat–oilseed rape–pulses	18	63.1	(59.9, 66.2)
If biological N fixation is excluded	18	82.1	(77.4, 86.7)
If N content of winter rapeseed is adjusted	18	65.4	(62.3, 68.5)
If biological fixation is excluded and N content of winter rapeseed is adjusted	18	85.1	(80.5, 89.7)
Wheat–barley–oilseed rape	9	63.0	(57.0, 69.0)
If N content of winter rapeseed is adjusted	9	65.0	(58.6, 71.4)
Wheat–oilseed rape–fallow	7	61.4	(54.1, 68.8)
If N content of winter rapeseed is adjusted	7	65.2	(57.4, 73.0)
Green maize–other field crops	2	72.9	(47.8, 98.0)

* Fields where only synthetic fertilizers were applied. ** 90% confidence interval.

The low performance of crop rotations that include oilseed rape can be attributed to the N content of rapeseed derived from the value reported by Karkliņš and Ruža (see Section 2.1). As already mentioned, these values are probably too low. Although the use of adjusted N content of winter rapeseed increased the average NUE, as well as the lower bound confidence intervals, the increase was not significant. Therefore, these results suggest that the inclusion of winter rape in crop rotation is highly likely to reduce the NUE of crop rotation, even when assessed for a 4-year period.

The low performance of crop rotations that include pulses can be explained by the possible overestimation of biological N fixation. Consequently, an additional assessment of NUE was conducted by excluding biological N fixation. These results indicate significantly higher average NUE values and lower bounds of confidence intervals. Therefore, if the proposal by the PSF to exclude biological N fixation is applied, wheat–pulses and wheat–oilseed rape–pulses rotations demonstrate the highest average NUE. Moreover, wheat–oilseed rape–pulses rotation statistically significantly outperforms wheat rotation.

3.2. Effect of Crop Rotation on Gross Margin

When evaluating the gross margin for the main types of crop rotations within field monitoring, the highest average annual value was obtained in wheat–oilseed rape and wheat–oilseed rape–pulses rotations, which are the most common crop rotations in the monitored fields (see Table 6). Conversely, a lower average annual gross margin was obtained in crop rotation of various cereals (excluding fields where wheat was grown as a monoculture), which can be explained by the high proportion of summer crops in such a rotation. Regionally, these fields are located in parts of Latvia that are less suitable for wheat and rapeseed production. The difference between the gross margin of various cereals and other types of crop rotations (except wheat) is statistically significant (90% confidence intervals do not overlap). Another crop rotation with a statistically significant difference relative to wheat–oilseed rape and wheat–oilseed rape–pulses rotations was wheat–pulses.

Table 6. Gross margin and consumption of PPP, N, and diesel by crop rotations in monitored farm fields in 2018–2021.

Crop Rotation	Number of Farm Fields	Average Annual Gross Margin, EUR ha^{-1}	Average Annual Consumption of PPPs, EUR ha^{-1}	Average Annual Consumption of N, kg ha^{-1}	Average Annual Consumption of Diesel, liter ha^{-1}
Wheat	5	401 (217.4, 583.6) **	82 (39.1, 124.3)	149 (101.7, 195.4)	65 (59.2, 70.5)
Various species of cereals	15	183 (117.0, 248.8)	36 (25.6, 45.8)	110 (95.6, 124.5)	61 (57.5, 64.4)
Wheat–oilseed rape	51	439 (401.3, 477.5)	98 (91.2, 105.2)	175 (168.7, 180.9)	60 (58.4, 62.1)
Wheat–pulses	7	331 (294.7, 366.4)	91 (59.5, 122.5)	132 (102.8, 160.7)	60 (52.8, 66.3)
Wheat–oilseed rape–pulses	19	444 (407.0, 480.5)	89 (77.6, 101.0)	136 (129.3, 142.2)	59 (55.7, 61.9)
Wheat–barley–oilseed rape	11	358 (270.9, 445.6)	87 (74.8, 98.4)	165 (146.5, 183.5)	60 (55.6, 63.5)
Wheat–oilseed rape–fallow *	7	425 (291.0, 559.6)	88 (73.0, 103.3)	159 (151.4, 165.9)	67 (58.0, 76.8)
Green maize–other field crops	6	375 (298.4, 451.7)	56 (38.4, 74.1)	184 (131.9, 236.3)	69 (50.2, 88.7)

* The average annual values were obtained based on the summed 4-year values by dividing them by 4. However, for the wheat–rape–fallow rotation, the values were divided by 3 instead. ** Numbers in brackets show the lower and upper bounds of the 90% confidence interval.

Upon summarizing the use of PPPs in different crop rotations (see Table 6), it was observed that the highest amount of PPPs was used in the wheat–oilseed rape rotation, followed by crop rotations that included pulses or oilseed rape. Lower annual average PPP consumption was observed in various cereals, as well as in crop rotation in which maize (for silage and green feed) was grown at least once in a 4-year period. The average annual consumption of PPPs in crop rotations including oilseed rape or pulses does not differ statistically significantly between these groups (the 90% confidence intervals overlap). However, for most crop rotations that include oilseed rape or pulses (except for wheat–pulses and wheat–oilseed rape–fallow rotations), PPP usage differs statistically significantly from that associated with various cereals and green maize–other field crop rotations.

After evaluating the use of nitrogen (from synthetic fertilizers and estimated N from manure), it was observed that the highest average annual usage occurred in green maize–other field crops and wheat–oilseed rape rotations (Table 6). These were closely followed by wheat–barley–oilseed rape and wheat–oilseed rape–fallow rotations, as well as wheat rotation. Lower nitrogen usage was observed when pulses were grown alongside wheat or oilseed rape, as well as when various cereals (with a higher proportion of summer crops) were included in the crop rotation. For the widely adopted wheat–oilseed rape rotation, the average N consumption differs statistically significantly from all other crop rotations, except for wheat and wheat–barley–oilseed rape and green maize–other field crops. Meanwhile, the N consumption of wheat–oilseed rape–pulses rotation does not differ statistically significantly from that of wheat, wheat–pulses, and green maize–other field crops rotations. The average annual N consumption in the crop rotation of green maize–other field crops differs statistically significantly only from the average N use of various cereals. The average N use of wheat–pulses rotations also differs statistically significant only from the value in wheat–oilseed rape rotation. The average N value of various cereals differs statistically significantly from all other crop rotations, except wheat and wheat–pulses.

The assessment of diesel consumption in different types of crop rotations shows (Table 6) that the highest annual average is obtained in the crop rotation of green maize–other field crops, followed by wheat–oilseed rape–fallow and wheat rotations. In other plant rotations, the average diesel consumption is quite similar. The higher average annual diesel consumption in the wheat–oilseed rape–fallow rotation is explained by the fact that in some monitored fields agrotechnical operations were performed during the fallow year which increased the average fuel consumption over a 3-year period when revenue was generated. As the 90% confidence intervals overlap, the average annual diesel consumption does not differ statistically significantly between any of the crop rotation types. Along with costs, diesel consumption also impacts the emissions of greenhouse gases (GHGs). As diesel consumption increases, so does the amount of CO_2 emissions from agricultural transport (fuel combustion). One liter of diesel emits about 2.65 kg CO_2 according to Auzins et al. (2021) [37].

3.3. Effect of Tillage Type on NUE

The assessed results of field case studies where different tillage types were applied are presented in Table 7. Overall, these results show divergent outcomes regarding the effect of tillage types on NUE. In almost all field trials, the average NUE for min-till was lower than for ploughing (conventional tillage). However, one trial (field A) demonstrated that no-till had a higher NUE compared to both ploughing and min-till. In contrast, field B and field D had average NUE values for no-till was lower than for min-till and ploughing (field D). Therefore, the findings do not suggest that lesser extent of tillage results in a higher NUE.

Table 7. Average NUE of different tillage types (for the period of 2020–2022), %.

Field Case Study	Ploughing	Min-Till	Strip-Till	No-Till
Crop rotation involving only cereals				
Field A	57	51	–	59
Crop rotation including maize				
Field B	–	82	–	72
Field C	74	63	–	–
Crop rotation involving cereals, oilseed rape, and faba beans				
Field D	70	70	–	64
Field E *	–	80	82	–
Field F	75	74	72	–

* Ploughing has not been practiced for more than 10 years. "–" indicates no application of the respective tillage type.

However, the trials of field E demonstrated a NUE of 80% for min-till and 82% for strip-till. These levels were significantly higher than those observed in the other cause studies (except for field B in the case of min-till).

A possible interpretation of these findings is that almost all fields had undergone ploughing before the trials. The exception was field E, which had not been ploughed for more than 10 years. Consequently, the transitional processes in the soil associated with the shift from ploughing to reduced tillage types could have affected NUE and overshadowed the impact of other factors. The results of field E suggest that reduced tillage types can outperform ploughing when practiced for an extended period of time (10 years or more).

3.4. Effect of Tillage Type on Gross Margin

Evaluation of the economic performance associated with different tillage types based on the field case studies does not reveal homogeneous results (see Tables 8–10). This indicates that economic performance is determined not only by the type of tillage but also by various other factors. Considering that non-inversion tillage is a less energy-intensive practice, lower diesel consumption is observed in trials with min-till or no-till compared to ploughing.

Table 8. Gross margin and consumption of diesel by tillage type in crop rotation involving only cereals according to field case studies in 2019–2021.

Field Case Study (Field A)	Ploughing	Min-till/ Ploughing—Difference in %	No-Till/ Ploughing—Difference in %
Average annual gross margin (EUR ha^{-1})	73	24	87
Average annual consumption of diesel (l ha^{-1})	65	−32	−43

Table 9. Gross margin and consumption of diesel by tillage type in crop rotation including maize according to field case studies in 2019–2021.

Field Case Study	Field B			Field C	
	Ploughing	Min-Till/ Ploughing— Difference in %	No-Till/ Ploughing— Difference in %	Min-Till	No-Till/ Min-Till— Difference in %
Average annual gross margin (EUR ha^{-1})	387	31	27	297	−37
Average annual consumption of diesel (l ha^{-1})	88	−8	−34	95	−19

Table 10. Gross margin and consumption of diesel by tillage type in crop rotation involving cereals, oilseed rape, and faba beans according to field case studies in 2019–2021.

Field Case Studies	Field D			Field E *		Field F		
	Ploughing	Min-Till/ Ploughing— Difference in %	No-Till/ Ploughing— Difference in %	Min-Till	Strip-Till/ Min-Till— Difference in %	Ploughing	Min-Till/Ploughing— Difference in %	Strip-Till/ Ploughing— Difference in %
Average annual gross margin (EUR ha^{-1})	381	−1	−11	579	9	497	3	−5
Average annual consumption of diesel (l ha^{-1})	84	−21	−39	51	−10	68	−24	−29

* Ploughing has not been practiced for more than 10 years.

Evaluation of the economic performance associated with different tillage types for the most common crop rotation within the field monitoring (wheat–oilseed rape) indicated a higher gross margin for non-inversion tillage (Table 11). In part, this can be explained by a higher share of monitored fields belonging to the Zemgale region, in which the most fertile soils are located, as well as a higher proportion of winter wheat and winter oilseed rape in the monitored farms practicing non-inversion tillage compared to those using ploughing. Due to the insufficient number of fields belonging to other crop rotation types, their economic analysis was not performed.

Table 11. Gross margin and consumption of PPPs, N, and diesel by tillage type in wheat–oilseed rape rotation in monitored fields in 2018–2021.

Crop Rotation: Wheat–Oilseed Rape Tillage System	Number of Farm Fields	Average Annual Gross Margin, EUR ha^{-1}	Average Annual Consumption of PPPs, EUR ha^{-1}	Average Annual Consumption of N, kg ha^{-1}	Average Annual Consumption of Diesel, liter ha^{-1}
Ploughing	14	377 (302.5, 452.0) *	89 (73.2, 104.5)	177 (161.1, 193.7)	67 (64.7, 69.3)
Non-inversion tillage	21	487 (437.6, 537.1)	91 (63.9, 118.7)	167 (146.6, 187.8)	55 (47.9, 61.4)

* Numbers in brackets show the lower and upper bound of the 90% confidence interval.

The average annual consumption of PPPs in the two tillage systems for wheat–oilseed rape crop rotation was almost the same. The average annual N consumption was slightly higher when practicing ploughing, while non-inversion tillage resulted in lower average annual diesel consumption. Based on the 90% confidence intervals, diesel consumption was the only indicator that showed a statistically significant difference between the two tillage types.

3.5. Environmental and Economic Performance of Catch Crops

Catch crop management within the cropping system can be a beneficial strategy and an addition to fulfilling specific agroecosystem function requirements. The literature presents a wide range of variations regarding the potential of catch crops, suggesting their use as parameters to better understand the effects of catch crops on soil and nutrient uptake. However, the effectiveness of catch crops depends on factors such as plant species, soil characteristics, climate conditions, biomass volume, and agronomic practices [38,39].

To better understand the potential of catch crop mixtures, expected results of catch crop performance and their advantages are summarized in this study (Figure 6) based on literature analysis. The literature analysis was incorporated in the study to present arguments for making better decisions regarding the selection of the most appropriate catch crop mixtures for practical implementation on Latvian farms. Selected mixtures with different species can provide varying degrees of chemical, biological, and mechanical impacts. All selected species in the mixtures are more adaptive to the climatic conditions in Latvia characterized by a short growing season and rapid growth in the early stages of development. According to the conducted analysis (Figure 6), the rye–oilseed rape–phacelia/vetch mixture has the greatest impact on soil erosion, topsoil, allelopathy, the release of P and K, and nitrogen accumulation (legumes). Mustard and radish have the greatest impact on the subsoiling. Ryegrass, buckwheat, and phacelia have an excellent impact on topsoil loosening and the release of P and K in available forms for plants. Three legume-based mixtures include two types of plants with different N source possibilities. All mixtures contain different species with specific natural diseases and nematode suppression abilities in the soil, which, when incorporated in an appropriate crop rotation, can limit these biological agents.

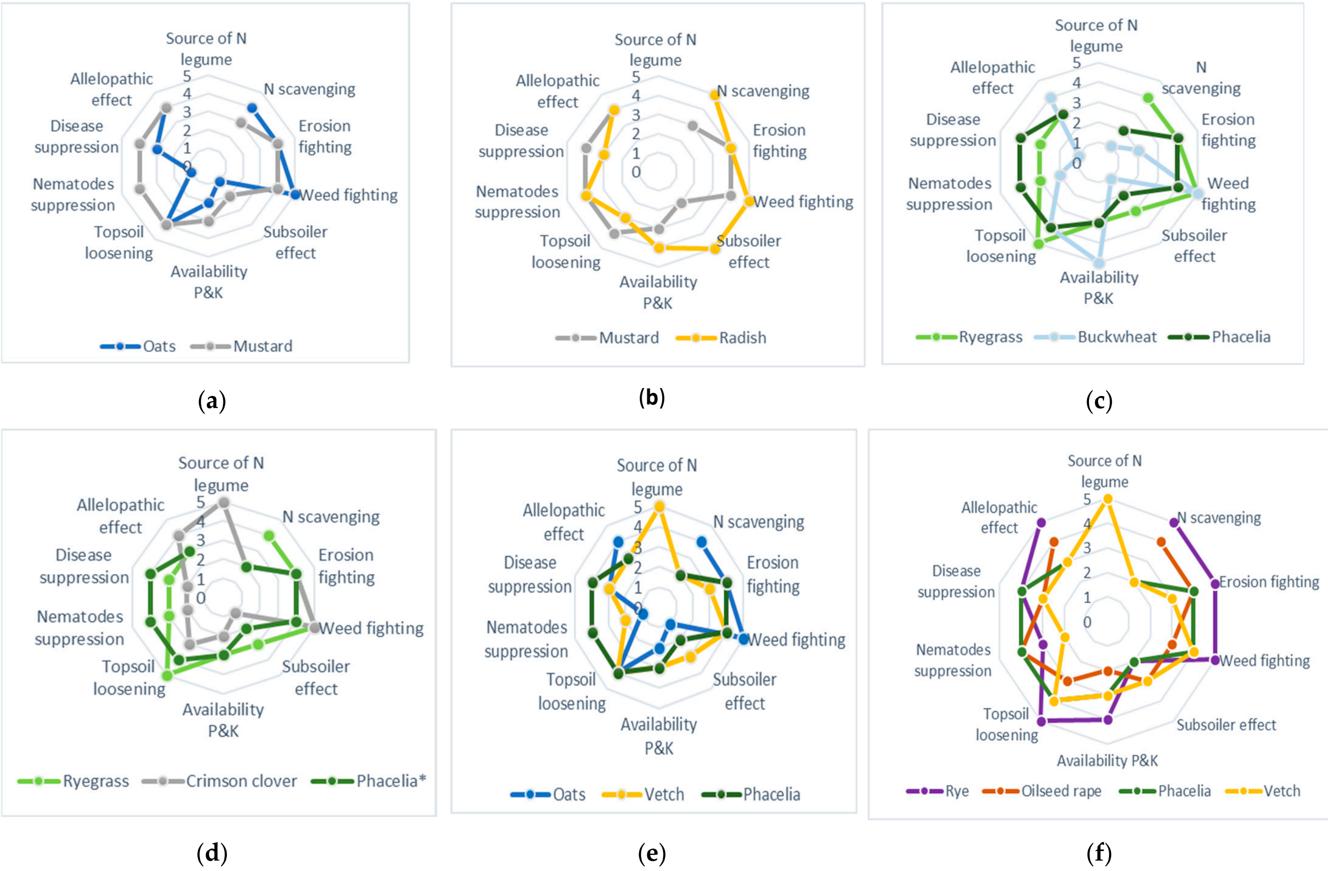


Figure 6. Performance and potential advantages of non-legume and legume-based catch crop mixtures. Value indicators: 1—poor; 2—fair; 3—good; 4—very good; 5—excellent [40–44]. * Phacelia was not included in the mixture all years. (**a**) Mixture of oats and mustard; (**b**) mixture of mustard and radish; (**c**) mixture of ryegrass, buckwheat, and phacelia; (**d**) mixture of ryegrass, crimson clover, and phacelia *; (**e**) mixture of oats, vetch, and phacelia; (**f**) mixture of rye, oilseed rape, phacelia/vetch.

According to the catch crop field trials conducted at two locations, the mustard–radish mixture in Stende yielded the highest average shoot DM yield of 0.91 t ha^{-1} while simultaneously recording the lowest average root DM yield of 0.29 t ha^{-1} compared to all other mixtures grown there (see Table 12). In Vitini, the range of the average shoot DM yield was 0.81 t ha^{-1} from ryegrass, crimson clover, and phacelia to 1.71 t ha^{-1} from the oat–mustard mixture. The lowest average root DM yield in Vitini was 0.42 t ha^{-1} from the mustard–radish mixture (similarly to in Stende). However, studies in Estonia and Germany revealed that the most optimal catch crop mixture is radish and mustard [45,46]. A statistically significant ($p \leq 0.01$, $p \leq 0.05$) positive correlation confirmed the relationships between shoot and root DM yield calculated for each mixture using annual data. The obtained results indicate that as shoot dry matter (DM) yield increases, root DM yield also increases for all mixtures. However, depending on the year, the ryegrass–crimson clover–phacelia mixture exhibited a higher root DM yield than shoot DM yield.

Depending on the year, the quantity of catch crop dry matter (DM) yield exhibited great fluctuations, which were attributed to the hydrothermal conditions during the growing season from August to October. Our trials demonstrated that DM yield was negatively correlated with the hydrothermal coefficient for each catch crop mixture. The results show that extremely high humidity levels in the autumn had a negative impact on the DM yield of plants. A significant ($p \leq 0.01$, $p \leq 0.05$) impact on yield loss in humid conditions was observed for non-legume-based mixtures: oats–mustard, mustard–radish, and ryegrass–buckwheat–phacelia.

Table 12. Average shoot and root dry matter (2019–2021), total N and C, and C: N ratio (2021) of different catch crop mixtures.

Mix/Control	Location	Part of Plant	Dry Matter Yield, t ha^{-1} ± SD	$r_{dw/HTC}$	$r_{Shdw/Rdw}$	N_{total}, g kg^{-1}	C_{total}, g kg^{-1}	C:N
Control	S	Sh	0.37 ± 0.19	−0.85	0.62	-	-	-
		R	0.29 ± 0.20	−0.1		-	-	-
	V	Sh	0.75 ± 0.42	−0.75	0.77	-	-	-
		R	0.75 ± 0.43	−0.99 ***		-	-	-
Oats and mustard	S	Sh	0.88 ± 0.56	−0.95 **	0.99 ***	36.82	441.86	12
		R	0.38 ± 0.20	−0.89		15.07	346.72	23
	V	Sh	1.71 ± 0.95	−0.97 **	0.99 ***	29.35	410.92	14
		R	0.57 ± 0.27	−0.97 **		14.68	337.55	23
Mustard and radish	S	Sh	0.91 ± 0.60	−0.94	0.97 **	32.46	421.97	13
		R	0.29 ± 0.15	−0.83		14.14	367.76	26
	V	Sh	1.18 ± 0.81	−0.51	0.99 ***	31.46	377.55	12
		R	0.42 ± 0.25	−0.63		17.67	406.47	23
Ryegrass, buckwheat, and phacelia	S	Sh	0.60 ± 0.34	−0.91	0.98 ***	25.53	383.00	15
		R	0.39 ± 0.02	−0.82		19.23	403.86	21
	V	Sh	0.98 ± 0.74	−0.58	0.99 ***	30.24	393.18	13
		R	0.62 ± 0.28	−0.54		18.18	345.35	19
Ryegrass, crimson clover, and phacelia *	S	Sh	0.67 ± 0.43	−0.99 ***	0.83	36.72	440.66	12
		R	0.79 ± 0.34	−0.77		13.77	371.86	27
	V	Sh	0.81 ± 0.39	−0.89	0.88	26.06	364.86	14
		R	0.80 ± 0.47	−0.57		14.74	339.00	23
Oats, spring vetch, and phacelia	S	Sh	0.62 ± 0.41	−0.99 ***	0.69	39.33	432.61	11
		R	0.43 ± 0.22	−0.64		15.70	314.07	20
	V	Sh	1.23 ± 0.94	−0.53	0.99 ***	28.45	426.79	15
		R	0.55 ± 0.25	−0.59		10.43	229.36	22
Rye, oilseed rape, and winter vetch/phacelia	S	Sh	0.52 ± 0.31	−0.84	0.83	33.06	396.73	12
		R	0.42 ± 0.21	−0.38		22.31	401.56	18
	V	Sh	1.03 ± 0.59	−0.72	0.94	30.25	363.06	12
		R	0.53 ± 0.28	−0.92		20.37	387.08	19

S—Stende; V—Vitini; Sh—shoots; R—roots; SD—standard deviation; $r_{dm/HTC}$—correlation coefficient between plant dry matter yield and HTC; $r_{Shdm/Rdm}$—correlation coefficient between shoot and root dry matter yield; * Phacelia was not included in the mixture all year; ** correlation significant at $p \leq 0.05$; *** at $p \leq 0.01$.

This study confirms that in Latvia, the autumns have extremely high humidity that can negatively affect soil productive capacity, for example, through N leaching. The average total N uptake of catch crops was the highest in the shoot DM yield for all mixtures (Table 12). In Stende, the highest total N content in shoot dry matter yield was obtained from oats, vetch, and phacelia, while in Vitini, it was from mustard and radish. The highest N content in root dry matter yield was observed in the rye–oilseed rape–vetch/phacelia mixture, surpassing all other mixtures in both locations. The best total N balance between shoot and root DM yield was observed in ryegrass–buckwheat–phacelia and rye–oilseed rape–vetch/phacelia mixtures.

The highest C content of the root DM yield was observed for the mustard–radish mixture in Vitini and for ryegrass–buckwheat–phacelia in Stende, while it was high in the shoot DM yield and lower in the root DM yield for oats–vetch–phacelia in both locations (Table 12).

A higher C:N ratio was observed in roots for all selected mixtures. Results confirm that roots decompose slowly, leading to the later release of nitrogen and a longer-lasting effect. On the other hand, the shoot mass decomposes faster, providing additional nutrients for the following main crop. Similar results have been confirmed in other experiments, such as those conducted in Estonia [47]. The rate of organic matter decomposition is determined not only by a plant species, its biomass volume, and C:N ratio but also by soil conditions (temperature, moisture content, acidity, aeration, etc.) [48]. The humification rate of organic matter from catch crops is estimated at 28%, which is much higher than in cereal straw (11–14%) [49]. The lower C:N of the mixtures with legumes can thus potentially increase the risk of N leaching [48]. Based on an experiment conducted in Switzerland and a linear model that estimates the contributions of species identities and interactions to biomass found that a combination of 24% of a legume cover crop and 76% of a non-legume cover crop produced the highest biomass [50]. Field trials of catch crop mixtures yielded results on their biomass and N content, serving for NUE calculations.

Relative differences between the average NUE for different catch crop mixtures and stubble after disc harrowing are presented in Table 13. Overall, the results indicate that catch crop mixes increased the average NUE. In Stende, the mixture of ryegrass, buckwheat, and phacelia and the mixture radish/oil radish and mustard demonstrated the highest positive impact on NUE. In Vitini, the highest positive impact was achieved by the mixture of radish/oil radish and mustard; the mixture of oats and mustard; and the mixture of ryegrass, buckwheat, and phacelia. However, it should be noted that two mixtures had a negative impact on NUE according to Vitini field trials.

Table 13. Difference in average NUE compared to stubble after disc harrowing, %.

Tested Catch Crop Mixtures	2019–2020	2020–2021	2021–2022	Average
Field trials in Stende:				
Rye, winter oilseed rape, and phacelia/winter vetch	+5.9	+2.7	−0.8	+2.6
Oats, spring vetch, and phacelia	+9.1	−1.4	+2.3	+3.3
Oats and mustard	−3.7	+8.9	−0.7	+1.5
Radish and mustard	+5.6	+10.5	−2.3	+4.6
Ryegrass, buckwheat, and phacelia	+3.0	+12.1	+3.5	+6.2
Oats, crimson clover, and phacelia *	+2.7	+0.9	−3.2	+0.2
Field trials in Vitini:				
Rye, winter oilseed rape, and phacelia	−3.9	+2.2	−0.1	−0.6
Oats, spring vetch, and phacelia	+3.7	+2.1	+1.2	+2.3
Oats and mustard	+11.3	+5.6	+1.0	+5.9
Radish and mustard	+18.0	+4.7	−0.8	+7.3
Ryegrass, buckwheat, and phacelia	+9.1	+5.7	−0.1	+4.9
Oats, crimson clover, and phacelia *	−4.9	+1.3	−0.8	−1.5

* Phacelia was not included in the mixture all years.

Additionally, the field trials in Stende enabled us to compare the catch crop mixtures with ploughing, which is a more typical alternative to catch crops (Table 14). These results demonstrated a more convincing positive impact of catch crops on the average NUE. The best-performing mixture was ryegrass, buckwheat, and phacelia.

Table 14. Difference in average NUE compared to ploughing (in Stende), %.

Tested Catch Crop Mixture	2020–2021	2021–2022	Average
Rye, winter oilseed rape, and phacelia/winter vetch	+8.5	+3.3	+5.9
Oats, spring vetch, and phacelia	+4.1	+6.6	+5.4
Oats and mustard	+15.0	+3.4	+9.2
Radish and mustard	+16.7	+1.8	+9.2
Ryegrass, buckwheat, and phacelia	+18.4	+7.8	+13.1
Oats, crimson clover, and phacelia *	+6.6	+0.9	+3.7

* Phacelia was not included in the mixture all years.

The capacity of catch crops to reduce N leaching is directly linked to their ability (and the conditions) to generate biomass in which N is captured. It is also essential to consider the economic aspects of the introduction of catch crops, which involve evaluation of the costs associated with seeds, establishment operations, and, if necessary, termination operations. Considering that catch crops are not harvested, the calculation of gross margin is not applicable for the assessment of economic performance. However, within the project, we evaluated the amount of N captured per hectare and the associated costs per unit of captured N, resulting from the implementation of catch crops (Figure 7).

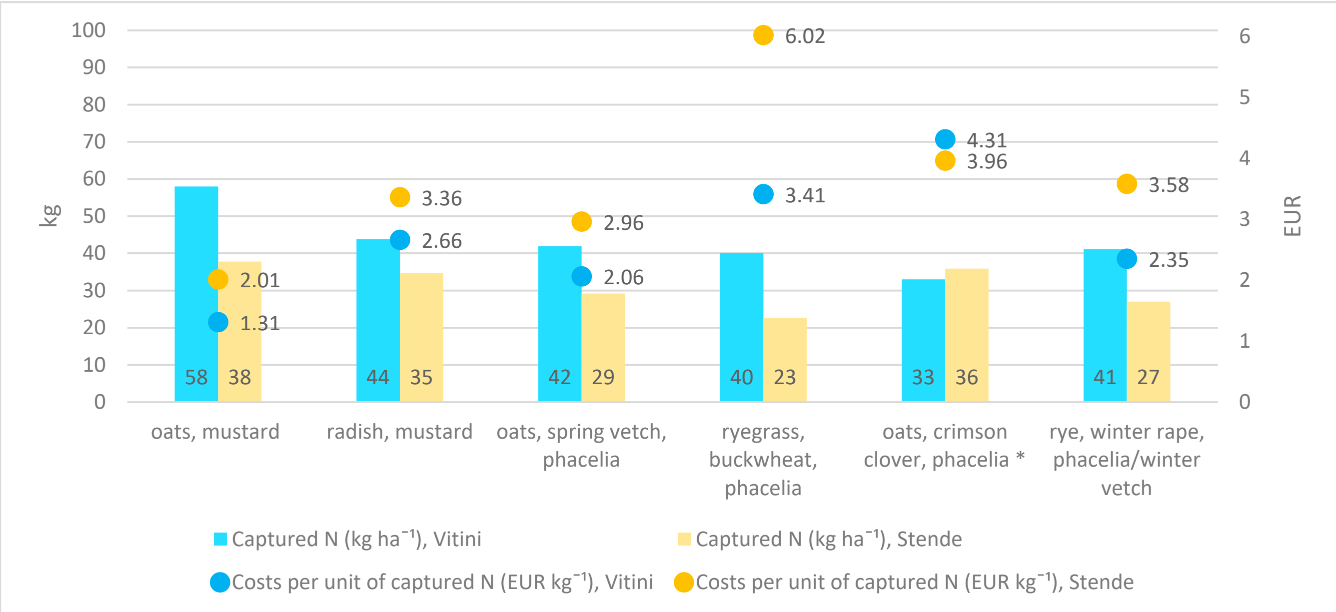


Figure 7. N (kg ha^{-1}) captured by catch crop mixtures and costs (EUR kg^{-1}) per unit of captured N according to field trials in Stende and Vitini in 2021. * Phacelia was not included in the mixture all years.

The capacity of the catch crop mixtures to capture N varied depending on the trial location and the composition of the mixture, ranging from 23 to 58 kg N ha^{-1}. Generally, higher levels of captured N were observed in the field trials conducted in Vitini compared to the field trials in Stende. The mixture containing mustard and oats exhibited the best ratio of captured N to cost per unit, whereas the mixtures of ryegrass, buckwheat, and phacelia and oats, spring vetch, and phacelia had higher production costs and relatively lower amounts of captured N.

4. Discussion

The PSF have proposed a minimum NUE of 70% for crop production as an important criterion of substantial contribution to the protection and restoration of biodiversity and ecosystems (the sixth environmental objective) within the framework of the EU Taxonomy [27,28]. Thus, NUE is likely to play a significant role in assessing the environmental suitability of crop production. The findings of this study indicate that achieving the minimum NUE is challenging. Only wheat rotation and various cereals rotation demonstrated an average NUE above 70%. Green maize–other field crops rotation also showed an average NUE above the threshold, although the confidence interval was extremely wide. When excluding biological N fixation, crop rations including pulses (wheat–pulses, wheat–oilseed rape–pulses) also exhibited an average NUE above the threshold. On the other hand, crop rotations that include oilseed rape, particularly the common wheat–oilseed rape rotation, had an average NUE below the threshold, even after adjusting for the N content of winter rapeseed.

Although the divergent results of the field case studies limited their interpretation from the perspective of the minimum NUE criterion, they did demonstrate that the long-term practice of reduced tillage supported a high NUE (above 70%), even when incorporating pulses and oilseed rape in the crop rotation. The results of the field trials mainly indicated the relative performance of catch crops. However, these results implied the potential contribution of catch crops in achieving a minimum NUE of at least 70%. For example, the mixture of oats, crimson clover, and phacelia demonstrated an increase of 13% in the average NUE. Such an increase is considerable and can help to raise the NUE above the threshold of 70%.

It should be mentioned that the divergent findings of this study regarding the effect of tillage types on NUE are similar to the findings of other studies. For example, Smith and Chalk reported that their results indicated a minimal impact of tillage on N mineralization, immobilization, and NUE [51]. An ^{15}N labeling study conducted in Northern China reported that long-term no-tillage with wheat straw incorporation alleviated N limitation compared with conventional tillage and increased straw N recovered as particulate organic matter N [52]. Although this study did not specifically focus on NUE, its findings implied that no-till and, possibly, reduced tillage can increase NUE. Additionally, according to the study by Price et al., reduced tillage and no-till can reduce NO_{3^-} leaching loss by up to 20% [53]. Therefore, this study, which is also referred to by the PSF, suggests that reduced tillage and no-till have a meaningful potential to increase NUE.

We introduced a novel approach with respect to how to assess the environmental performance of catch crops: calculation of field-level NUE for two-year period that covers both the year before the catch crop and the year after the catch crop (see Section 2.1). This approach has not been used in previous studies. This new approach can be easily incorporated into typical field trials, as it requires hardly any additional operations and data recording. This approach is quite general and straightforward. Therefore, it can be implemented not only in Latvia or Baltic counties but also in other countries/regions. It can also be applied to meta-analysis.

The Latvian Rural Advisory and Training Centre prepares annual gross margin calculations for the main agricultural products in Latvia [35]. These calculations are essential for both newcomers and established farms, as they serve as a basis for planning, representing the optimal production technology. For the past five years, the gross margin calculations for field crops by the LRATC in collaboration with sector experts (farm managers) have also included the results for reduced tillage systems.

Based on the presented gross margins calculated by LRARC, winter oilseed rape consistently emerges as the most profitable crop. Winter wheat follows winter oilseed rape as the next most profitable crop. In certain years, the gross margin of faba beans competes with that of winter wheat, although its ranking is more volatile from year to year. The leading crops in N consumption are winter wheat, winter oilseed rape, green maize, and summer oilseed rape. The crops with the highest average consumption of PPPs are oilseed rape, winter wheat, field peas, and faba beans. These results are generally in line with the findings of our study for the monitored fields.

Regarding the difference between ploughing and reduced tillage, the results from LRARC indicate that winter wheat in reduced tillage generated a slightly better result (almost +20 EUR ha^{-1}, on average, annually over five years, reaching +50 EUR ha^{-1} in 2022). The main contribution to the higher gross margin was lower costs of agrotechnical operations and less fertilizer used. In contrast, winter oilseed rape under reduced tillage demonstrated poorer economic performance, consistently yielding a lower gross margin (on average, -135 EUR ha^{-1} annually in a five-year period). This result can be attributed to higher costs of PPPs and fertilizer, despite lower costs of agrotechnical operations.

When considering equal planned yields for ploughing and reduced tillage instead of yields associated with optimal technology and impacted by weather conditions, technological crop models for Latvia have been developed within the EIP-Agri project "Development of electronic farm management system" [54]. According to the latest version of these models, the gross margin of winter wheat with a planned yield of 5 tonnes per ha under reduced tillage is by about 20 EUR ha^{-1} higher. This is due to the lower costs of agrotechnological operations, as N consumption, fertilizer, and PPP costs are higher. When considering winter oilseed rape with a planned yield of 3 tonnes per hectare, the gross margin under reduced tillage is almost the same. Similar to winter wheat, this is achieved by reduced agrotechnical operational expenses, despite higher fertilizer and PPP costs.

Crop production is undergoing significant changes and awaiting a new equilibrium. The rising costs of resources, specifically nitrogen (N), have significantly altered the agricultural landscape, compelling farmers to address issues that were previously considered less important. While in the past, NUE was primarily associated with mitigating N leaching and other environmental concerns, in today's scenario, issues related to nitrogen use not only impact public interests but also directly influence the economic viability of farms. Consequently, the solutions and practices that tackle these challenges have become critically important and require the generation of new knowledge. This newfound significance emphasizes the need for a deeper understanding of NUE issues that could support decision-making processes both at the farm level and in the formulation of future policies.

5. Conclusions

Crop rotation in Latvia tends to be monotonous, with wheat and oilseed rape dominating over 60% of the cultivated conventional area due to their profitability. The incorporation of pulses and other protein crops into crop rotation is not yet widely adopted, resulting in a missed opportunity to fix nitrogen from the atmosphere.

The findings of this study indicate that achieving a minimum NUE of 70% (as proposed by the PSF) is challenging. Crop rotations including oilseed rape, particularly the common wheat–oilseed rape rotation, have an average NUE below the proposed threshold.

The use of catch crops as intermediate crops is not yet common in crop production in Latvia, as revealed by crop rotation analysis, primarily due to the prevailing practice of cultivating winter crops as main crops. However, it is anticipated that the availability of areas for catch crops will increase with the introduction of more legumes or other spring crops into the crop rotation. Three-year field trials demonstrate that proper use of catch crops may increase nitrogen use efficiency (NUE) by up to 7–9%. These results imply that catch crops may decrease the leaching of nitrogen from cropping systems, which leads to less nitrogen pollution in the environment. Our literature review and field study suggest that non-legume-based and legume-based catch crop mixtures may be a promising approach to increase multiservices in cropping systems.

As in previous studies carried out by other researchers, the three-year field trials on commercial farms, where various tillage practices were applied, yielded divergent findings about the impact of conventional, reduced, and no-tillage practices on NUE. However, the field trials in the farm that has practiced reduced tillage (min-till and strip-till) for more than ten years, show a higher NUE for reduced tillage compared to ploughing. The advantage of reduced tillage was also supported by the obtained results indicating lower costs of agrotechnical operations, including less diesel consumption.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agriculture13081539/s1, Figure S1: Farm field monitoring questionnaire form.

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