EFFECT OF CROP ROTATION ON NITROGEN USE EFFICIENCY– CASE STUDY OF LATVIA

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Abstract. Nitrogen losses from crop production have several negative effects on environment and human health: nitrogen emissions in form of nitrous oxide, which is one of the greenhouse gases (GHG), contribute to climate warming that affects biodiversity in different ecosystems; nitrogen leaching contaminates above- and belowground waters causing environmental pollution/eutrophication and affecting drinking water quality. The Platform on Sustainable Finance has proposed nitrogen use efficiency (NUE) as an important criterion to assess the environmental sustainability of crop production in the framework of the EU Taxonomy. Moreover, the Platform has proposed a minimum NUE 70% for crop production. As there is still a lack of knowledge about NUE in crop production in Latvia, especially in conventional and integrated crop production, the aim of the study was to examine NUE for most frequent crop rotations in conventional and integrated crop production in Latvia. The most frequent (typical) crop rotations were identified according to the crop fields' survey (period 2018-2021) as well as the spatial analysis of arable land in Latvia. The empirical data derived from the crop fields' survey have been used to assess NUE. The crop fields' survey implies that the majority of the fields were managed as two-crop and three-crop rotations; however, some farmers practised the wheat monoculture. The results of this study suggest that NUE is quite low for practised crop rotations in conventional and integrated farming in Latvia and that ensuring minimum NUE at least 70% could be challenging.

Keywords: nitrogen use efficiency, nitrogen balance, crop rotation, GHG emissions.

Introduction

The use of nitrogen fertilisers in the world has increased significantly in recent decades; however, the yield of crops has not increased proportionally to these nitrogen fertilisers used [1]. It points to the significant inefficiency of the use of nitrogen fertilisers. Nitrogen losses from crop production cause several negative effects on environment and human health. Nitrogen emissions from arable lands, primarily in response to enhanced nitrogen fertilisers use, mainly in form of nitrous oxide, N_2O, which is one of the greenhouse gases (GHG), affect biodiversity in different ecosystems indirectly by climate change. N_2O has been registered as the dominant ozone-depleting substance emitted in the 21st century, and due to depletion of the stratospheric ozone layer also an increase in occurrence of skin cancers has been observed. Nitrogen losses in form of nitrates, NO_3^-, by leaching contribute to eutrophication and acidification of aquatic ecosystems, as well as to pollution of groundwater and drinking water [2-5].

The reduction of nitrogen losses is also relevant in the framework of the EU Taxonomy as it is closely related to the environmental objectives established by the Taxonomy Regulation [6], especially to climate change mitigation and the protection and restoration of biodiversity and ecosystems. In August 2021 the Platform on Sustainable Finance proposed nitrogen use efficiency (NUE) as an important criterion to assess the environmental sustainability of crop production in the framework of the EU Taxonomy [7]. Moreover, the Platform proposed a minimum NUE 70% for crop production. This 70% threshold has raised concerns about achieving this level of NUE in Latvia's conventional and integrated crop production [8].

Recently, research on nitrogen efficiency for various field crops has become relevant, e.g. cotton [9], cereals [10], etc. Nevertheless, there is still a lack of knowledge about NUE in crop production in Latvia, especially in conventional and integrated crop production. Therefore, the aim of the study is to examine NUE for most frequent crop rotations in conventional and integrated crop production in Latvia. The study also attempts to assess the possibilities (probabilities) for different crop rotations to achieve this 70% threshold.

Materials and methods

The empirical data for this study have been derived from the 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". Farmers reported detailed information about their fields, including the sowing rate of field crop, use of fertilisers and field crop yield. The data processing methods used in this study reduced the measurement errors made by individual farms and their impact on the summary result. In total, 118 anonymous field data of the crop fields' survey (carried out in a four year period from 2018 to 2021) have been used to assess nitrogen use efficiency (NUE). The data on fields managed under conventional or integrated farming, where only synthetic fertilisers (not using organic fertilisers) had been used, were investigated in this case study. The most frequent (typical) crop rotations were identified according to the survey as well as the spatial analysis of arable land in Latvia (also conducted within this EIP-AGRI project).

NUE, which is an indicator for resource use efficiency, is calculated for each field by using the following formula:

$$NUE = \frac{\sum(Noutput)}{\sum(Ninput)} * 100, \tag{1}$$

where NUE – nitrogen use efficiency, %;
$Noutput$ – nitrogen removed with yield (for period 2018-2021), kg·ha^{-1};
$Ninput$ – nitrogen input with seed and synthetic fertiliser (for period 2018-2021), kg·ha^{-1}.

Noutput and *Ninput* are calculated as the sum of annual $Noutput_i$ and $Ninput_i$. Annual $Noutput_i$ for every field is calculated by using formula (2).

$$Noutput_i = Y_i * Ncont_Y, \tag{2}$$

where $Noutput_i$ – nitrogen removed with yield in year *i*, kg;
Y_i – dry matter yield, t·ha^{-1};
$Ncont_Y$ – nitrogen content in dry matter yield, kg·t^{-1} dry matter.

Nitrogen content of dry matter yield for every field crop is derived from the values by A.Karklins and A.Ruza (see Table 1) [11]. Annual $Ninput_i$ for every field is calculated by using the following formula:

$$Ninput_i = Ns_i + Nfert_i + Nfix_i, \tag{3}$$

where $Nintput_i$ – nitrogen input in year *i*, kg·ha^{-1};
Ns_i – nitrogen input with seed in year *i*, kg·ha^{-1};
$Nfert_i$ – nitrogen input with synthetic fertilisers in year $_i$, kg·ha^{-1};
$Nfix_i$ – nitrogen biologically fixed by grain legumes in year *i*, kg·ha^{-1}.

Ns_i is assessed in the same way as $Noutput_i$ by applying the same $Ncont_Y$. According to the research project "Legume-supported cropping systems for Europe (Legume Futures)", on average each yield tonne of field beans fixes 62.4 kg N, field pea – 40.2 kg N, but vetches – 63.2 kg N [12]. These values are used to calculate $Nfix_i$.

Table 1

Nitrogen removal with yield of different field crops

Field crop	Product	Dry matter, %	N content, kg·t^{-1} dry matter
Winter wheat	Grain	86	22.0
Winter wheat (protein content > 13.5%)	Grain	86	27.3
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, field beans	Seeds	86	45.7
Winter rapeseed	Seeds	92	29.1
Spring rapeseed	Seeds	92	38.3

Source: derived from A.Karklins and A.Ruza [11]

The results of the survey reveal four groups of crop rotation – monoculture (5 fields), two-crop rotation (51 fields), three-crop rotation (50 fields) and four-crop rotation (12 fields). There have been indentified separate crop rotations in each group, except for four-crop rotation (see Table 2). The crop rotations have been identified according to the number of crops (similar crops) recorded in the period 2018-2021 regardless of the sequence of crops or the frequency in the sequence. Each crop rotation is treated as a separate sample.

The methods of descriptive statistics and inferential statistics have been used in this study. First, the indicators of descriptive statistics (average NUE (mean, $\bar{x}$) and standard deviation(s)) have been calculated for each crop rotation (sample). Second, 90% confidence intervals (CI) have been determined for average NUE and standard deviation. Confidence interval for average (NUE) is determined by using a t-statistic (Student distribution). In addition, relative standard error (RSE) has been assessed. Confidence interval for standard deviation is determined by using Chi-Square critical values (chi-squared distribution).

Third, in order to explore the range of NUE in population, fractile 0.05 and fractile 0.95 have been assessed as the lower value and upper value. The inverse cumulative function of normal distribution $\Phi^{-1}(p)$ has been used to assess these fractiles:

$$NUE_p = \Phi^{-1}(p, \mu, \sigma), \tag{4}$$

where NUE_p – fractile p;
$\Phi^{-1}(p,\mu,\sigma)$ – inverse cumulative function of normal distribution;
p – probability (0.05 or 0.95);
μ – mean of population (assessed);
σ – standard deviation of population (assessed).

The most likely estimates of fractile 0.05 and fractile 0.95 have been assessed by applying average NUE (sample mean) and sample standard deviation. In addition, 90% confidence intervals have been determined for both fractiles by using the lower bound and upper bound of the mean's and standard deviation's CI. The lower bound of fractile 0.05 has been assessed by applying the lower bound of the assessed mean and the upper bound of the assessed standard deviation. The upper bound of fractile 0.05 has been assessed by applying the upper bound of the assessed mean and the lower bound of the assessed standard deviation. The lower bound of fractile 0.95 has been assessed by applying the lower bound of the assessed mean and the lower bound of the assessed standard deviation. The upper bound of fractile 0.95 has been assessed by applying the upper bound of the assessed mean and the upper bound of the assessed standard deviation.

Fourth, in order to assess the chances that indentified crop rotations can achieve the minimum NUE at least 70% proposed by the Platform (see above), the probability that NUE is equal or higher than 70% ($p(NUE \geq 70\%)$) has been assessed for crop rotations. The cumulative distribution function of normal distribution $\Phi(x)$ has been used for these assessments:

$$p(NUE \geq 70\%) = 1 - \Phi(70\%, \mu, \sigma), \tag{5}$$

where $p(NUE \geq 70\%)$ – probability that NUE ≥ 70%;
$\Phi\,(70\%,\mu,\sigma)$ – cumulative function of normal distribution.

The most likely estimate of $p(NEU \geq 70\%)$ has been estimated by applying average NUE (sample mean) and sample standard deviation. In addition, the 90% confidence intervals have been determined for $p(NUE \geq 70\%)$. The lower bound and upper bound of $p(NUE \geq 70\%)$ have been assessed by applying the lower and upper bound of average NUE and standard deviation (calculating the 4×4 matrix). The bounds of CI have been derived from the minimum and maximum value in the 4×4 matrix respectively.

Results and discussion

The results of the crop fields' survey indicate that most of the fields were managed as two-crop rotations and three-crop rotations (see Fig. 1). Twelve fields were managed as four-crop rotations, however, almost every field had its own crop rotation. Therefore, these fields are excluded from further analysis (NUE is not calculated for these fields).

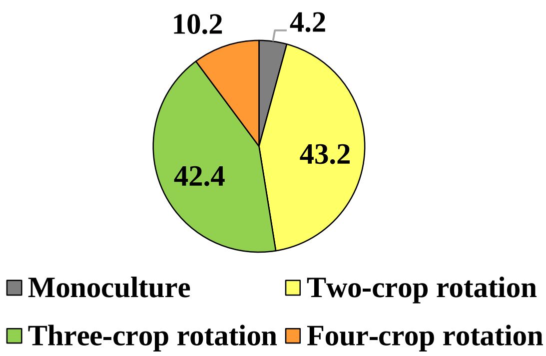

Fig. 1. **Structure of identified crop rotations, %**

The only monoculture system recorded in the field survey was wheat (winter, spring) monoculture, and 60% of these fields were comprised of solely winter wheat monoculture. In total, five different two-crop rotations were registered, with dominance of rapeseed–wheat crop rotation (78% of all two-crop rotation fields). Other two-crop rotations were: wheat–legumes (12% of all two-crop rotation fields), wheat–barley (6%), wheat–fallow and oats–wheat (one case of each). In total, 10 different three-crop rotations were registered, with dominance of wheat–legumes–rapeseed crop rotation (40% of all three-crop rotation fields), followed by barley–wheat–rapeseed (22%), wheat–rapeseed–fallow (12%), rapeseed–wheat–rye (8%), rapeseed–oats–wheat (6%), wheat–rye–oats (4%). Other three-crop rotations were separate cases (see Table 2).

Based on the methodology, the data and the assumptions described above, the indicators of descriptive statistics and inferential statistics have been assessed for monoculture, two-crop rotation and three-crop rotation. The assessed average NUE and its variation (standard deviation) are presented in Table 2.

Table 2

Average NUE (%) and its variation for different crop rotations (for period 2018-2021)

Crop rotation	*n*	Average (mean)			Standard deviation	
		$\bar{x}$	CI 90%	RSE	*s*	CI 90%
Monoculture:						
Wheat (winter, spring)*	5	77.4	(69.0, 85.8)	5.1%	8.8	(5.7, 21.0)
Winter wheat	3	73.5	(58.2, 88.7)	7.1%	9.0	(5.2, 39.9)
Two-crop rotation:						
Rapeseed, wheat	40	62.3	(59.4, 65.2)	2.8%	10.9	(9.2, 13.4)
Wheat, legumes	6	67.2	(62.1, 72.3)	3.8%	6.2	(4.2, 13.0)
Wheat, barley**	3	78.1	(45.4, 100.0)	14.3%	19.4	(11.2, 85.5)
Wheat, fallow	1	63.8	N.A.	N.A.	N.A.	N.A.
Oats, wheat	1	77.2	N.A.	N.A.	N.A.	N.A.
Three-crop rotation:						
Wheat, legumes, rapeseed	20	64.1	(61.7, 66.6)	2.2%	6.4	(5.1, 8.7)
Barley, wheat, rapeseed	11	65.4	(58.8, 72.0)	5.6%	12.1	(8.9, 19.3)
Wheat, rapeseed, fallow	6	66.3	(55.6, 77.1)	8.1%	13.1	(8.8, 27.4)
Rapeseed, wheat, rye	4	61.9	(54.5, 69.4)	5.1%	6.3	(3.9, 18.5)
Rapeseed, oats, wheat	3	67.1	(57.4, 76.8)	4.9%	5.7	(3.3, 25.3)
Wheat, rye, oats	2	60.3	N.A.	N.A.	N.A.	N.A.
Barley, wheat, rye	1	55.5	N.A.	N.A.	N.A.	N.A.
Wheat, legumes, barley	1	86.7	N.A.	N.A.	N.A.	N.A.
Barley, wheat, fallow	1	76.6	N.A.	N.A.	N.A.	N.A.
Fallow, wheat, legumes	1	96.7	N.A.	N.A.	N.A.	N.A.

* includes also winter wheat monoculture

** sample does not represent the population appropriately due to very high sampling error

N.A. – not possible to assess/determine

Source: the authors' calculations

The assessed other indicators (fractile 0.05 and fractile 0.95 as well as $p(NUE \geq 70\%)$) are presented in Table 3.

Table 3

Other indicators of NUE (%) for different crop rotations (for period 2018-2021)

Crop rotation	Fractile 0.05		Fractile 0.95		$p(NUE \geq 70\%)$	
	Most likely	CI 90%	Most likely	CI 90%	Most likely	CI 90%
Monoculture:						
Wheat (winter, spring)*	62.8	(34.5, 76.4)	91.9	(78.4, 100.0)	79.8%	(42.9%, 99.7%)
Winter wheat	58.6	(0.0, 80.1)	88.3	(66.8, 100.0)	64.9%	(1.2%, 100.0%)
Two-crop rotation:						
Rapeseed, wheat	44.4	(37.4, 50.1)	80.2	(74.6, 87.3)	24.0%	(12.5%, 36.0%)
Wheat, legumes	57.0	(40.8, 65.4)	77.4	(68.9, 93.6)	32.3%	(2.8%, 70.6%)
Wheat, barley	46.2	(0.0, 92.3)	100.0	(63.8, 100.0)	66.2%	(1.4%, 100.0%)
Three-crop rotation:						
Wheat, legumes, rapeseed	53.7	(47.3, 58.3)	74.6	(70.0, 81.0)	17.9%	(5.0%, 34.9%)
Barley, wheat, rapeseed	45.5	(27.1, 57.3)	85.3	(73.5, 100.0)	35.2%	(10.5%, 58.9%)
Wheat, rapeseed, fallow	44.7	(10.4, 62.6)	87.9	(70.1, 100.0)	39.0%	(5.1%, 78.9%)
Rapeseed, wheat, rye	51.5	(24.1, 62.9)	72.4	(61.0, 99.8)	10.1%	(0.0%, 48.7%)
Rapeseed, oats, wheat	57.7	(15.8, 71.3)	76.5	(62.9, 100.0)	30.6%	(0.0%, 97.9%)

* includes also winter wheat monoculture

Source: the authors' calculations

The results of this study indicate that there are wide (in some cases, extremely wide) confidence intervals for average NUE and its standard deviation. Moreover, some crop rotations have high RSE. Therefore, the generalisation of these findings is limited. However, it is possible to draw quite an unambiguous conclusion that wheat (winter, spring) monoculture has higher NUE than rapeseed–wheat rotation on average (with 90% confidence) because the confidence intervals for averages do not overlap.

The assessment of fractile 0.05 and fractile 0.95 shows a very wide range for almost all crop rotations and thus implies that NUE values are volatile even for the four year period. Moreover, the confidence intervals for the fractiles are very wide. The most likely estimates of fractile 0.95 exceed 70% threshold for all the crop rotations in Table 3. Nevertheless, the lower bound of the confidence interval is below 70% for several crop rotations indicating that these crop rotations have possibly a low chance (even below 5%) to achieve NUE 70%.

The most likely estimates of $p(NUE \geq 70\%)$ imply that only three crop rotations (wheat (winter, spring) monoculture, winter wheat monoculture and wheat–barley rotation) have higher than 50% probability to achieve/exceed the 70% threshold for NUE. $p(NUE \geq 70\%)$ is much lower if the lower bound of the confidence interval is considered. Actually, only wheat (winter, spring) monoculture has the reasonable value of the lower bound (42.9%). Therefore, these findings are consistent with the concerns expressed by the researchers of the Institute of Agricultural Resources and Economics [8].

Although the results of this study suggest that wheat monoculture has probably higher NUE than other crop rotations (two-crop rotation, three-crop rotation), it should be noted that these results are based on the preliminary results of the survey. The final results of the survey will cover a five year period (2018-2022) and provide more comprehensive data. Therefore, it is necessary to verify these findings when the survey is finished. The final results of the survey will allow clarifying typical crop rotations as well as possibly reducing sampling errors (narrowing confidence intervals).

Among the EU countries monoculture systems that include cereals are mostly identified in Northern Europe. However, monoculture systems are not advised as they increase the risk of contamination the arable fields with the same pests and weeds can negatively affect soil quality, lead to decrease of biodiversity in the rural landscape [13].

Conclusions

1. The fields' survey showed that in the four year period 85% of studied fields were managed as two-crop and three-crop rotations, dominated by crop rotations with wheat, rapeseed and grain legumes.

2. On average, wheat (winter, spring) monoculture has higher NUE (average NUE 77.4%) than rapeseed–wheat rotation (62%) with confidence 90%, as their confidence intervals do not overlap.
3. The preliminary results of this study suggest that NUE is quite low for practised crop rotations in conventional and integrated farming in Latvia and that ensuring minimum NUE at least 70% could be challenging. Only three crop rotations (wheat (winter, spring) monoculture, winter wheat monoculture and wheat–barley rotation) have higher than 50% probability to achieve/exceed this 70% threshold.
4. The results of the study have been derived from the preliminary results of the field survey that covers only a four year period (2018-2021). When the field survey is finished, it will cover a five year period (2018-2022) and provide more comprehensive data. These results could allow reducing sampling errors and carrying out more accurate assessments of NUE.
5. This study explored only conventionally and integrated managed fields with synthetic fertilisation. Therefore, further research is required to investigate also fields with organic fertilisation and fields under organic farming.

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Author contributions:

Conceptualization, A.Auzins; methodology, A.Auzins, D.P. and A.Aboltins; validation, A.Auzins; investigation, A.Auzins, and D.P., data curation, A.Auzins; writing-original draft preparation, A.Auzins, D.P. and A.Aboltins; writing-review and editing, A.Auzins, D.P. and A.Aboltins; visualization, D.P. and A.Auzins; project administration, A.Auzins. All authors have read and agreed to the published version of the manuscript.

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