Nitrogen Fertilization of Grass Leys: Yield Production and Risk of Nitrogen Leaching

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Abstract. The soil surface balance of nitrogen (N), calculated as the difference between N inputs and output, is a principal agri-environmental indicator that provides information on the potential loss of N to surface or groundwater. (Research purpose) Determination of relevant models of yield response to N fertilization could prove helpful in minimizing N balance and simultaneously maintaining high-yield production. (Materials and methods) The authors used meta-analysis to quantitatively summarize 40 N fertilization experiments on perennial grass leys in Finland and assessed the effect of inorganic N fertilization on grass yields and N balances, and further estimated potential to reduce N input and N balances. The relationship was estimated by using the COUP model (a coupled heat and mass transfer model for ‘soil-plant-atmosphere’ systems) and by reviewing the 12 Nordic studies on N leaching experiments involving lysimeters and drained field plots. (Results and discussion) It was found that the optimal N content in mineral soils is 230 kilograms per hectare, in organic – 190. In the first case, the economic effect of nitrogen introduction is 206 euro per hectare, in the second one – 62. (Conclusions) The developed yield response models can serve to construct a dynamic tool for growers to adjust N applications for maximizing economic profitability. The authors proved that the values predicted by the COUP model for N leaching losses after the application of mineral N fertilizer to perennial grass leys were in accordance with the low values measured, which ranged from 1.2 to 10-15 kilograms per hectare a year in Finland and in the Nordic-Baltic countries. It was also revealed that a possible risk of N leaching losses when using only inorganic N fertilization seems less crucial due to its low level and weak association with N balances.

Keywords: yield; grass leys; nitrogen balance; nitrogen leaching; meta-analysis; coupled heat and mass transfer model.

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Внесение азотных удобрений на лугах и пастбищах: урожайность и риск азотного выщелачивания

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Реферат. Баланс содержания азота в верхнем слое почвы, рассчитанный как разница между количеством внесенного и остаточного азота, считается основным агроэкологическим показателем, который предоставляет информацию о возможном выносе азота с поверхностными или грунтовыми водами. (Цель исследования) Определить модели зависимости урожайности зеленой массы от количества внесенного азотного удобрения, которые могут быть использованы для минимизации баланса азота и одновременного поддержания высокого урожая трав. (Материалы и методы) На основе мета-анализа осуществили количественную оценку результатов 40 опытов по азотной подкормке многолетних травяных угодий в Финляндии. Изучили влияние неорганического азотного удобрения на
урожай трав и баланс азота, а также перспективы снижения потребления азота и баланса азота. Для оценки использовали сопряженную модель тепломассопереноса для систем «почва – растение – атмосфера». Осуществили 12 экспериментов по выщелачиванию азота в северных широтах. Провели лизиметрические исследования. Изучили осушенные участки лугов и пастбищ. (Результаты и обсуждение) Установили, что оптимальное содержание азота в минеральных почвах составляет 230 килограммов на гектар, в органических – 190. В первом случае экономиче-

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**N balance (kg ha\(^{-1}\) yr\(^{-1}\)) = N input (kg ha\(^{-1}\)yr\(^{-1}\)) – N output (kg ha\(^{-1}\)yr\(^{-1}\)),**

(1)

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**ЭКОЛОГИЯ**

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Иn the Nordic-Baltic countries, grass leys usually receive substantial amounts of N fertilizer, which may lead to high N balances of up to 130 kg ha\(^{-1}\) yr\(^{-1}\) [1]. Reducing N inputs should prove to be an effective environmental practice that directly affects soil N balances, as demonstrated for spring cereals [2]. Moreover, adjusting N input according to yield response models causes no economic loss.

Soil surface N balance is a principal agri-environmental indicator that provides information on the potential loss of N to surface or groundwater. However, the link between N balance and N leaching loss from grass leys as well as from cereals measured at field and catchment scales is often complex and may vary widely across different soils, crops, N sources and managements [1, 3, 4]. For grasses, in only a few studies on sandy soils, did researchers calculate the regressions for ungrazed [5] and grazed [6] grassland fertilized with both inorganic N fertilizers and slurry. According to the regressions, for example, an average European N balance of 65 kg ha\(^{-1}\) yr\(^{-1}\) [7] would correspond to an N leaching loss of 18 kg ha\(^{-1}\) yr\(^{-1}\) [5] or 30 kg ha\(^{-1}\) yr\(^{-1}\) [6]. Although these losses seem adequate for slurry applications, they may represent overestimations when applying only inorganic fertilizer to ungrazed grassland.

**The research purpose** is to explore the relationships between N rates and grass yield responses, N balances, and N leaching loss, after applying only inorganic N fertilizer to ungrazed perennial grass leys.

**MATERIALS AND METHODS.** For this purpose, we summarized 40 relevant Finnish field experiments conducted on mineral and organic soils during the last five decades and estimated the potential to reduce N balances without sacrificing yield. We further estimated N leaching losses from N balances by using the COUP model and by reviewing the 12 Nordic studies on N leaching experiments involving lysimeters and drained field plots.

The database of grass yield response to inorganic N fertilization consisted of published and unpublished reports of experiments conducted at MTT Agrifood Research Finland (Jokioinen, Finland) and other Research Stations. The main grass species were timothy (Phleum pratense L.), meadow fescue (Festuca pratensis L.), cocksfoot grasses (Dactylis glomerata), and a mixture of them. In addition, two studies included tall fescue (F. arundinacea) and bromegrass (Bromus inermis).

Altogether 40 experiments took place between 1957 and 2004 at 17 sites on clay – 11 studies, coarse-textured mineral soils – 21 studies and organic soils – 8 studies (Fig. 1). A total of 28 studies reported ranges of soil pH, determined in water suspension, from 4.7 to 7, and of the precise soil organic matter (SOM) content in topsoil, from 2.5 to 45.7%. Four studies reported SOM content as a class (“medium”, 3-6%, or “rich”, 6-12%), while the remaining eight studies failed to report it. Fertilizer P (mean 40 kg ha\(^{-1}\)) and K (mean 100 kg ha\(^{-1}\)) were applied according to the existing recommendations in order to provide sufficient amounts for grass growth. The annual application of N ranged from 50 to 600 kg ha\(^{-1}\).

**Response and explanatory variables**

As response variables, the database for the meta-analysis included the total DM of the grass leys (kg ha\(^{-1}\)) and N balance (kg ha\(^{-1}\) yr\(^{-1}\)). We calculated the soil surface N balance as described in [8]:
where $N_{input}$ was $N$ applied as inorganic fertilizers; $N_{output}$ was the $N$ content in the harvested yield. We calculated $N_{output}$ as follows:

$$N_{output} \text{ (kg ha}^{-1}) = \frac{\text{Protein} \times \text{DM Yield}}{a} \times 100 \%,$$

where $a$ is a coefficient equal to 6.25.

From the output we excluded any $N$ lost to the environment through the volatilization of ammonia or denitrification, or leaching, as well as from $N$ input asymbiotic $N$ fixation and atmospheric deposition, the latter in Finland amounting to 4-6 kg ha$^{-1}$ [9]. A negative $N$ balance thus roughly indicates depletion of the soil $N$ stocks, whereas a positive balance correlates to accumulation that can increase the risk of losses to the environment.

**Effect size calculation**

Meta-analysis and the Meta Win 2.0 statistical program served to analyze the effects of $N$ fertilization on grass yield and $N$ balance [10]. For yield data, we used the response ratio (the ratio of mean outcome in the experimental group to that in the control group) as an index of the effect size [11]. We calculated a separate estimate of the natural logarithm of the response ratio for each site, $N$ rates and randomly selected grass species as:

$$\ln r = \ln \left( \frac{X_{PKN}}{X_{PK}} \right),$$

where $X_{PKN}$ and $X_{PK}$ represent yield means for PKN and PK (i.e., the control) treatments, respectively, averaged over the duration of an experiment. $S_{PKN}$ and $S_{PK}$ are the corresponding standard deviations, and $n_{PKN}$ and $n_{PK}$ are the sample sizes equal to the duration of an experiment in years. To measure the effect of explanatory variables on yield response and to exclude the effect of increasing $N$ rates, we selected one $N$ rate, between 117 and 208 kg N ha$^{-1}$ with a mean of 158 kg N ha$^{-1}$, per study to ensure statistical independence of $\ln r$.

We then back-transformed log response ratios and reported them in the text as percentage changes from the control:

$$\text{Yield response } (%) = \left[ \exp(\ln r) - 1 \right] \times 100.$$

We considered responses due to $N$ fertilizer to be significantly different from the control if their 95% CIs did not overlap with zero.

**Yield response models**

Data for yield response models of mineral soils were available from 23 early and 9 recent experiments, from which we randomly selected one grass species or grass mixture and one $N$ rate per study to ensure statistical independence of $\ln r$. However, due to the small number of studies on organic soils (five early and three recent studies), we selected one grass species or grass mixture and two to three $N$ rates per study, resulting in 20 observations.

We tested possible sources of variation prior to building a model. To develop a model, we pooled experiments in which variances in the yield response showed no significant difference from those predicted by sampling error alone. We used a two-dimensional Gaussian function to describe the relationship between rising $N$ rates, $N_{0yield}$ and yield response:

$$\ln r = a e^{-0.5 \left[ \left( \frac{N_{0yield} - x_i}{b} \right)^2 + \left( \frac{N - y_i}{c} \right)^2 \right]},$$

where $\ln r$ is the yield response; $N_{0yield}$ is the control yield without added $N$; $N$ is $N$ rates; $b$ and $c$ are standard deviations of $x$ and $y$, respectively; $x_i$ and $y_i$ is the center of the model; $a$ is amplitude.

We ran the models using the SigmaPlot 12.0 program (SYSTAT Software, San Jose, CA, USA) with weights defined by the reciprocal of the sample variance. The Shapiro-Wilk test served to determine whether the weighted residuals (observed yield increase – estimated yield increase) of the model were normally distributed (SYSTAT Software).

**Calculation of economically optimal $N$ rates ($N_{opt}$)**

The following calculation served to derive the grower’s profit from the application of $N$ [12]:

$$\text{Profit (} \varepsilon \text{ ha}^{-1}) = \left[ \text{Yield increase due to } N \text{ fertilization (kg ha}^{-1} \right] \times \text{DM yield value (} \varepsilon \text{ kg}^{-1}) - \left[ \text{Applied N (kg ha}^{-1} \right] \times \text{N fertilizer price (} \varepsilon \text{ kg}^{-1})].$$
We considered the profit from the application of N optimized when the difference between the extra income due to the yield increase and the cost of the N fertilizer was at its peak value. The average value of the yield increase term originated from the two-dimensional Gaussian function (Eq. 5). In calculating examples of \( N_{\text{opt}} \), we set the average \( N_{\text{yields}} \) to 3900 and 4500 kg ha\(^{-1}\) for mineral and organic soils, respectively, and the high \( N_{\text{yields}} \) to 6000 and 8000 kg ha\(^{-1}\), respectively. We calculated examples of \( N_{\text{opt}} \) for the prices of N fertilizer (1 € kg\(^{-1}\)) and the DM yield values of grass leys (0.1 € kg\(^{-1}\)), thus yielding a fertilizer N-to-yield price ratio of ten.

**Linear regression analysis**

We used a simple linear regression to examine the relationship between N rates and N balances:

\[
N_{\text{bal}} = y_0 + aN,
\]

where \( N_{\text{bal}} \) is the N balance (kg ha\(^{-1}\) y\(^{-1}\));
\( N \) is the N fertilizer rate (kg ha\(^{-1}\));
\( y_0 \) is the intercept parameter;
\( a \) is the slope parameter.

We derived data from 21 early and 7 recent studies on mineral soils and 4 early and 3 recent studies on organic soils. To avoid bias, we randomly selected one grass species and one N rate per study for the linear regressions, and the average annual N balance for the duration of an experiment served as a dependent variable. We also tested the data for normal distribution and equal variance.

**COUP model**

Precipitation is one of the main drivers of N leaching. However, field experiments typically represent a limited combination of weather conditions, soils and cultivation practices; therefore, we used climatic data from several years as the driving force to simulate a larger set of N leaching values. The mathematical model COUP is a dynamic, process-based model for calculating water and heat flux as well as combined carbon (C) and N dynamic, process-based model for calculating water

\[
\text{bal} = \text{opt} \times \text{eq}
\]

Due to a lack of runoff water collectors in the practical grass fields, we calibrated the model against measurements of soil mineral N concentrations in spring and autumn, as well as crop N uptake. Rankinen et al. [14] previously described the original calibration.

The modeled cases included first-year grass, one year from the middle of the rotation, and the ploughing year (after three years’ of grass rotation). We then modeled N leaching and N balances to obtain the theoretical upper and lower limits for their relationship by changing the fertilization amounts in steps of 20 kg N ha\(^{-1}\). The simulations covered the range of the N balance from –100 to 150 kg ha\(^{-1}\). We simulated a set of individual cases by using one-year datasets for the entire five-year period. We therefore did not include simulated N accumulation in the soil, but started all annual simulations from the observed physical and chemical properties of the soil.

**RESULTS AND DISCUSSION**

**Yield response models**

We developed the models separately for mineral and organic soils, and since \( N_{\text{yields}} \) substantially affected the yield responses, we included it as an independent variable along with N rates (Table 1). The coefficients of determination (\( R^2 \)) indicated that the N rate and \( N_{\text{yields}} \) together accounted for 80-95% of the variation in the yield response of grass leys.

| Soil type   | \( \ln r = a e^{b x} + c [(N-y_0)b + (N-y_0)c] \) | \( a \) | \( x_0 \) | \( b \) | \( y_0 \) | \( c \) | \( R^2 \) | \( F \) test | \( n \) |
|-------------|--------------------------------------------------|-------|----------|-------|-------|-------|---------|------------|------|
| Mineral     | \( \ln r = a - 6.5 \times [(N-y_0)b + (N-y_0)c] \) | 3010  | -62253   | 16429 | 466   | 383   | 0.80    | 28          | 32   |
| Organic     | \( \ln r = b \times (N-y_0) + c \)                | 135   | -35349   | 12067 | 345   | 214   | 0.95    | 87          | 20   |

Bold numbers indicate \( P < 0.0001; \)
\( n \) indicates number of experiments for mineral soils and number of observations for organic soils. For back-transformation of \( \ln r \), see Equation 4.

The models are valid for N rates >50 kg ha\(^{-1}\) (mineral soils) and N rates >75 kg ha\(^{-1}\) (organic soils).

The models estimated that the yield response to N rates decreased considerably with increasing \( N_{\text{yields}} \) (Fig. 2). On mineral soils, for example, the largest yield response over that of the control dropped from 318% (\( \ln r = 1.43 \)) to 70% (\( \ln r = 0.54 \)) while increasing the \( N_{\text{yields}} \) from 2000 to 6000 kg ha\(^{-1}\) (Fig. 2a). Respectively, on organic soils, the largest response dropped from 200% (\( \ln r = 1.1 \)) to 23% (\( \ln r = 0.21 \)) while increasing the \( N_{\text{yields}} \) from 2000 to 8000 kg ha\(^{-1}\).

**N balance**

We performed the linear regression analysis between rising N rates and N balance (Fig. 3, Table 2). The coefficient of determination (\( R^2 \)) indicated that 86-88% of the variation in the N balance stemmed from its relationship with the N rates. On mineral soils, an increase of 10 kg N ha\(^{-1}\) associated with an average increase of 4.8 (4.1-5.6) kg ha\(^{-1}\) yr\(^{-1}\) in the N balance,
and on organic soils, with an average increase of 6.4 (3.4-9.4) kg ha\(^{-1}\) yr\(^{-1}\), respectively. According to the regressions, adding no N fertilizer yielded an N balance equal on average to –53 (–71 to –35) kg ha\(^{-1}\) yr\(^{-1}\) on mineral soils and to –123 (–203 to –42) kg ha\(^{-1}\) yr\(^{-1}\) on organic soils. We expected a zero N balance at average N rates of 110 and 192 kg ha\(^{-1}\) in mineral and organic soils, respectively.

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**Observed and simulated N leaching loss from mineral soils**

The review of published Nordic studies showed that the smallest observed annual N leaching loss was 1.2 kg ha\(^{-1}\) from clay soil and the largest value was 13 kg ha\(^{-1}\) from sand soil (Fig. 4a). Within the range of observations, N leaching showed no clear relationship with N balances. For example, a large range of N balances (e.g., –80 to 105 kg ha\(^{-1}\) yr\(^{-1}\)) across several experiments yielded annual N leaching losses as low

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**Table 2**

| Soil type | Coefficients | t  | P  | 95% CIs Low | Up | R\(^2\) | F test | P  | n |
|-----------|--------------|----|----|-------------|----|---------|--------|----|---|
| Mineral   | \(y_0 = -53\) | -6.1 | *** | -71 | -35 | 0.88 | 194 | **** | 28 |
|           | a = 0.48     | 13.9 | *** | 0.41 | 0.56 |       |        |     |    |
| Organic   | \(y_0 = -123\) | -3.9 | *  | -203 | -42 | 0.86 | 31  | **  | 7  |
|           | a = 0.64     | 5.5  | **  | 0.34 | 0.94 |       |        |     |    |

*P < 0.05; ** P < 0.01; *** P < 0.001; **** P < 0.0001; CIs, confidence intervals; n, number of experiments
as 2-4 kg ha⁻¹ (Fig. 4a). On the other hand, with a narrow range for the N balance (e.g., 10-20 kg ha⁻¹ yr⁻¹), N leaching losses varied from 2.2 to 6.0 kg ha⁻¹ yr⁻¹.

Simulated N leaching loss for the first year of grass production increased slowly, by 0.6 kg ha⁻¹ yr⁻¹, with an N balance rising from −100 to 100 kg ha⁻¹ yr⁻¹ (Fig. 4b). During production years, the N leaching loss was low (2.4 kg ha⁻¹ yr⁻¹) for the range of N balances. In contrast, for the last year of grass production involving autumn ploughing and bare soil over the following winter, simulated N leaching increased from 5.6 to 12.5 kg ha⁻¹ yr⁻¹ when N balances rose from −100 to 100 kg ha⁻¹ yr⁻¹. An N input of 110 kg ha⁻¹ would then yield a zero N balance and an N leaching loss of 8.4 kg ha⁻¹ yr⁻¹. In the driest year, however, when the simulated runoff from fields was about 210 mm, simulated N leaching during the ploughing year was low (about 2.7 kg ha⁻¹ yr⁻¹) regardless of rising N balances.

Regarding organic soils under grass leys, we were unable to simulate N leaching losses after the application of mineral N fertilizer or to survey articles published in Nordic countries due to lack of data and experiments. Estimates of Nopt, respective N balance and N leaching loss

We estimated Nopt separately for average and high N₀ yields and compared them to the Finnish Agri-Environmental Programme’s maximum permissible N rates (N_max) [15]. For both mineral and organic soils, Nopt clearly depends on N₀ yields: to maximize profit, a field with high N₀ yields requires only 20-40% of the N fertilizer needed for a field with average N₀ yields, resulting in negative N balances (Table 3).

For the average N₀ yields in mineral soils, estimates demonstrated that at a fertilizer N-to-yield price ratio of ten, Nopt is equivalent to the permitted N_max (230 kg ha⁻¹) for soils rich in SOM, yielding an N balance of 57 kg ha⁻¹ yr⁻¹ and a simulated N leaching loss of 2.4-10.6 kg ha⁻¹ yr⁻¹. In contrast, the application of permitted N_max to fields

![Fig. 4. Leaching losses:](image_url)

**Table 3**

| Estimates | Mineral soils | Organic soils |
|-----------|---------------|--------------|
|           | Nopt *        | N_max **     | Nopt | N_max |
| 230       | 50            | 230          | 190   | 75   |
| N₀ yield (kg ha⁻¹) | 3900 (average) | 6000 (high) | 6000 (high) | 4500 (average) | 8000 (high) | 8000 (high) |
| Yield increase due to N (kg ha⁻¹) | 4400 | 2100 | 3400 | 2500 | 800 | 1400 |
| Profit from N fertilizer (€ ha⁻¹)*** | 206 | 159 | 106 | 62 | 6 | −48 |
| N balance (kg ha⁻¹ yr⁻¹) | 57 | −29 | 57 | −1 | −75 | −1 |
| Simulated N leaching losses (kg ha⁻¹ yr⁻¹) **** | 2.4-10.6 | 2.4-7.5 | 2.4-10.6 | Not simulated |

*Nopt, economically optimal N rates (kg ha⁻¹).
**N_max, the Finnish Agri-Environmental Programme’s maximum permissible N rates (kg ha⁻¹).
***The prices of N fertilizer (1 € kg⁻¹) and the DM yield values of grass leys (0.1 € kg⁻¹). Fertilizer N-to-yield price ratio of ten.
****The low and upper values indicate production and ploughing years, respectively.
with the high $N_0$ yields would be uneconomically high and could be therefore reduced to 50 kg ha$^{-1}$. However, despite the considerably lower N rate and N balance attained, and even negative values for the latter, the simulated annual N leaching loss would decrease by only 3.1 kg ha$^{-1}$.

Similarly, in organic soils with average $N_0$ yields, $N_{\text{opt}}$ is equivalent to $N_{\text{max}}$ (i.e., 190 kg ha$^{-1}$), resulting in an N balance of about zero. Again, in fields with high $N_0$ yields, N rates could be reduced up to 75 kg ha$^{-1}$, since the application of $N_{\text{max}}$ to such fields would pose a financial burden on growers. This practice would reduce the N balance to $–75$ kg ha$^{-1}$ yr$^{-1}$. For organic soils, we were unable to assess the associated environmental impact.

**Yield response**

From the growers’ point of view, fertilizer applications should be based on relevant yield response models and be economically justified. However, year-to-year, site-specific and climatic variability leads to numerous response curves as well as uncertainty in estimating $N_{\text{opt}}$. To overcome these challenges, we applied meta-analysis in the present study to test the sources of variation and to improve the robustness and reliability of the yield response curves. They were fitted to average grass yield increases over the duration of an experiment and to a large number of experiments on different soils located at 17 sites with growth periods ranging from 130 to 175 days. In our previous meta-analysis of cereals, the $N_0$ yield was a major factor governing the magnitude of the yield response to N fertilization [2]. In this study we included the $N_0$ yields as a continuous variable that enabled improvement of the models’ reliability ($R^2 = 0.80$-0.95).

Although SOM is broadly recognized as an important parameter affecting soil quality and crop yield, large dataset analyses of cereals have shown either its weak correlation with $N_0$ yield [2] or no statistically significant correlations at all [16]. The latter result agreed with that of the present study on grass leys. We suggest that the variations in $N_0$ yield observed in the present study were determined largely by unaccounted factors such as, e.g., soil structure. Soil structure can influence crop yields by affecting root growth and distribution, soil aeration, water availability, as well as soil microbial activity and nutrient cycling.

In light of the present results, current fertilizer recommendations, which are based on the grower’s yield expectation (i.e., the higher the expected yield, the higher the N fertilization), do not lead to optimal N management. Indeed, the $N_{\text{max}}$ permitted by FAEP on a field without consideration of its $N_0$ yield and responsiveness may be unnecessarily high and lead to excessive N inputs and thus to economic losses for a grower. According to the models, on low responsive fields the application of permitted $N_{\text{max}}$ would lead to a yield increase of 1000 kg ha$^{-1}$ less than on highly responsive fields, regardless of the soil type. Thus, the yield response models developed in the present study can contribute to the construction of a dynamic tool for growers to more effectively adjust N applications in order to maximize economic profitability. However, such a tool would require growers to estimate the magnitude of $N_0$ yields from his fields by, for example, leaving some representative areas unfertilized for a few years.

**N balance and N leaching loss**

This study showed that N rates explained a large part of the variation (86-88%) in N balances for grass leys, which agrees with the results of our previous study on cereals [2], and the effect of N fertilization on N balance was consistent across the studies. The results also indicate that for grass production on mineral soils, as with wheat production, an increase of 10 kg ha$^{-1}$ in fertilization associated with about 5 kg ha$^{-1}$ increase in the N balances [2].

On organic soils, the application of $N_{\text{max}}$, permitted by the FAEP (i.e., 190 kg ha$^{-1}$), the N balance would be approximately zero. On mineral soils, the larger $N_{\text{max}}$ (230 kg N ha$^{-1}$) would result in an N balance of 57 kg ha$^{-1}$ yr$^{-1}$, slightly exceeding the average national N balance of 50 kg ha$^{-1}$ yr$^{-1}$ [9]. In particular, growers could reduce N inputs on mineral soils with high $N_0$ yields considerably, down to 50 kg ha$^{-1}$, and the N balance down to $–29$ kg ha$^{-1}$ yr$^{-1}$ with no economic loss. Similarly, the respective cases for spring wheat production have the potential to reduce N inputs from 120 to 45 kg ha$^{-1}$ and the N balance from 33 to $–5$ kg ha$^{-1}$ yr$^{-1}$ with no economic loss [2].

The values predicted by the COUP model for N leaching losses after the application of mineral N fertilizer to perennial grass leys were in accordance with the low values measured, which ranged from 1.2 to 10-15 kg ha$^{-1}$ yr$^{-1}$ in Finland [5] and in the Nordic-Baltic countries [17, 18]. Numerous studies demonstrated that N leaching losses from perennial grassland are inherently smaller than those from arable land, since N uptake covers a longer period and the soil normally remains untilled for at least three years, thereby reducing N leaching [19-21].

Even with wide variation across management regimes and years, a recent Danish study of grasslands under different grazing, cutting and manure treatments found that N surpluses related only weakly to N leaching and accounted for only 5% of the variation, thus revealing the huge capacity of soils to accumulate large N inputs [3]. The model in the present study predicted a weak relationship between N leaching losses and N balances on mineral soils, but only for inorganic N input. Even in a ploughing year, when N leaching losses were expected to rise due to mineralization and the accumulation of inorganic N in the soil [22], simulated
N losses rose by only 6.9 kg ha⁻¹ yr⁻¹, when N balances rose considerably by 200 kg ha⁻¹ yr⁻¹.

Assessments have shown that, along with the low N leaching loss, also the volatilization of ammonia and nitrous oxide from grass leys on mineral soils with the recommended rates of mineral N fertilizers have been low, about 1 and 1.5-4 kg ha⁻¹ yr⁻¹, respectively [9, 23]. This indicates that an N balance of 57 kg ha⁻¹ yr⁻¹ contributes to a residual soil N pool that amounts to about 40-50 kg ha⁻¹ yr⁻¹. In grasslands, the largest pool of N is SOM, and since the net N mineralization rate is generally low, the residence time of N in SOM in most undisturbed grasslands would be decades or even centuries [24].

However, the ploughing of grass leys receiving mineral fertilizer with the subsequent cultivation of spring cereals may either return N leaching losses to the pre-ley levels [25] or slightly raise it by 3 kg ha⁻¹ yr⁻¹ during the two to three years after ploughing [26]. In the cereal phase of grass-arable rotation, the under-sowing of non-legume catch crops, such as ryegrass, is considered an effective strategy for avoiding N losses [27]. A recent meta-analysis confirmed that using catch crops in spring cereal production reduced N leaching losses by 50% across the range of soils and weather conditions in the Nordic countries [28].

Along with commercial fertilizers, the use of animal manure on grasslands is commonplace. On a catchment scale, N balances in areas that received manure applications are often higher than those that received only mineral fertilizer [1]. In addition to the quantity of N applied, N losses from manure depend on several other factors, such as the timing and method of application, particularly in relation to subsequent rainfall [20]. In contrast to inorganic N input, the application of slurry can lead to higher N leaching losses of up to 60-190 kg ha⁻¹ [3, 5]. In grazed pasture, the potential for N leaching increases more than five-fold that of mowed pastures [29], since a large proportion (between 60-90%) of the N ingested returns to the soil pasture system as urine and manure.

**Conclusions.** In grass ley production, N fertilizer management should aim for N₀opt as determined by N₀yields. Otherwise, N input may be unnecessarily high, leading to economic losses for growers. We propose that unaccounted factors, such as soil structure, largely caused the variations in N₀yields observed in the field experiments summarized in the present study. Growers are therefore encouraged to estimate the magnitude of N₀yields directly from their fields by, for example, leaving some representative areas unfertilized for a few years. On mineral soils, however, concerns about the risk of N leaching losses when using only inorganic N fertilization seems less crucial due to its low level and weak association with N balances. Further research is needed to explore the relationship between N balances and N leaching on organic soils.

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