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Reducing N fertilization in the framework of the European Farm to Fork strategy under global change: Impacts on yields, N_2O emissions and N leaching of temperate grasslands in the Alpine region

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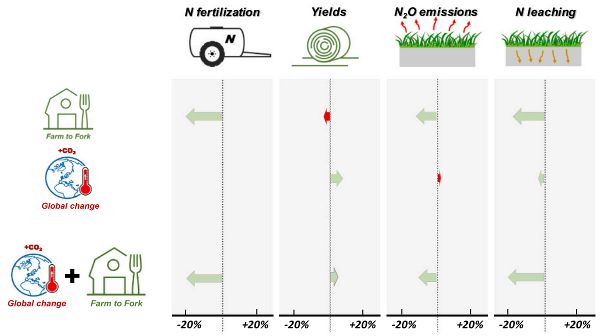
HIGHLIGHTS

- Reducing N fertilization and losses plays a central role in the EU's Farm to Fork (F2F) strategy.
- Possible side effects on yields of Alpine grasslands were quantified using a mechanistic model.
- Yield losses due to reduced N fertilization are offset by positive effects of rising CO_2 levels.
- Yield-scaled N losses as N_2O and leaching tend to decrease in future scenarios with global change and the F2F strategy.
- The impact of integrating all aspects of the F2F strategy should be further investigated.

GRAPHICAL ABSTRACT



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ABSTRACT

Context: The reduction of N fertilization in agriculture as part of the Farm to Fork (F2F) strategy plays a central role in the integrated nutrient management action plan of the European Commission. However, the implications of this strategy for mitigating N losses and possible side-effects on grassland yields under global change are largely unknow.

Objective: We examined how a 20% reduction in N fertilization according to the F2F strategy is likely to impact yields, N_2O emissions and N leaching of four intensively managed temperate grasslands in the Alpine region, two of them located in Switzerland, the other two in Germany.

Methods: Following automatic data-driven calibration supported by inverse modeling and a cross-validation step, the process-based model DayCent was used for conducting the analysis. Global change scenarios under the representative concentration pathways (RCPs) 4.5 and 8.5 and a baseline scenario (current climate) were created for the time frame 2041–2060 with the help of the stochastic weather generator LARS-WG.

Results and conclusions: Our results indicated that, under current conditions of climate and CO_2 levels (400 ppm), a 20% decrease in N fertilization would lead to a 5% drop in yields, but also in a 15% decline in N_2O emissions and a 21% decline in N leaching (largely as NO_3^-). Under global change conditions (*i.e.*, climate change and

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higher atmospheric CO_2 levels), we found that increased yields, mainly induced by higher CO_2 levels, are likely to compensate for yield losses resulting from the reduction in N fertilization. In addition, we found that the effectiveness of the F2F strategy to mitigate N losses is likely to be preserved under global change, still with stronger effect on N leaching. The F2F-induced decline in N losses was stronger when the latter were expressed per unit of harvested dry matter, *i.e.*, up to 17% for N_2O and up to 42% for N leaching. Although significant, these abatements in N losses are still below the 50% reduction level envisaged by the F2F strategy. Actions related to other axes of the strategy (*e.g.*, sustainable food consumption) will be necessary to further reduce N fertilization and, therefore, to reach this ambitious goal.

Significance: Our results highlight the usefulness of models in accounting for interacting effects of global change and mitigation practices on multiple ecosystem services of grasslands. They allow quantification of the impact of new policies.

1. Introduction

Grasslands are one of the most widespread ecosystems in the world. They cover about 40% of the surface of the earth excluding Greenland and Antarctica (White et al., 2000). About one third of the agricultural area of the European Union is permanently covered by grasslands (EUROSTAT, 2020). A significant part of these grasslands is characterized by intensive management, *i.e.* high N fertilization rates and high frequency of biomass removal by mowing or grazing (Schils et al., 2022). Despite ensuring high capacity of provisioning animal feed, high N fertilization levels in grasslands have negative side-effects (trade-offs). A first one is the contribution to global change, since the N fertilization increase emissions of N_2O, a powerful greenhouse gas (GHG) with a global warming potential of 273 (CO_2 equivalent) for a 100-year time horizon (Smith et al., 2021). A second side-effect of high N fertilization levels is the pollution of groundwater, considering that N surpluses generate N leaching, mostly in the form of NO_3^- (Lassaletta et al., 2023; Smerald et al., 2023). Nitrogen leaching is also a significant indirect source of N_2O emissions (Abdalla et al., 2019). Considering these types of issues related to the excessive use of nutrients in agriculture, the European Commission has initiated an integrated nutrient management action plan, as part of a strategy known as Farm to Fork (F2F) (European Commission, 2023). This strategy is the core component of the European Green Deal (European Commission, 2023, 2024).

The F2F strategy consists of four axes of action: (i) sustainable food production, (ii) sustainable food processing and distribution, (iii) sustainable food consumption, and (iv) food loss and waste prevention. A specific goal of the first axis of the strategy is the reduction of 20% in nutrient inputs and 50% in nutrient losses, including N, without deteriorating soil fertility (European Commission, 2023). Although an abatement of N losses by adoption of the F2F strategy is expected, the achievability of the 50% reduction target is largely unknown. Besides this, there is a lack of knowledge about possible negative impacts of the strategy on the provisioning of animal feed. Lower grassland yields without a proportional reduction in livestock population would need to be compensated through the import of animal feed resulting in negative environmental impacts beyond European borders and dependence on countries from other regions.

Another unexplored aspect related to the adoption of F2F in the future is how global change will interact with the effectiveness of the strategy to mitigate N losses. More specifically, the interactive effect of the reduction in N fertilization and anomalous precipitation regimes, warming, and increasing CO_2 levels on grassland productivity is not well understood. In Europe, grassland productivity can be significantly affected by an increasing frequency of droughts and rainfall variability, which has been assessed by observations (Hahn et al., 2021; Jentsch et al., 2011) and mechanistic modeling studies (Calanca, 2007; Calanca et al., 2016; Carozzi et al., 2022). Understanding the processes determining the sensitivity of grassland biomass production to extreme climate events is critical for projecting the impacts of global change on grassland ecosystems and the interaction with mitigation strategies based on the reduction of N fertilization rates.

It is well established from field experiments that elevated CO_2 concentrations increase grassland productivity by enhancing the net C uptake (Hopkins and Del Prado, 2007; Soussana and Lüscher, 2007), which is associated to reducing negative effects of droughts due to earlier stomata closure (Cherwin and Knapp, 2012; Roy et al., 2016). On the other hand, how the soil N cycle will respond to elevated atmospheric CO_2 has been a largely discussed topic. Several studies suggested an increasing N demand by plants as a consequence of the positive effect of increasing CO_2 levels on productivity, which can result in reduced N losses (Cui et al., 2023; Luo et al., 2004). Therefore, this change in the N demand can modulate the grassland yield responses to the reduction of N fertilization by adoption of the F2F strategy.

Our aim in the present study was to examine how reduced N fertilization according to the F2F strategy of the European Union will affect yields and N losses of temperate grasslands in the Alpine region under global change conditions. Specifically, our objectives were (i) to assess the effectiveness of the F2F strategy in reducing N losses as N_2O emissions and N leaching in permanent grasslands under intensive management and (ii) to evaluate the potential side-effects of this strategy on grassland yields, taking into account the effects of warming, anomalous precipitation and increasing CO_2 levels under global change scenarios.

2. Material and methods

2.1. Field data

Detailed field measurements from long-term experiments in four permanent temperate grassland sites in Western Europe were included in the present study for model calibration, validation and scenario runs. Two sites are located in the Swiss Plateau (Chamau and Oensingen) and the other two in the pre-alpine region of Bavaria, Southern Germany (Fendt and Graswang) (Fig. 1). The description of soil, weather and measurements are presented in Table 1. At each site, the grasslands were subjected to different management practices regarding the intensity of cutting and the N fertilization rates, as described in further detail in the Supplementary Material.

2.2. Modeling approach

In this study we used the process-based model DayCent, version DD17centEVI (Hartmann et al., 2019), for the simulation of grassland yields and N losses as N_2O emissions and N leaching. DayCent is a biogeochemical model that simulates the dynamics of vegetation growth, soil organic C pools, nutrient cycling (N, P and S), and the fate of CH_4 and N trace gases (Hartmann et al., 2019; Parton et al., 1998). The model accounts for the effect of management practices, including fertilization, fire, irrigation, drainage, grazing, soil cultivation and harvest. The main model inputs are soil texture, management, vegetation type and daily weather variables.

We performed our simulations using the “weather extra drivers” mode, which is based on the use of daily values of precipitation, maximum and minimum air temperature, solar radiation, air relative humidity and wind speed. We used weather data recorded at each site, which we gap-filled based on meteorological stations located nearby.

The time period spanned in the simulations is presented in Table 1.

The model calibration was performed with the support of inverse modeling based on the PEST tool, which is the abbreviation of "Model-Independent Parameter Estimator" (Doherty, 2020). This procedure has been successfully applied for the calibration of DayCent with respect to N_2O emissions at cropland sites (Martins et al., 2022; Necpalova et al., 2018; Rafique et al., 2013). It is based on selecting the combination of parameter values providing the best fit of the modeled to the observed values (Fig. S1, Table S1). After calibration, and again following Martins et al. (2022), we assessed the predictive ability of the model based on out-of-sample simulations. Further details of the model mechanistic structure, calibration and validation are presented in the Supplementary Material.

2.3. 2.4. Global change scenarios

Considering the significant biases associated with site-specific projections from general circulation models (GCMs), following Petersen et al. (2021), we developed weather data for DayCent simulation of global change impacts using the stochastic weather generator LARS-WG, version 6 (Semenov and Stratonovitch, 2010). For each site, we generated daily weather data for a 20-year baseline representing current climatic conditions and for the mid-century time window spanning 2041–2060 under the assumption of emissions scenarios RCP 4.5 and RCP 8.5. In each case, 10 different realizations were generated using different random seeds.

For the simulation of future scenarios, we extracted the climate change signal from the output of GCM simulations contributing to the Coupled Model Intercomparison Project Phase 5 (CMIP5). We selected HadGEM2-ES as GCM taking in consideration its ability to reproduce weather patterns as influenced by altitude and latitude in the region of the experimental sites included in the present study (Petersen et al., 2021; Zubler et al., 2016). This model suggests that, under global change, precipitation increases in the first half of the year and decreases in the second half (Fig. S2) and the mean annual temperatures increase, on average, by 2.1 °C under the RCP 4.5 and by 2.4 °C under the RCP 8.5 (Fig. S3).

LARS-WG generates daily series of precipitation, minimum and

Table 1
Characteristics of the four grassland sites used for simulations with the DayCent model.

Description	Grassland sites			
	Chamau	Oensingen	Fendt	Graswang
Country	Switzerland	Switzerland	Germany	Germany
Latitude	47°13′N	47°17′N	47°49′N	47°34′N
Longitude	8°25′E	7°44′E	11°4′E	11°2′E
Altitude (m a.s.l.)	393	452	600	860
MAP [a] (mm)	1151	1086	1033	1398
MAT [b] (°C)	9.1	9.8	8.6	6.5
Soil Class (FAO-WRB, 2015)	Gleysol-Cambisol	Eutri-stagnic Cambisol	Cambic Stagnosol	Fluvic Calcaric Cambisol
Clay (%) [c]	19	43	31	51
Silt (%)	45	47	42	39
Sand (%)	36	10	27	9
SOC [d] (%)	2.8	2.1	2.2	3.0
pH	6.5	6.4	5.8	6.7
BD [e] (g cm^{-3})	1.10	1.23	1.30	1.07
Period of simulation[f]	2001–2016	2001–2007	2011–2021	2011–2021
Period of N_2O flux and/or N leaching measurements [g]	Jan. 2013–Dec. 2016	Mar. 2004–Dec. 2007	Jan. 2012–Dec. 2014	Jan. 2012–Dec. 2014
References	Fuchs et al. (2018), Merbold et al. (2021)	Ammann et al. (2007, 2009, 2020)	Fu et al. (2017), Lu (2016), Kiese et al. (2018)	Fu et al. (2017), Lu (2016), Kiese et al. (2018)

[a] MAP: mean annual precipitation. [b] MAT: mean annual temperature. [c] Soil properties represent the 0–30 cm layer (values used as model inputs). [d] SOC: soil organic carbon. [e] BD: bulk density. [f] Years with renovation of grasslands were not included in the model calibration and validation, considering that it is not a typical management practice in Western European grasslands. [g] Only the period considered in the present study.

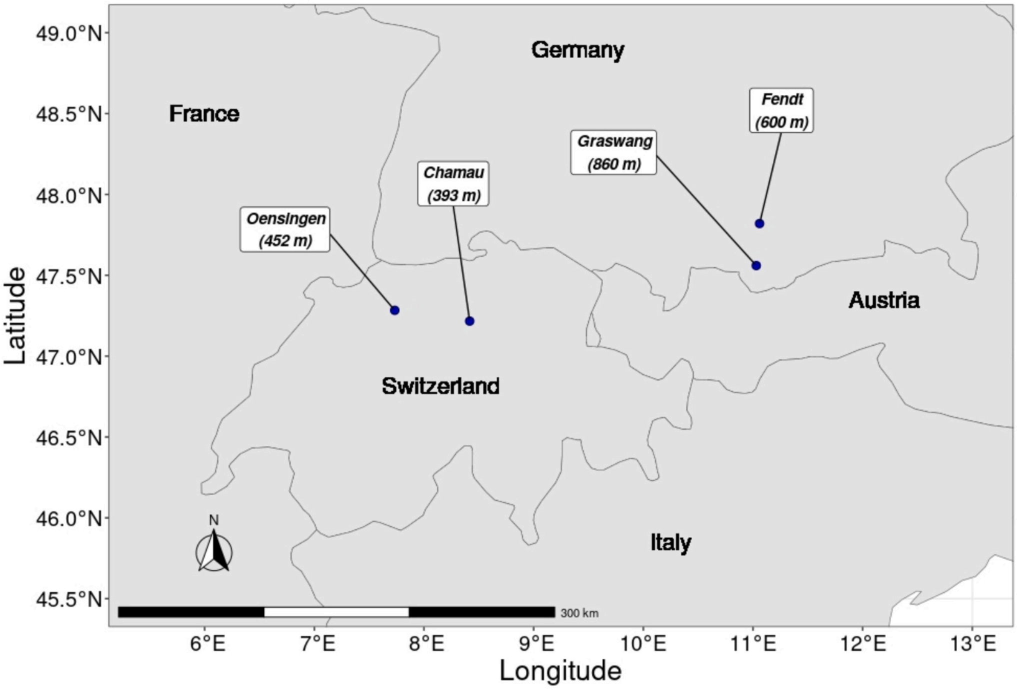

Fig. 1. Location of the four permanent grassland sites considered in the present study. The values in parentheses indicate the altitude above sea level.

maximum air temperature and solar radiation. In addition to these variables, DayCent also requires relative air humidity and wind speed. We estimated relative air humidity as a function of air temperature following the procedure outlined in the FAO Paper 56 (Allen et al., 1998). Concerning wind speed, we used long-term daily mean values, which we replicated 20 times to obtain a full record.

A concentration of 400 ppm was used as atmospheric CO_2 level to represent current conditions, while values of 487 ppm (RCP 4.5) and 541 ppm (RCP 8.5) were adopted as representative for the mid-century (Meinshausen et al., 2011). A static intensive management of grasslands was considered for all scenarios, sites and years. The management was defined specifying 4 cuts and 4 slurry applications per year, the latter being equivalent to a total annual N-input of 192 kg N ha^{-1}. The chosen cutting frequency is one of the most common in the study region (Huguenin-Elie et al., 2017; Reinermann et al., 2022). Slurry was considered to be applied one week after each grass cutting event generally following farmers practice in the study regions.

2.4. Simulation of reduced N fertilization as part of the farm to fork strategy

The F2F strategy aims to reduce the use of fertilizers by at least 20% in the framework of an integrated nutrient management action plan (European Commission, 2020). To simulate the adoption of the F2F

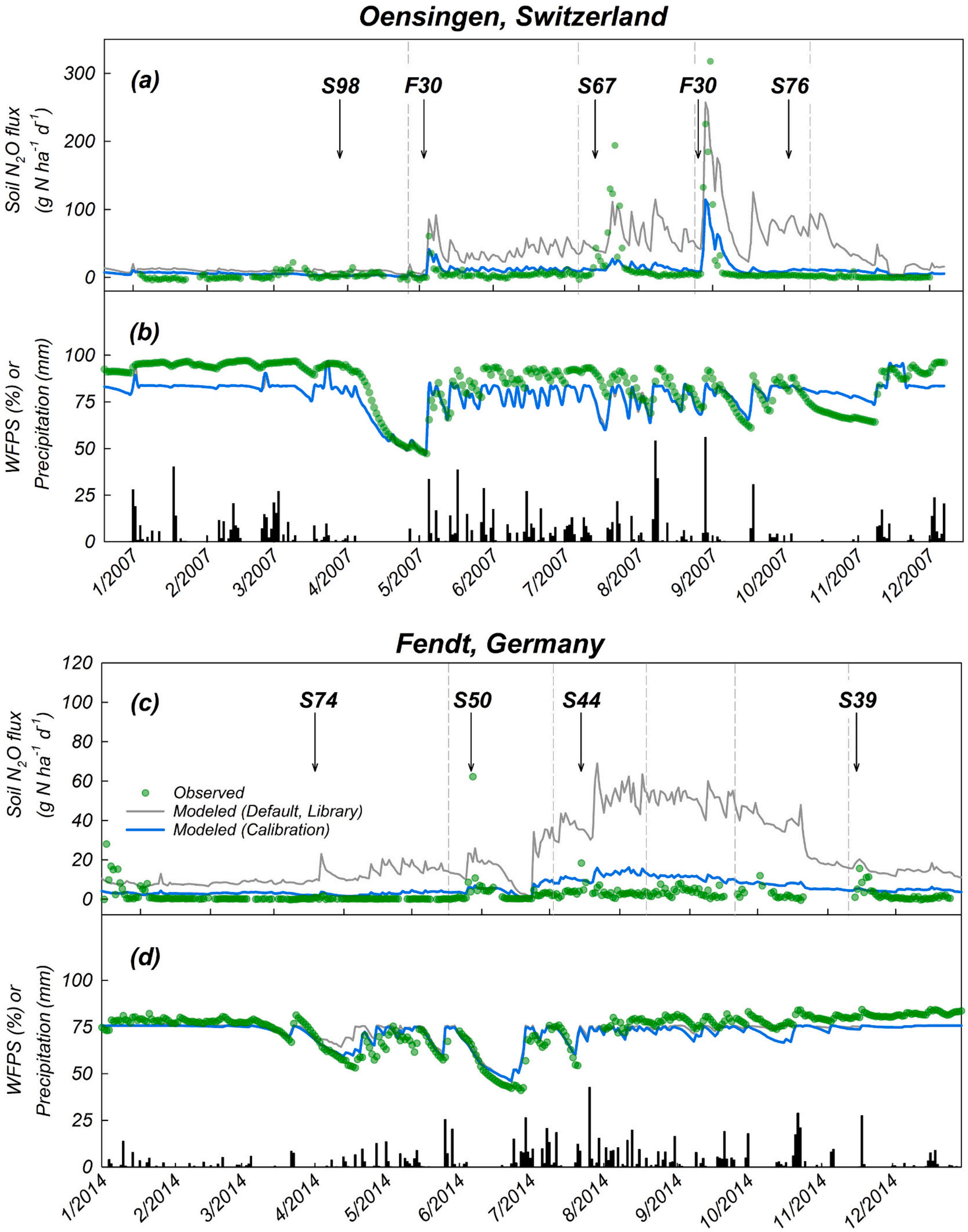

Fig. 2. Time series of modeled (lines) *versus* observed (symbols) daily soil N_2O fluxes (*a, resp. c*) and water-filled pore space (WFPS) (*b, resp. d*) for the grassland sites at Oensingen (Switzerland) and Fendt (Germany). Vertical dashed lines indicate harvest events. Arrows associated with uppercase letters followed by values indicate N fertilization, in kg N ha^{-1}, as synthetic fertilizer (*F*) or slurry (*S*). For example, '*S98*' indicates an application of slurry at a rate of 98 kg N ha^{-1}.

strategy in the management of the grasslands, we reduced each N application as slurry by 20%, keeping all other management aspects fixed. Although it is possible to simulate phosphorus (P) dynamics with DayCent, in the present study we included only the simulations of the C and N dynamics. The effects of a reduction in pesticide amounts were also not considered.

3. Results

3.1. Model calibration and validation

A substantial improvement of the model simulation of C and N yields in the harvested biomass was obtained with the calibration of model parameters controlling the maximum BNF rates and the thresholds of N sufficiency and deficiency, which are respectively represented by minimum and maximum C/N ratios during plant growth (Fig. S1, Table S1). Therefore, the roughly 2-fold overestimation in the C/N ratio associated with the default parameterization was substantially reduced in all sites and cutting events (Fig. S4). Overestimates in modeled N losses as N_2O emissions and N leaching were also consistently decreased by calibration (Fig. 2, Fig. S5). Specifically concerning N_2O emissions, we show that background fluxes, which usually dominate total cumulated emissions, are clearly better reproduced by the model after calibration (Fig. 2 and Figs. S6-S9). Part of the improvement in the simulation of N losses results from tuning parameters controlling soil N cycling (Fig. S1). Out-of-sample predictions also significantly improved in comparison to simulations with default parameterization. This is well illustrated by comparing modeled and observed annual N losses as N_2O and N leaching (Fig. S10 and Table S2). For example, the R^2 for the prediction of annual N_2O emissions increased from 0.45 before model calibration to 0.77 with site-specific calibration and to 0.65 in leave-one-out cross-validation (Fig. S10). Respectively, the relative root mean square error (rRMSE) decreased from 2.61 to 0.40 and 0.52 and the bias from 5.07 to 0.16 and –0.04 kg N ha^{-1}.

3.2. Future scenarios

In order to put the F2F strategy and future scenarios into context, we first discuss the baseline. Under current climate conditions and atmospheric CO_2 levels (400 ppm), annual grassland yields vary substantially between sites (Fig. 3). The lowest yields are observed at Oensingen (8.1 Mg ha^{-1}), the site with the lowest summer precipitation (Fig. S2), and Graswang (8.7 Mg ha^{-1}), the site with the lowest temperatures (Fig. S3). In the baseline scenario (current climate), the 20% reduction of N fertilization prescribed by the F2F strategy (“BL.f2f”, Fig. 3) results in yield losses of 5% on average, ranging from 2% in Chamau to 8% in Oensingen. For global change conditions (“GC”, Fig. 3), only the results for the RCP8.5 scenario are shown, since no substantial differences were observed between this scenario and the one referring to RCP 4.5 for the mid-century. A consistent increase in yields under global change conditions is projected for all sites, averaging to 9% and ranging from 7% in Oensingen to 14% in Graswang. This increase is essentially due to raised CO_2 levels, because we observe a slight reduction in yields ranging from 1% to 4% at the sites with the lowest altitudes, *i.e.*, Chamau, Oensingen, and Fendt when the CO_2 levels are kept at 400 ppm, with only a modest 3% yield gain at Graswang, the highest site (results not shown). Evidently, at this latter site the warming associated with global change and the consequent lengthening of the growing season was sufficient to increase yields even without considering the beneficial effects of elevated CO_2 (Fig. S3).

Compared to the results for only global change (“GC”, Fig. 3), yield losses are simulated for the global change scenario that assumes the

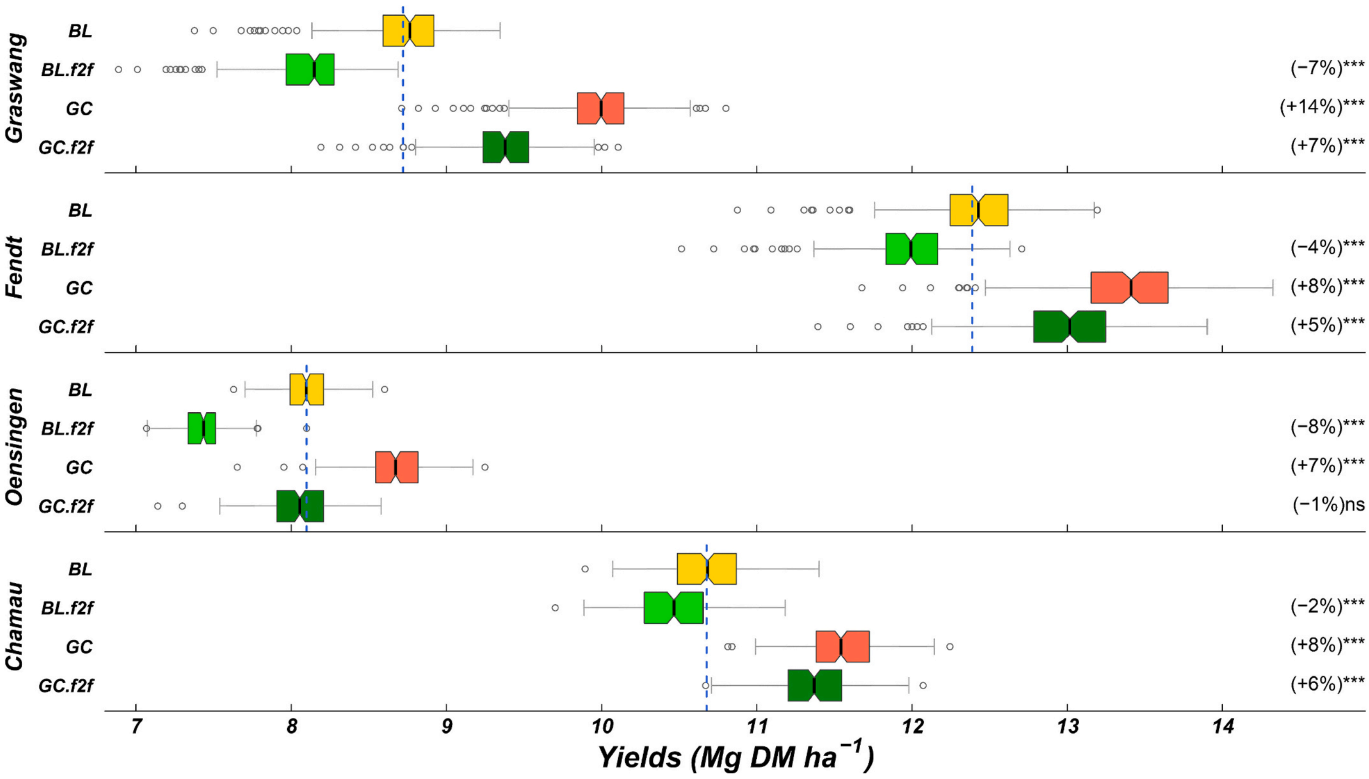

Fig. 3. Box-plot representation of simulated annual dry matter (DM) yield at the four study sites. “BL” represents the baseline (current CO_2 level at 400 ppm); “GC” represents the global change scenario for the mid-century (2041–2060) under RCP 8.5 with an atmospheric CO_2 level at 541 ppm; “f2f” indicates the adoption of the Farm to Fork (F2F) strategy with a 20% reduction in N fertilization. Vertical dashed lines indicate the mean values of the BL scenario; relative changes for the other scenarios with respect to these mean values are indicated in parentheses on the right-hand side along with the results of Kolmogorov–Smirnov tests (ns: not significant with $P > 0.05$, **: $P < 0.01$, ***: $P < 0.001$). In these plots, $n = 200$ (10 weather realizations × 20 years of simulation).

implementation of the F2F strategy (“GC.f2f”, Fig. 3). However, for all sites except Oensingen, these yield levels are still higher than those simulated for the baseline, indicating that the application of the F2F strategy under conditions of global change does not reduce the current provisioning capacity of managed grasslands in the Alpine region.

Similar to yields, annual baseline N losses as N_2O emissions and N leaching vary significantly between sites (Fig. 4). Overall, the baseline averages for annual N_2O emissions range from 1.4 to 3.2 kg N ha^{-1} and for N leaching from 2.7 to 9.6 kg N ha^{-1} (largely as NO_3^-, results not shown). In the baseline scenario, the 20% reduction in N fertilization prescribed by the F2F strategy results in a decline of 12% to 19% in N_2O emissions, and 15% to 30% in N leaching (“BL.f2f”, Fig. 4). Although substantial, these N loss reduction values are still well below the 50% level targeted by the F2F strategy. Under global change alone, N_2O emissions tend to increase slightly, by 3% on average (“GC”, Fig. 4). The impact of global change on N leaching varied significantly at different sites, ranging from positive shifts at Oensingen (18%) and Graswang (13%) to negative shifts at Chamau (−16%) and Fendt (−25%). The combination of global change conditions and the F2F strategy resulted in a reduction of N leaching ranging from 9 to 39% (“GC.f2f”, Fig. 4). Although a decrease is consistently observed at all sites, this wide range of values indicates that other factors, including site-specific edaphoclimatic conditions, control the potential of N leaching in temperate grasslands.

One way of balancing N losses and yields is to consider the losses per yield. We find a reduction of such scaled N losses and for all the future scenarios compared to the baseline and for both N_2O and N leaching (Fig. 5). Regarding the sites, the only exception is Oensingen, for which the yield-scaled N leaching increases in the global change scenario (“GC”, Fig. 5). Overall, the mitigation of N losses resulting from the F2F strategy in combination with global change conditions is generally more prominent when the N losses are yield-scaled than when considered in absolute terms (“GC.f2f”, Figs. 4 and 5). For instance, under this scenario, the mitigation of N leaching per dry matter yield is up to 42% (Fig. 5).

4. Discussion

Minimizing the N surplus is a key target of the F2F strategy as part of a broad effort to mitigate the impact of agriculture on both global change and environmental pollution (European Commission, 2024). However, a critical concern of adopting mitigation practices based on the reduction of N fertilization is the potential trade-off on yields. Our results highlighted that, in mowed grasslands in the Alpine region, the adoption of the F2F strategy is expected to result in a slight decrease in yields under current climatic conditions, but this effect is likely to be compensated in the future (mid-century) by positive effects of increased CO_2 levels (Fig. 3).

To understand the positive impact of global change on grassland yields, it is important to disentangle the effects of increasing atmospheric CO_2 levels from climate effects, *i.e.*, those induced by warming and shifts in the precipitation regime. Without an increase in atmospheric CO_2, an overall negative effect of global change on grassland yields was found for different sites, with the exception of Graswang (results not shown), which is located at the highest altitude (860 m a.s.l.). It is important to note that the annual precipitation at this site (1506 mm) is currently significantly larger than at the other sites (901 to 1120 mm), implying that a decrease in summer precipitation in the order of 10%, as prospected by the HadGEM2-ES model (Fig. S2), does not lead to drought-induced limitations in plant productivity at Graswang. This is consistent with the findings in previous studies indicating that grasslands in wetter conditions are less sensitive to anomalies in precipitation (Cherwin and Knapp, 2012; Henry et al., 2019; Schlingmann et al., 2020). Without water limitation, increases in yields can partly be attributed to warming, which brings temperatures closer to optimum for plant growth (Grigulis and Lavorel, 2020; Rustad et al., 2001) and extends the length of the growing season (Menzel et al., 2006). Under higher CO_2 levels, the projected increase in grassland yields at all sites of the present study (Fig. 3) is coherent with the CO_2 fertilization effect well demonstrated in field experiments with sufficient nutrient supply (*e.g.*, Roy et al., 2016; see below). Positive effects of higher atmospheric

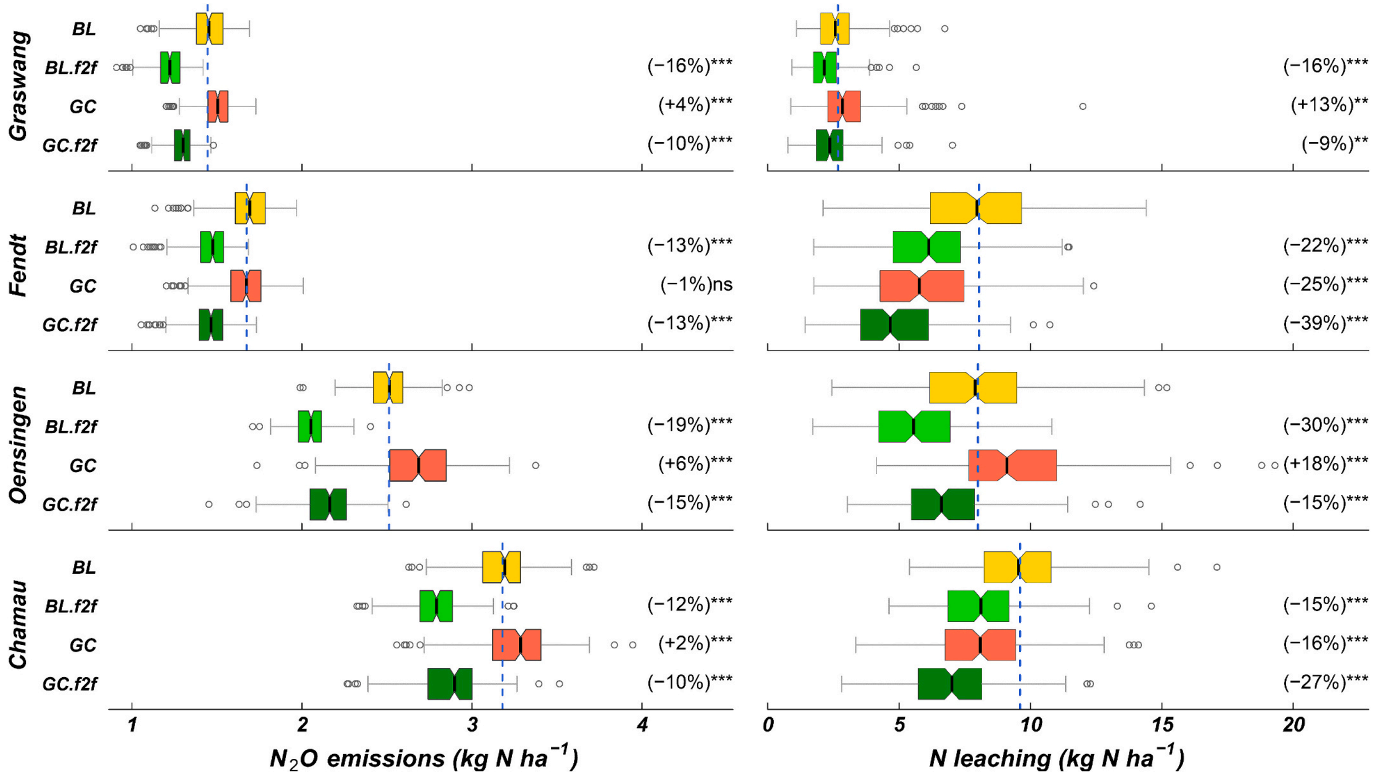

Fig. 4. Same as Fig. 3 but for annual N_2O emissions (left) and N leaching (right).

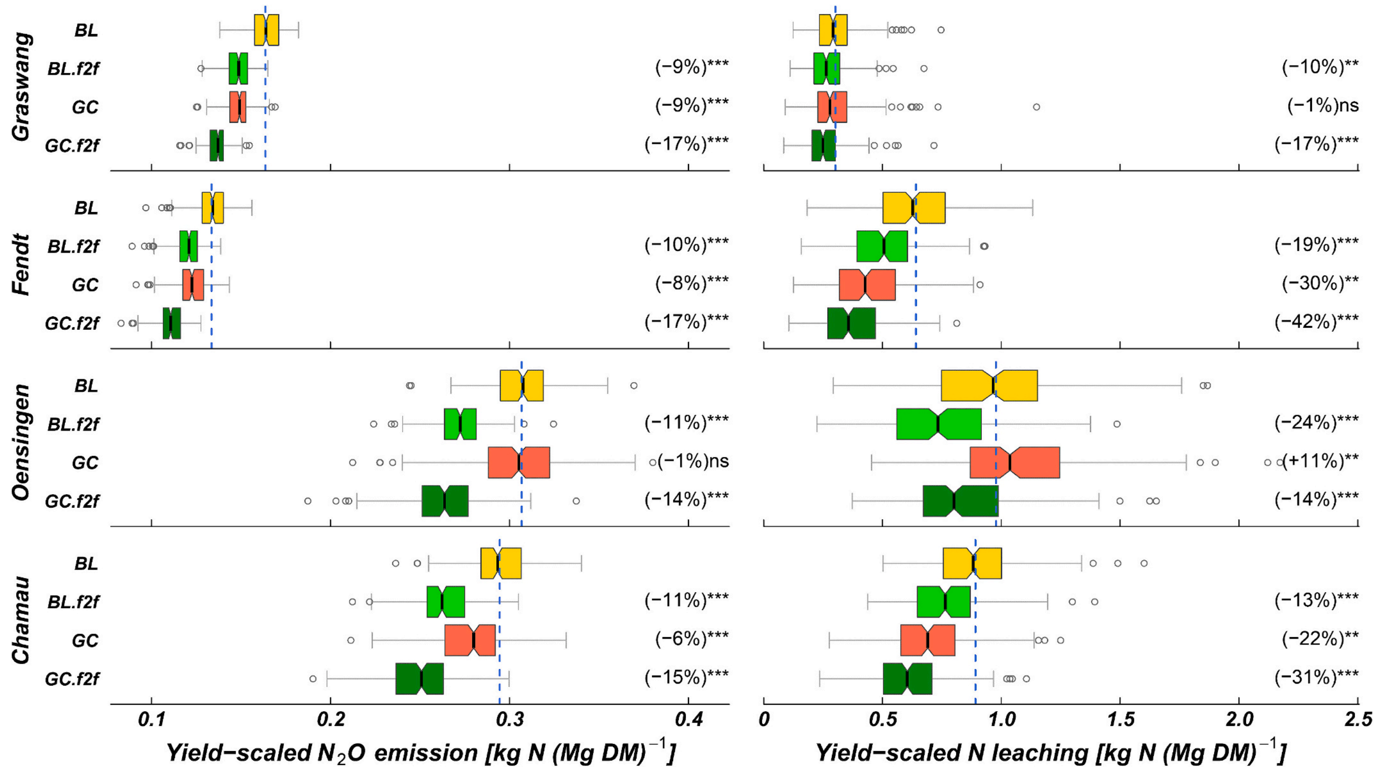

Fig. 5. Same as Fig. 3 but for yield-scaled N_2O emissions (left) and N leaching (right).

CO_2 levels on grassland productivity are related to increasing assimilation rates and an improvement of the water-use efficiency (Jones, 2019; Soussana and Lüscher, 2007; Walker et al., 2021). Both processes are mechanistically represented in DayCent (Hartmann et al., 2019).

Although positive responses of plant growth to elevated CO_2 and warming are well established, some constraints have been widely discussed in the past, such as the role of N availability further modulating the ecosystem response (Henry et al., 2019; Hungate et al., 2009; Soussana and Lüscher, 2007). Studies suggested that N availability in grassland soils is limited as a result of the increased N demand induced by a higher productivity through CO_2 fertilization (Diemer and Körner, 1998; Loiseau and Soussana, 1999; Sillen and Dieleman, 2012). In the present study, the positive effects of elevated CO_2 on yields were less pronounced under the assumption of reduced N fertilization (Fig. 3), suggesting that N limitation to grassland productivity could indeed occur under future climatic conditions. However, the simulated yields associated with the F2F strategy under global change ("GC.f2f") were at least as high (Oensingen) or higher (all other sites) than in the baseline (Fig. 3). Further, it is worth mentioning that the simulated losses in yields associated with the F2F strategy were much smaller than the prescribed 20% reduction in N fertilization. It is seen that only under current conditions the adoption of the F2F strategy ("BL.f2f") would result in a slightly lower provisioning ability in comparison to the baseline, but not anymore by the mid-century (Fig. 3).

In this context, it is also worth bearing in mind that livestock numbers in Europe have been decreasing in the recent past (EUROSTAT, 2023), which tends to reduce the pressure on feed production and therefore the need for high N fertilization levels. Continuing the efforts to reduce the number of livestock could help to mitigate N losses associated with feed production, leading to a faster achievement of abatement target envisaged by the F2F strategy.

In relation to productive grasslands, another relevant aspect is the potential increase of BNF efficiency with elevated CO_2 (Lam et al., 2012), which could counteract increasing N limitation resulting from the reduction of N fertilization as part of the F2F strategy. This effect has been associated with higher supply of photo-assimilates for legume nodules under higher CO_2 levels (Rogers et al., 2009) and to changes in the botanical composition in response to global change, with the possibility of an increase in the proportion of legumes (Lazzarotto et al., 2010; Soussana and Hartwig, 1995; Soussana and Lüscher, 2007). In DayCent, the parameter '*snfxmx(1)*' represents the maximum amount of N_2 fixed symbiotically per amount of C fixed in the biomass (Table S1, Fig. S1). This parameter was kept fixed in our simulations, implying that our results cannot reflect a possible increase in productivity as promoted by the increase in legume share and BNF contribution under global change. In future applications of DayCent, this problem could be addressed with a scalar adjustment of the parameter *'snfxmx(1)'* in relation to the prescribed atmospheric CO_2 levels. More field experiments evaluating BNF under elevated CO_2 levels could provide a better basis for guiding this adjustment.

We highlighted that although it is unlikely that the 50% reduction of N losses envisaged by the F2F strategy will be attained in managed grasslands, the reduction of N_2O emissions and N leaching will be far from negligible, especially when yield-scaled N losses are considered (Fig. 5). Overall, a lower decrease in N_2O emissions than the prescribed reduction of N fertilization is expected, which can be explained by the fact that N sources other than fertilization usually contribute significantly to emissions, such as N derived from mineralization of soil organic matter (Shimizu et al., 2013), from low C/N ratio residues of N_2-fixing legumes (Schwenke et al., 2015; Taghizadeh-Toosi et al., 2021) or atmospheric N deposition (van der Gon and Bleeker, 2005).

The mitigation of N leaching by adoption of the F2F strategy is clearly stronger than for N_2O emissions (Figs. 4 and 5). Although a substantial variability in N leaching was observed among sites, our study indicates that the reduction in N leaching can be higher than the prescribed 20% decrease in N fertilization. The more pronounced impact of the F2F strategy on N leaching in these grasslands could be explained by a higher reduction of N surplus. In other words, decreasing N fertilization has a critical impact on the amounts of N remaining in the soil after the nutritional needs of the plants are satisfied, which is a key factor driving N leaching (De Notaris et al., 2018). Regarding the lower mitigation of N_2O emissions compared to N leaching, it is worth noting that the key N transformation process controlling the latter is nitrification, which produces NO_3^-, while the former is controlled by both nitrification and denitrification (Bateman and Baggs, 2005; Mosier et al., 2002). Therefore, the relatively higher complexity in the processes generating N_2O emissions, depending on more drivers (*e.g.,* aeration status, labile C, temperature, pH) for occurrence of N losses, likely results in lower sensitivity to N inputs in comparison to N leaching.

With regard to the effects of global change on N losses, previous studies have highlighted that key controlling factors potentially impacted by shifts in climatic conditions are (*i*) N use efficiency by plants, which is closely associated with plant productivity (Carozzi et al., 2022), (*ii*) soil water dynamics, which controls both microbial N transformation causing gaseous N losses (Bateman and Baggs, 2005; Mosier et al., 2002) and N movement in the soil profile producing leaching (Meisinger and Delgado, 2002), and (*iii*) temperature-modulated turnover of soil organic matter resulting in net N mineralization (de Vries et al., 2012; Rustad et al., 2001). In the present study, the variation in these factors could explain the variability of simulated impacts of global change on N losses at different sites and for different scenarios. For instance, compensatory effects on N losses could be a reason for low impact of global change on N_2O emissions (Fig. 4). On the one hand, warming increases the availability of N prone to losses due to greater mineralization of soil organic matter (de Vries et al., 2012; Rustad et al., 2001). On the other hand, less precipitation in the middle of the growing season (Fig. S2) counteracts the positive effect on N_2O production from increased N availability, since the soil is less anaerobic (Álvaro-Fuentes et al., 2017; Zhu et al., 2013). Besides of this, elevated atmospheric CO_2 levels lead to a higher N use efficiency (Loiseau and Soussana, 1999), which can prevent N losses.

Looking ahead, we would like to point out that other aspects of grassland dynamics not addressed in the present study, in particular soil carbon storage (Carozzi et al., 2022; Scheffer, 2020), biodiversity (Lavorel, 2019) and forage quality (Augustine et al., 2018; Raynor et al., 2024), could also be affected by both global change and the adoption of the F2F strategy, with implications for the delivery of ecosystem services. Besides this, additional targets of the F2F strategy, other than those related to the reduction of N surpluses and losses, should also be considered. For example, a lower consumption of animal-based products and reduced food waste could allow a more extensive use of grasslands and hence lower N fertilization rates. The integration of all the measures within the scope of the F2F strategy can greatly contribute to the achievement of the ambitious goal of reducing nutrient losses by at least 50%.

5. Conclusions

Our results indicated that, under future global conditions, slight yield losses due to a 20% reduction in N fertilization in intensively managed grasslands in the Alpine region, implied by the adoption of the F2F strategy, will most likely be compensated by gains associated with increased atmospheric CO_2. Even if the F2F target of reducing N losses to the environment by 50% was not supported by our model results, we found a substantial decrease in N_2O emissions and N leaching, with larger abatement potential for the latter. The reduction potential was higher when N losses were expressed per unit of harvested dry matter, with up to 17% reduction for N_2O and up to 42% reduction for N leaching. This outcome underlines the importance of the F2F strategy in the framework of the integrated nutrient management action plan as part of the European Green Deal. Future modeling studies are required to explore in more detail the implication of adopting this strategy and also to consider a wider range of agricultural systems.

Declaration of generative AI in scientific writing

The authors declare that they did not use generative artificial intelligence (AI) or AI-assisted technologies in the writing process.

Submission declaration

The authors declare that this study has not been published previously, that it is not under consideration for publication elsewhere, that its publication is approved by all authors and tacitly or explicitly by the responsible authorities where the work was carried out. If accepted, it will not be published elsewhere in the same form, in English or in any other language, including electronically without the written consent of the copyright-holder.

CRediT authorship contribution statement

Márcio dos Reis Martins: Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Christof Ammann:** Writing – review & editing, Methodology. **Carolin Boos:** Writing – review & editing, Resources. **Pierluigi Calanca:** Writing – review & editing, Software, Methodology. **Ralf Kiese:** Writing – review & editing, Resources. **Benjamin Wolf:** Writing – review & editing, Resources. **Sonja G. Keel:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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