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Research article

Regional nitrogen budgets of agricultural production systems in Austria constrained by natural boundary conditions

Eva Strenge [a,*], Ottavia Zoboli [a], Bano Mehdi-Schulz [b], Juraj Parajka [c], Martin Schönhart [d], Jörg Krampe [a], Matthias Zessner [a]

[a] *Institute for Water Quality and Resource Management, TU Wien, Karlsplatz 13/226, 1040, Vienna, Austria*
[b] *Institute of Hydrology and Water Management, University of Natural Resources and Life Sciences, Muthgasse 18, 1190, Vienna, Austria*
[c] *Institute of Hydraulic Engineering and Water Resources Management, TU Wien, Karlsplatz 13/222, 1040, Vienna, Austria*
[d] *Institute of Sustainable Economic Development, University of Natural Resources and Life Sciences, Feistmantelstraße 4, 1180, Vienna, Austria*

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ABSTRACT

Nitrogen (N) budgets are valuable tools to increase the understanding of causalities between agricultural production and N emissions to support agri-environmental policy instruments. However, regional agricultural N budgets for an entire country covering all major N flows across sectors and environmental compartments, which also distinguish between different N forms, are largely lacking. This study comprehensively analyses regional differences in N budgets pertainting to agricultural production and consumption in the largely alpine and spatially heterogeneous country of Austria. A special focus is on the interconnections between regional agricultural production systems, N emissions, nitrogen use efficiencies (NUE), and natural boundary conditions. Seven regional and one national balance are undertaken via material flow analysis and are analysed with regards to losses into soils, water bodies and atmosphere. Further, NUE is calculated for two conceptual systems of plant and plant-livestock production. The results reveal major differences among regions, with significant implications for agri-environmental management. The high-alpine region, characterized by alpine pastures with a low livestock density, shows consequent low N inputs, the lowest area-specific N outputs and the most inefficient NUE. In contrast, the highest NUE is achieved in a lowland region specialized in arable farming with a low livestock density and a predominance of mineral fertilizer over manure application. In this region, the N surplus is almost as low as in the high-alpine region due to both significantly higher N inputs and outputs compared to the high-alpine region. Nevertheless, due to low precipitation levels, widespread exceedances of the nitrate target level concentration take place in the groundwater. The same issue arises in another non-alpine region characterized by arable farming and high livestock densities. Here, the highest N inputs, primarily via manure, result in the highest N surplus and related nitrate groundwater exceedances despite an acceptable NUE. These examples show that NUE alone is an insufficient target and that adapted criteria are needed for different regions to consider natural constraints and specific framework conditions. In a geographically heterogeneous country like Austria, the regional circumstances strongly define and limit the scope and the potential effectiveness of agricultural N management strategies. These aspects should be integrated into the design, assessment and implementation of agri-environmental programmes.

1. Introduction

Inputs of reactive nitrogen (N) into the environment are well known to pose several severe risks to the environment and humans. The agricultural sector is mainly responsible for such inputs as it is the worldwide largest user of N (Kimura et al., 2012; Hutchings et al., 2014; Oenema et al., 2015). Agriculture-driven N losses, primarily via leaching or lateral flow of nitrate into water bodies and via volatilization of ammonia and nitrogen oxides into the atmosphere, are responsible for terrestrial and aquatic acidification, surface and groundwater pollution, eutrophication, biodiversity loss and contribute to climate change mainly via the release of the greenhouse gas nitrous oxide (OECD, 2008; Sutton et al., 2011; De Vries et al., 2011a; Kuosmanen, 2014; Oenema et al., 2015; Groenestein et al., 2018; Hutchings et al., 2020;

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* Corresponding author.
E-mail address: eva.strenge@tuwien.ac.at (E. Strenge).

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Bhattacharyya et al., 2021). Studies on the so-called planetary boundaries estimate that the current N emissions into soil, water and atmosphere are too high to keep the Earth's system environmentally stable and to enable justice of society (Rockström et al., 2023). The growing population and associated growth in consumption will further increase the need for N application, which may amplify the N losses and thus, the environmental problems (Quemada et al., 2020; Bhattacharyya et al., 2021). Therefore, improvements in N management aimed at reducing losses and increasing use efficiencies in agricultural production and food consumption are of key importance for the future (Foley et al., 2011; Galloway et al., 2008; Sutton et al., 2011; Quemada et al., 2020).

Nitrogen balances are considered valuable tools to display and explain the complexity of N emissions into the environment by comparing N inputs and outputs in geographically and functionally well-defined systems (Hoang and Alauddin, 2010; Sutton et al., 2011; Bhattacharyya et al., 2021; Häußermann et al., 2021). They are widely used as an assessment tool for N flows related to agriculture and support regulatory policy instruments in many countries (Hoang and Alauddin, 2010; Kuosmanen, 2014; Häußermann et al., 2021). Nevertheless, complete N balances of agricultural food production and consumption incorporating all major N flows across sectors and environmental compartments, and considering the different N forms are scarce. The N balances of existing studies are often incomplete due to spatial restrictions to individual farms, fields, or watersheds (Bechini and Castoldi, 2006; Xing and Zhu, 2002; Leip et al., 2011a), or system boundary definitions that exclude important components, e.g. unmanaged natural sites or the influence of point source emissions (Lord et al., 2002; Bouwman et al., 2005; De Vries et al., 2011b; Viramontes et al., 2015; Kros et al., 2018; Lee et al., 2020). Additionally, most current studies focus on agricultural production rather than on different environmental effects of N emissions thereby aggregating all N emissions into a total surplus. This does not allow to consider the heterogenous impacts of different forms of N, such as di-nitrogen, nitrous oxide, and nitric oxide from denitrification and nitrification (Lord et al., 2002; Bouwman et al., 2005; Shindo, 2012; Ti et al., 2012).

Furthermore, to allow for the identification of regional distinctions, N budgets should also be estimated and compared at regional scales. The importance of regional-scale analysis, first developed in the 1970s (Schepers and Raun, 2008), is nowadays widely known (OECD, 2008; Sutton et al., 2011; De Vries et al., 2011b; Worrall et al., 2016; Kros et al., 2018; Fan et al., 2020). Regional variations of N balances are largely connected to the type of land use and thus to the amount, timing, and type of N inputs, such as mineral fertilizer and manure (Ruiz et al., 2002; Kimura et al., 2012; Zessner et al., 2017; Tecimen, 2017; Yoshida et al., 2017; Wang et al., 2020; Fan et al., 2020). Regional land use in turn is determined by bio-physical (e.g. topography, climate, and soil properties) and socio-economic production conditions (e.g. market prices, subsidy programmes; Jost et al., 2021). Even though partly modifiable, some of the bio-physical conditions cannot be changed on a large scale. Conditions such as elevation and slope as well as local climate can limit the possibilities and productivity of agricultural land use (Grigg, 2005; Baker and Capel, 2011; Cong, 2021). This particularly applies to mountainous countries such as Austria, characterized by a large diversity of bio-physical conditions in terms of climate, topography and soils leading to potentially large regional differences in agricultural N budgets. However, comprehensive regional N budgets of agricultural production and consumption that cover the causality of environmental conditions and agricultural land use, are rare. Shindo (2012) and Ti et al. (2012) for example calculated regional N budgets for land use in Asian countries incorporating all major N flows but they did not distinguish between all different types of gaseous emissions. Fan et al. (2020) present a comprehensive and complete N balance at 1 km^2 resolution for Great Britain distinguishing between land use and soil types. Nevertheless, the focus of the study lies on the total N budget and not on the detailed analysis of sources and fates of different N forms, particularly in the view of denitrification and nitrification processes. Tanzer et al. (2018) conducted a coupled material flow analysis of phosphorous and nitrogen in Austria but without considering regional distinctions and different forms of gaseous N emissions. Thus, complete regional N budgets comparable to the one presented by Fan et al. (2020) but specific regarding the form of N have not been carried out so far to the best of our knowledge.

Therefore, the aim of this study is the comprehensive investigation of national and regional N balances including all major N flows and their fate related to agricultural production and consumption within the largely alpine and heterogeneous country of Austria. The regional N balances shall reveal spatial differences and their causalities in terms of agricultural land use and environmental conditions. Two main research questions are addressed: i) how do regions differ from each other and compared to the aggregated national level regarding their N emissions into soil, water, and atmosphere as well as concerning their nitrogen use efficiency (NUE)? ii) How are regional differences in N balances connected to regional agricultural practices and environmental conditions particularly in mountainous regions? We hypothesize that mountainous regions reveal lower N inputs and N outputs as well as lower NUE due to their high share of ruminant livestock production. Low-land production regions are expected to reveal higher N inputs and outputs and potentially higher NUE but also potentially higher N emissions depending mostly on the type of agricultural practice and fertilizer management.

2. Spatial system boundaries

The spatial system boundaries are set to one national and seven regional clusters covering most of Austria. The regional clusters are based on the Austrian main agricultural production regions (LWHPG) and river catchments. LWHPG considers similarities regarding landscape, topography and altitude as well as agricultural production systems (Wagner, 1990). The river catchments within the MONERIS model are considered, since several input data are calculated by the model at the catchment level. The regional clusters thus consist of the MONERIS river catchments covered or intersected by an LWHPG (Fig. 1). However, only catchments that are completely or to a large extent included in an LWHPG are selected for a cluster to focus on unique and representative traits of the production regions. The national cluster consists of all MONERIS catchments located inside Austria. The regional clusters are named according to the original LWHPG as follows: Hochalpen, Voralpen, Alpenostrand, Alpenvorland, Wald- and Muehlviertel, Nordoestliches Flach-und Huegelland, Suedoestliches Flach-und Huegelland. The eighth LWHPG Kaerntner Becken is incorporated into the cluster Alpenostrand due to its small spatial extent and catchment number. The seven regional clusters are further grouped into the classification high-alpine (Hochalpen), alpine (Voralpen, Alpenostrand), and non-alpine (Alpenvorland, Wald- and Muehlviertel, Nordoestliches Flach-und Huegelland, Suedoestliches Flach-und Huegelland) based on their predominant natural traits and related agricultural production (seeTab. A1). Each cluster covers more than 80% of the area of the original LWHPG except for Alpenvorland and Nordoestliches Flach-und Huegelland with lower coverages (Table 1). The lower coverages are due to several catchments in the clusters with water courses stemming from other LWHPG, which were therefore excluded.

The lowest shares of the total area dedicated to agriculture appear in the two alpine clusters Voralpen and Alpenostrand (24% and 32% respectively), while the highest one is in the cluster Nordoestliches Flach-und Huegelland (66%, see Table 1). The three alpine clusters Alpenostrand, Hochalpen, and Voralpen, which together account for 57% of the total area of Austria, are characterized by a predominant use of grassland with significant shares of alpine pastures. This is particularly evident in the high-alpine cluster Hochalpen with 99% share of grassland in the agricultural area, the majority of which is being used as alpine pastures (79%). The opposite situation, with nearly all of the agricultural area used as arable land (99% share), can be observed in Nordoestliches Flach-und Huegelland.

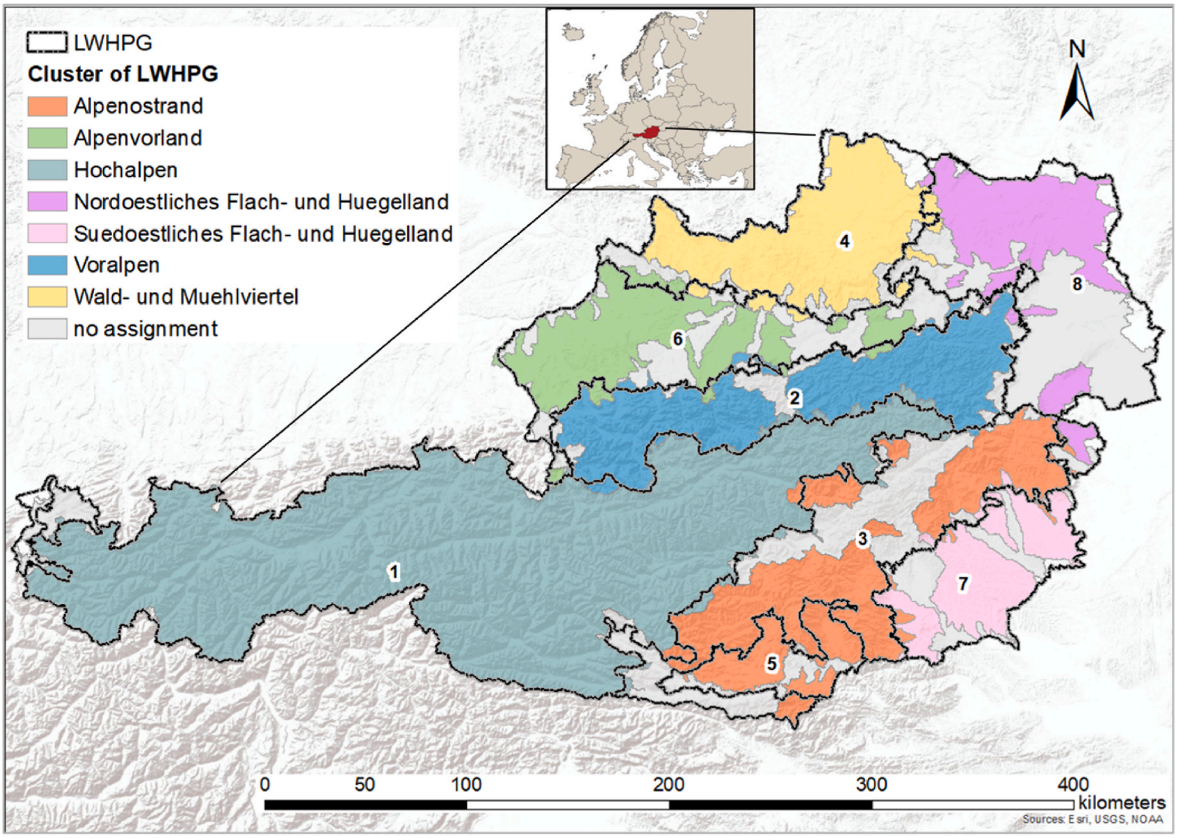

Fig. 1. Spatial extent of the regional clusters compared to the original Austrian agricultural main production regions (the numbers belong to original LWHPG; 1: Hochalpen (Central Alps, high-alpine), 2: Voralpen (Alps, alpine), 3: Alpenostrand (Central Alps and basin, alpine), 4: Wald-und Muehlviertel (Highlands, non-alpine), 5: Kaerntner Becken (basin), 6: Alpenvorland (Alpine foothills, non-alpine), 7: Suedoestliches Flach-und Huegelland (Alpine foothills, non-alpine), 8: Nordoestliches Flach-und Huegelland (Plains and hills, non-alpine); Note: 5 and 3 are aggregated in this study).

Table 1

Coverage of clusters of agricultural main production areas (LWHPG), the share of land uses in the clusters, and in the agricultural area (AA) and LSU. LSU density refers to LSU per hectare of the total agricultural area.

	cluster coverage of LWHPG	total area	forest in total area[a]	AA in total area[a]	arable land in AA[a]	grassland in AA[a] (alpine pasture in grassland[a])	LSU in Austrian LSU[b]	LSU density
	%	km^2	%	%	%	%	%	$\mathrm{LSU\ ha^{-1}}$ AA
Alpenostrand	81	9069	57	33	33	67 (33)	12	0.8
Alpenvorland	61	5290	24	62	62	38 (2)	18	1.1
Hochalpen	98	29,002	36	47	1	99 (79)	19	0.3
Nordoestliches Flach- und Huegelland	45	4560	21	66	99	1 (0)	2	0.1
Suedoestliches Flach- und Huegelland	98	4868	43	42	72	28 (5)	8	0.8
Voralpen	86	7995	62	24	7	93 (32)	7	0.7
Wald- und Muehlviertel	85	6429	42	48	61	39 (0)	13	0.8
Austria (AT)	97	81,341	40	44	39	61 (55)	100	0.5

[a] Retrieved from Federal Environmental Agency (2015)

[b] Retrieved from Loishandl-Weisz et al. (2020).

Since the cluster Nordoestliches Flach-und Huegelland covers less than 50% of the area of the original LWHPG, there are slight differences in land use shares between the two. The cluster slightly overrepresents agricultural area and particularly arable land since it shows a higher share of both in comparison to the original LWHPG. Nevertheless, the small difference is not expected to significantly affect the results and the conclusions with respect to this region.

Table 1 also presents the distribution of livestock, expressed as Livestock Unit (LSU; statistical aggregation scheme for livestock; one adult cattle is considered as 1 LSU). The clusters Hochalpen and Alpenvorland have the highest share in the total national LSU of 19% and 18%, respectively. However, the highest LSU density appears in Alpenvorland (1.1 LSU ha^{-1}), while the lowest can be found in Nordoestliches Flach-und Huegelland (0.1 LSU ha^{-1}; only a few professional livestock farmers due to the focus on arable farming) and Hochalpen (0.3 LSU ha^{-1}; widespread dominance of livestock farming with low stocking densities).

3. Methods

3.1. *Material flow analysis*

One national and seven regional nitrogen balances are carried out by using Material Flow Analysis (MFA) according to Brunner and Rechberger (2004). MFA is the systematic assessment of flows and stocks of a material, such as nitrogen, within a system predefined in space and time based on the principle of mass conservation (Brunner and Rechberger, 2004). The MFA model used here was already leveraged by several other studies (Cordell et al., 2009; Pires et al., 2011; Müller et al., 2014). In this study the model is applied on a yearly basis from 2012 to 2017 including the main relevant N flows concerning the national and regional agricultural food production and food consumption connected to the environmental compartments soil, atmosphere, and water bodies (Fig. 2). The main building blocks of the MFA model are called processes. These are agricultural soils, non-agricultural soils, livestock production, settlements, wastewater treatment, groundwater and surface water. The atmosphere is not depicted as a process as it cannot be considered as a closed system within the model system boundaries, but it is explicitly considered via the import flows of di-nitrogen (N_2), nitric oxide (NO), and nitrous oxide (N_2O) from denitrification and nitrification as well as ammonia (NH_3) from storage and application loss, and via the export flows of atmospheric deposition and biological fixation. Imports and exports by atmospheric N transport across borders are only considered within atmospheric deposition due to the focus on the national or regional impact of agricultural production and food consumption on the N balances. However, all remaining N flows also incorporate imports and exports across borders (such as mineral fertilizer, crops, and animal products) to allow mass balance computations.

The conceptual MFA model contains several assumptions. First, no significant changes in N storage in soils and groundwater are assumed since the model MONERIS, which calculates the N emissions into soils, ground- and surface water (see chapter 2.2 for further explanation), is set up based on average long-term conditions (Venohr et al., 2011). Second, for non-agricultural soils (forest, open areas, mountainous and glacial soils), removal by tree harvest is not considered since the related influence on the nitrogen flows within the system is negligible (Tanzer, 2019). Deposition rates of forests are assumed equal to those of nearby agricultural soils due to data limitations. N_2O and NO emissions from natural soils are based on measurements from studies solely carried out at forest sites, which can be assumed as representative since forests hold the predominant share of non-agricultural areas in Austria (WKO – Wirtschaftskammer Österreich, 2021). In terms of wastewater treatment, the flow “sewage sludge” is fully considered as export from the system due to the low relevance of its direct or indirect application in Austrian agriculture. N amounts in biogas crops and crop residues are returned to the agricultural fields via digestates and left on the fields, respectively. Thus, they are assumed to cycle within the process “agricultural soils” and are not depicted explicitly as flows. Moreover, N losses taking place out of the system boundaries, such as the ones arising during the production of feed, food or agrochemicals, are not

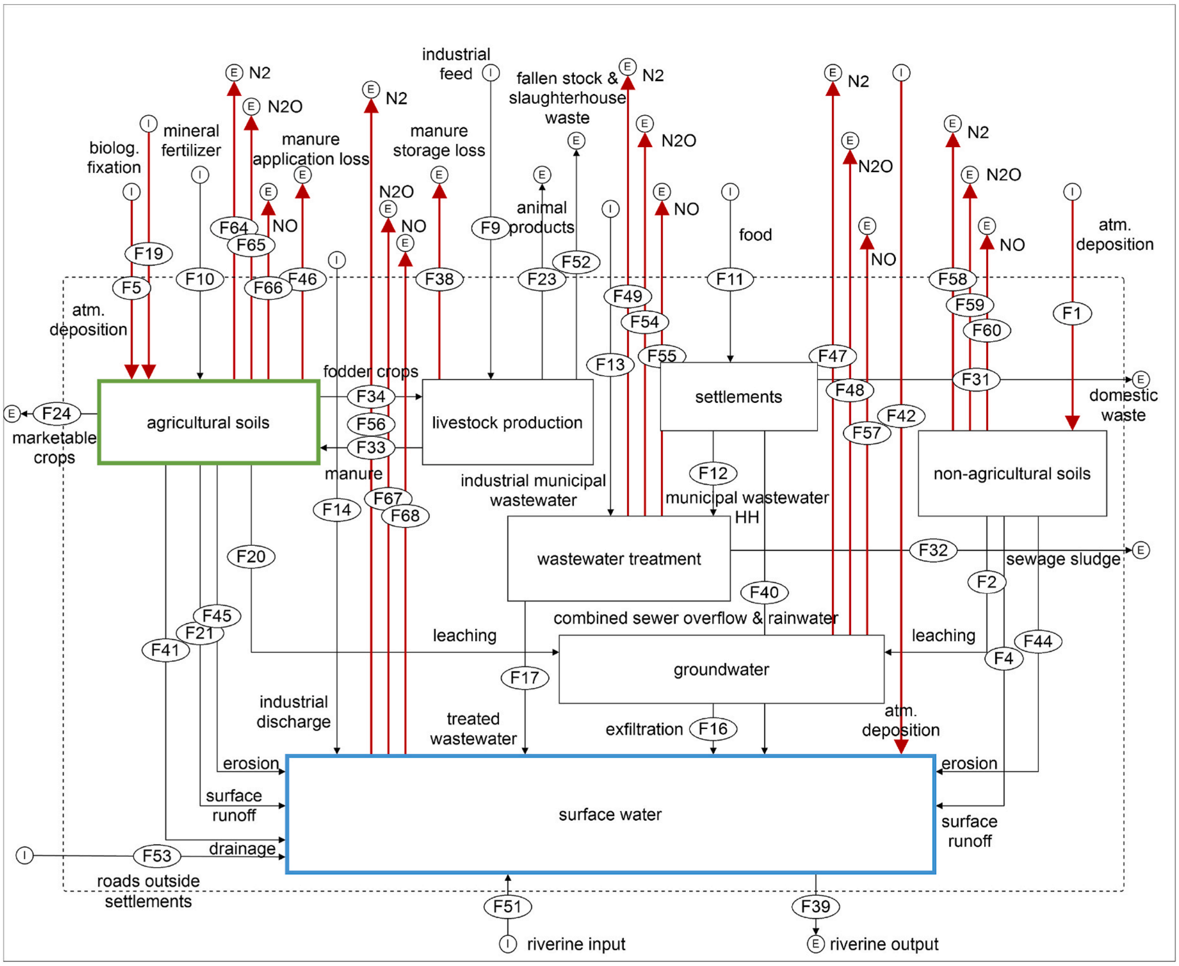

Fig. 2. Conceptual MFA model of the national and regional nitrogen balances implemented in the STAN software. The dotted line represents the system boundary (I = Import, E = export). The numbers written on the arrows are the flow numbers (see Table S1 in the supplementary material for further explanation). The colored boxes are key processes of the MFA. The red colored arrows are the import and export flows of the atmosphere.

considered. All nitrogen balances are calculated in the freeware STAN (Cencic and Rechberger, 2008; Cencic, 2016).

3.1.1. Data sources and calculation of flows

The input data for the MFA are derived from several sources. N flows which represent emission pathways into waters, such as erosion, leaching, and wastewater effluents are estimated by the nutrient emission model MONERIS (Modelling Nutrient Emissions into RIver Systems; (Behrendt and Opitz, 1999; Venohr et al., 2009; Venohr et al., 2011; Zessner et al., 2011; Zessner et al., 2017), implemented in the river basin management system MoRE (Modeling of Regionalized Emissions; Fuchs et al., 2017). The model calculates river loads at catchment outlets as well as emission loads from point and diffuse pathways. The emission loads are derived by multiplying the dissolved N concentration of the respective pathway, minus a retention by denitrification and nitrification where appropriate, with its water discharge. The river loads are the sum of all emission loads entering surface waters from the respective catchment and all upstream catchments minus a retention of N by denitrification and nitrification within the river. A detailed description of the load calculation can be found in Behrendt and Opitz (1999), Venohr et al. (2009) and Venohr et al., 2011.

The model MONERIS was originally developed for Germany and adapted for its application in Austria by Gabriel et al. (2011) and Zessner et al. (2011). The current version 2.14 is based on the Austria-wide application carried out by Zessner et al. (2017). In this study, time-independent data is taken from the MONERIS version of Zessner et al. (2017), whereas nitrogen surplus as time-dependent input data is recalculated for the period 2012 to 2017. This recalculation leads to modified river loads, which are thus validated against observed river loads for the same period. The observed river loads are derived with the calculation method according to Zessner et al. (2017), using data of measured dissolved inorganic nitrogen (DIN) concentrations obtained from the Austrian monitoring program based on the Ordinance on the Monitoring of the Quality of Water Bodies (GZÜV, 2021), and monitored discharges obtained from the Hydrographical Service of Austria (HZB, 2021). The validation reveals a goodness of fit of 0.64 for the coefficient of determination (R^2) and a percent bias of 27%, indicating an acceptable level of overestimation (seeFig. A1, Appendix). The model bias mainly occurs due to an improvement of the overall mass balance by recalculating the N surplus from the given data to account for the N in the feed for livestock.

The estimation of N flows concerning agricultural management (fertilizers, harvest, losses, etc.), food consumption and atmospheric deposition is based on official statistics and monitoring programs in Austria and Europe. The remaining N flows are derived from agencies and regulations or estimated with the help of national and international literature (Butterbach-Bahl et al., 2002; Zessner and Lindtner, 2005; Pilegaard et al., 2006; Kesik et al., 2006; Kitzler et al., 2006; Kampschreur et al., 2008; Leip et al., 2011b; Hu et al., 2016; Liu et al., 2017; Loishandl-Weisz et al., 2020; Federal Environmental Agency, 2020; Amann et al., 2021). Table S1 to Table S3 in the supplementary material reports in detail the calculation and the data sources for every single flow. If only national data and no robust factors for disaggregation from national to regional scale are available, the flow values are estimated from the mass balance by the software STAN. This applies to the N flows of waste from households, industrial feed, and N_2 release from surface waters.

3.1.2. Handling of data uncertainty

Statistical calculations of the uncertainty could not be carried out since the number of records used for the generation of the input data of the MFA (yearly records from 2012 to 2017) is insufficient for a statistical analysis. Instead, the approach according to Laner et al. (2016) is applied. This method derives the uncertainty of each input data by combining the data quality assessment within five categories (reliability, completeness, temporal correlation, geographical correlation, and other correlation) with the assessment of the sensitivity of the input data in each of the categories. The sensitivity expresses how sensitive the input data is to a deviation in one of the five data quality categories. Although subjective, this approach ensures consistency in the uncertainty estimation within the model and provides comprehensive documentation and transparency on how it has been carried out. The uncertainty of N flows estimated from the mass balance due to lacking suitable data is calculated by the software STAN based on error propagation. The software further carries out nonlinear data reconciliation based on the conventional weighted least-squares minimization approach in case of contradictions in input data. By changing the values of uncertain data to solve contradictions, the initial uncertainty of the reconciled data is reduced (Cencic, 2016).

3.2. Nitrogen use efficiency

In addition to the analysis of the N pathways into and out of the environmental compartments soil, atmosphere, and surface waters, a detailed analysis of the nitrogen use efficiency is applied. for two conceptual systems: a plant production system and a mixed plant-livestock production system (see Fig. A2andFig. A3). The justification for this twofold analysis lies in the underlying variability of NUE of livestock production systems, which aggravates the comparability of NUE among regions. Livestock production systems recycle N via manure excretion, storage, and fertilization. At each of these steps, N is lost into the environment, e.g. via NH_3, N_2O, or N_2. Hence, livestock production systems show a lower NUE compared to plant production systems. NUE further depends on the type of livestock and in mixed plant-livestock systems also on the proportion of livestock versus plants (Hoang and Alauddin, 2010; Godinot et al., 2015; Oenema et al., 2015; Groenestein et al., 2018; Quemada et al., 2020; Bhattacharyya et al., 2021). The plant production system presented here is biased since the further usage of the harvested fodder crops and the origin of manure is not considered. This should be considered when comparing NUE of the two conceptual systems. Nevertheless, the plant production system allows for direct comparisons of NUE among regions since NUE is not naturally constrained as it is the case for the mixed plant-livestock production system.

NUE is calculated by the ratio of N outputs and N inputs into a system allowing for the assessment of nitrogen use against nitrogen loss. For the plant production system, the calculation is based on yearly records from 2012 to 2017 and is carried out as follows:

$$\frac{N_{fodder} + N_{market}}{N_{man} + N_{min} + N_{fix} + N_{dep}} \cdot 100\ [\%]$$

where N_{fodder} is N in harvested fodder crops, N_{market} is N in harvested marketable crops, N_{man} is N in manure applied without N losses during manure storage, N_{min} is N in applied mineral fertilizer, N_{fix} is N in the soil by biological fixation, and N_{dep} is N input by atmospheric deposition (see Fig. 2, flow numbers F34, F24, F33, F10, F19, F5). Harvested fodder crops include the removal of fodder crops by both mowing and grazing.

For the mixed plant-livestock production system, NUE is calculated by yearly records from 2012 to 2015 since data on industrial feed was only available for this period:

$$\frac{N_{market} + N_{animal}}{N_{min} + N_{fix} + N_{dep} + N_{ind}} \cdot 100\ [\%]$$

where N_{animal} is N in animal products and N_{ind} is N in industrial feed (see Fig. 2, flow numbers F23, F9). The N flows fodder crops and manure are internalized in this system. N losses during the production process of industrial feed are not considered here since for the assumption of mixed plant-livestock production systems compared to livestock farming alone, the influence of externalized N is limited.

The EU Nitrogen Expert Panel (Oenema et al., 2015) proposes a uniform framework for the analysis of NUE by using a graphical approach presenting NUE, N output, N input, and N surplus in a connected manner, which is applied in this study. The N surplus is calculated by the N input minus the N output. NUE target values proposed by the EU Nitrogen Expert Panel are additionally included for a better assessment of NUE. The target values applied are the current average values of the European crop and livestock production (EU-27; Oenema et al., 2015).

4. Results

A complete overview of the MFA results for the national and regional clusters is given in the supplementary material (Fig. S1 – Fig. S8). The following section presents and discusses key results focusing on N emission into soil, atmosphere, and surface waters (see Fig. 2, colored key processes and red colored flows representing the atmosphere) as well as NUE of the two conceptual systems.

4.1. Nitrogen flows

4.1.1. Agricultural soils

This section presents the N flows into and out of agricultural soils related to the respective agricultural area (see Fig. 2, green box and Fig. 3 a, b for the N input and output flows). Among the regional clusters the N input flows range from 46 to 176 kg ha^{-1} agricultural area (Fig. 3a).

The total area-specific N input of all non-alpine clusters is 147 kg N ha^{-1}. The N input of the national cluster of 105 kg ha^{-1} is higher than the N input of all regional clusters of 97 kg N ha^{1}. This difference might be due to the exclusion of some catchments (see chapter 2). The main input flow of N (Fig. 3a) is manure in all regional clusters, except for Suedoestliches Flach-und Huegelland and Nordoestliches Flach-und Huegelland, in which mineral fertilizer is instead the main N input source. When considering the national level, mineral fertilizer is the dominant input flow of N, with manure being only slightly less

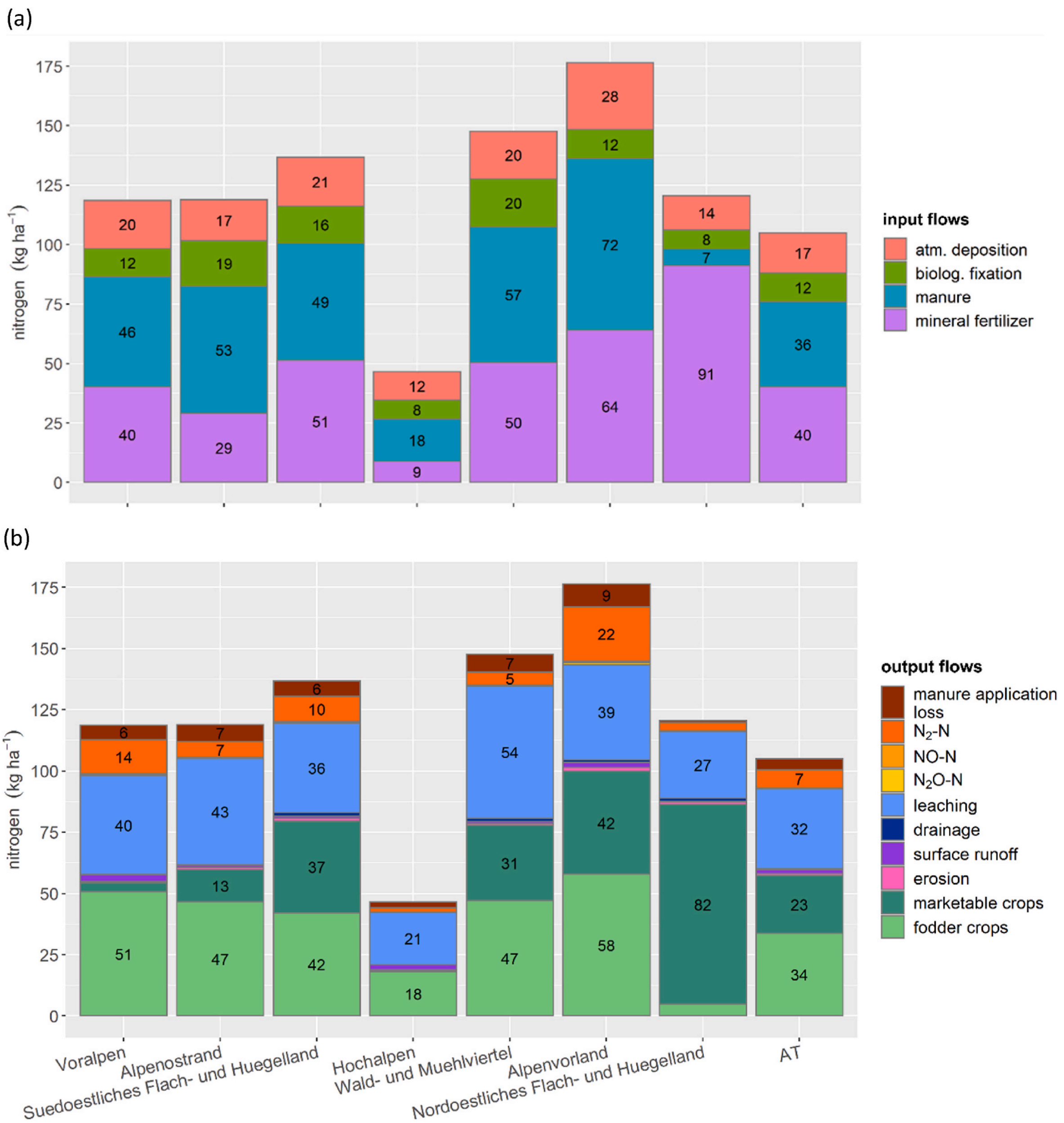

Fig. 3. (a) Input flows of N into agricultural soils and (b) output flows of N from agricultural soils (kg ha^{-1} agricultural area) for the national (AT) and regional clusters; reddish: gaseous releases, blueish: water-related emissions, greenish: crops; numbers are only shown for flows >5 kg N ha^{-1} agricultural area.

important.

The main output of N takes place via the flows crop harvest (mostly as fodder crops) and leaching into groundwater in the national and in all regional clusters (Fig. 3b). Other relevant output flows are volatilization of N_2 and NH_3 during manure application (manure application loss). Minor output flows with approximately 1 kg N ha^{-1} are surface runoff, which appears primarily in the alpine clusters, and erosion and drainage, with the latter one being only relevant in the non-alpine clusters.

A comparison of the regional clusters among each other reveals three noticeably different clusters concerning both the N input and output flows. These are the high-alpine cluster Hochalpen, and the two non-alpine clusters Alpenvorland and Nordoestliches Flach-und Huegelland.

The cluster Hochalpen is on the one hand characterized by the lowest total N input and the lowest area-specific N input via fertilizers. This leads to the smallest area-specific releases of N_2, N_2O, and NO. On the other hand, the share of manure in fertilizers applied is the highest among the clusters with N input via manure being about twice as high as via mineral fertilizer. This in turn results in relatively high volatilization values of NH_3 during manure application of 2.3 kg N ha^{-1}. The cluster characteristics can be explained by a high share of extensive alpine pastures without agricultural fertilization except for excretion during grazing (see Table 1, Tab A3). It leads to a low LSU density (0.3 LSU ha^{-1}), a low total amount of manure compared to the other regional clusters (except for Nordoestliches Flach-und Huegelland), and, consequently, the lowest absolute N surplus regarding losses to water and atmosphere (28 kg N ha^{-1}). By contrast, when looking at the relative emissions defined as N loss versus N uptake by crops, the cluster reveals the highest emissions among all clusters with a ratio of 1.5. All alpine clusters show similar results with N losses, mostly via leaching, volatilization during manure application, and during denitrification and nitrification in the form of N_2, being equally high or higher than N uptakes. When considering only reactive N (without N_2) the same ratio for Hochalpen and a slightly lower ratio of 0.9 for both Voralpen and Alpenostrand appears.

The N input in the cluster Nordoestliches Flach-und Huegelland is the lowest among the non-alpine clusters being similar to the N input in the two alpine clusters Alpenostrand and Voralpen. Additionally, contrary to all other clusters, predominantly mineral fertilizers are applied (93%). The reason for the noticeable low proportion of manure in fertilizers is the extremely low number of LSU leading to a low average LSU density of 0.1 LSU ha^{-1} in this arable farming-dominated cluster (see Table 1). It results in the lowest amount of area-specific NH_3 emissions, being 2.6-fold lower than in Hochalpen, as well as low emissions of NO and N_2O and low leaching amounts. The low gaseous releases also affect the atmospheric deposition by lower redeposition of N resulting in the smallest atmospheric deposition among almost all clusters. Consequently, the total N surplus of 34 kg N ha^{-1} is considerably lower than in the remaining non-alpine clusters, and the relative emission is the lowest among all clusters with N uptake by crops being 2.5-fold higher than N loss.

The cluster Alpenvorland is characterized by the highest total N input with the highest area-specific amount of manure among the regional clusters. The latter can be explained by the highest LSU density of 1.1 LSU ha^{-1} (see Table 1), which causes the highest N volatilization of N_2, N_2O, NO, and NH_3 during manure application. Due to redeposition, also the atmospheric deposition values are the largest among the clusters (Fig. 3a). Consequently, this cluster shows the highest total N surplus of 71 kg N ha^{-1}. Nonetheless, the relative N emissions of 0.77 in Alpenvorland are considerably lower than for the alpine clusters and are within the range of the relative emissions of the other non-alpine clusters (0.72–0.90) except for the cluster Nordoestliches Flach-und Huegelland. The reason is the high N uptake by crops leading to higher N outputs via harvest than N losses. Generally, all non-alpine clusters reveal higher N removals by crops than N losses. This is probably explained by the high percentage of targeted fertilization management in the non-alpine clusters compared to the alpine clusters with significant shares of grazed alpine pastures. There appears to be higher N uptakes by cultivated cropland in comparison to grassland in general. Finally, the hilly and lowland Alpenvorland may be favoured by better environmental growing conditions compared to the mountainous alpine clusters.

4.1.2. *Surface waters*

The N values presented in this section are the N input flows into surface waters in relation to the respective cluster area (see Fig. 2, blue box and Fig. 4 for the input flows). Riverine inputs from neighbouring clusters or regions outside of Austria are not considered. The total N inputs into surface waters range from 5 to 18 kg N ha^{-1} cluster area (Fig. 4). The prevailing N input flow is exfiltration of groundwater to surface waters in the national and all regional clusters. The second largest input flow is treated wastewater effluent for all clusters except for Voralpen, Hochalpen, and Nordoestliches Flach-und Huegelland. Other regionally relevant input flows are surface runoff from non-agricultural soils with a share of 14% and 12% in the total inputs in Voralpen and Hochalpen, respectively, N inputs via combined sewer overflow and rainwater drainage with the highest share of 20% in Nordoestliches Flach-und Huegelland, and surface runoff from agricultural soils with shares of 11% and 7% in Hochalpen and Alpenvorland, respectively.

Alpenvorland, Voralpen, and Nordoestliches Flach-und Huegelland significantly differ from the other clusters (Fig. 4). The differences are mostly caused by differing N inputs via exfiltration of groundwater to surface waters. The amount of exfiltrated N depends on the N surplus from non-agricultural and agricultural soils and on denitrification in the soil-groundwater passage. The model MONERIS calculates the amount of denitrification on the assumption of enhanced denitrification with low leachate and thus low groundwater recharge rates, and related increasing concentration of dissolved N (Behrendt and Opitz, 1999; Zessner et al. 2005, 2011, 2017; Venohr et al., 2009).

In the cluster Nordoestliches Flach-und Huegelland, the low N surplus and thus the low amount of N leaching from agricultural soils is one reason for the lowest N inputs from groundwater to surface waters. Besides, low precipitation (seeTab. A1, Appendix), and thus low leachate amounts result in the by far highest concentration of dissolved N in the leachate among all clusters (seeTab. A2, Appendix). This leads to a high denitrification rate (20 kg N ha^{--1} cluster area), which significantly lowers the N loads entering surface waters from groundwater. However, the high N concentration in the leachate causes high groundwater N concentrations leading to exceedances of the EU target value of nitrate in terms of a good chemical status at several measurement sites in this cluster (BML, 2020).

The cluster Alpenvorland shows the highest input via groundwater to surface waters per cluster area. The reason is mainly the high amount of N leaching from agricultural soils per cluster area since the cluster is dominated by agricultural soils (62%) with high N surpluses. This also leads to several measurement stations exceeding the target value for nitrate in groundwater (BMLFederal Ministry of Agriculture, 2020). A comparison with the cluster Wald-und Muehlviertel reveals higher N leaching amounts from agricultural soils than in Alpenvorland, but a substantially higher reduction of the N amount in the leachate by denitrification in soil and groundwater (Tab. A2, Appendix). This results in a significantly lower amount of exfiltrated N of groundwater and less exceedances of nitrate concentration levels in groundwater compared to Alpenvorland.

The second highest amount of exfiltrated N per cluster area in Voralpen is caused by N leached from agricultural soils and non-agricultural soils. Among all clusters, N leaching from non-agricultural soils is the highest in Voralpen resulting from a predominant share of non-agricultural area in the total cluster area (see Table 1). Additionally, the amount of N released by denitrification in soil and groundwater is the lowest among the clusters (Tab. A2, Appendix), which is a result of

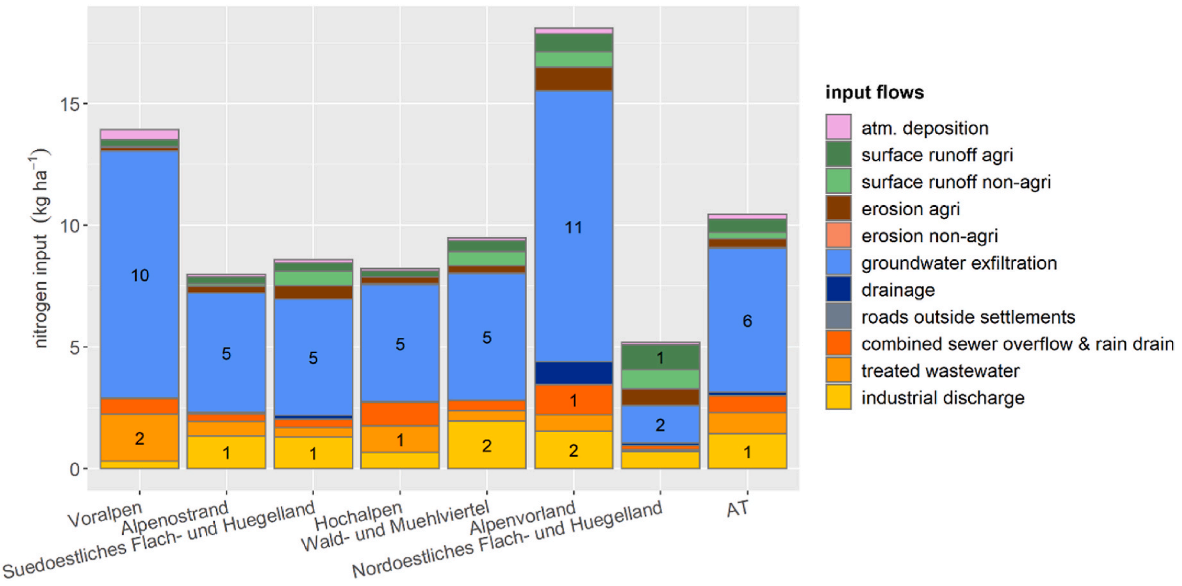

Fig. 4. Input flows of nitrogen into surface waters in kg ha^{-1} cluster area without riverine inputs from regions outside the cluster (agri = agricultural soils, non-agri = non-agricultural soils); numbers are only shown for flows ≥1 kg N ha^{-1}.

the low N concentration in the leachate. This in turn is linked to the high yearly precipitation amount causing a high level of the groundwater recharge rate (Tab. A1, Appendix).

4.1.3. Atmosphere

The results presented in this section are based on the N input flows into the atmosphere related to the respective cluster area (see Fig. 2, red export arrows). The prevalent form of N released into the atmosphere with respect to the N amount per cluster area is N_2 (13–42 kg N ha^{-1}), followed by NH_3 via manure storage loss (2–11 kg N ha^{-1}) and to a lower extent via volatilization during field application (0.6–6 kg N ha^{-1}) in the national and all regional clusters. The origins of gaseous N releases are mainly manure storage losses (61–72%) for NH_3, and denitrification and nitrification in agricultural soils as well as denitrification in groundwater for N_2, N_2O, and NO. The largest proportion of release of the latter three N forms is taking place in groundwater (39–85% for N_2, 44–87% for N_2O, 49–90% for NO), particularly in groundwater situated under agricultural soils in combination with the agricultural soils themselves (Fig. 5; 52–77% for N_2, 60–80% for N_2O, 66–89% for NO). The second largest input source for all clusters, except for Alpenvorland in the case of N_2, is denitrification in groundwater in combination with denitrification and nitrification in non-agricultural soils (3–6 kg N ha^{-1} from N_2, 0.1–0.2 kg N ha^{-1} from N_2O, 0.05–0.1 kg N ha^{-1} from NO) with the majority of N stemming from denitrification in groundwater. At the national level, surface waters are the third largest input source of N_2O and NO, and wastewater treatment plants (WWTP) are the third largest

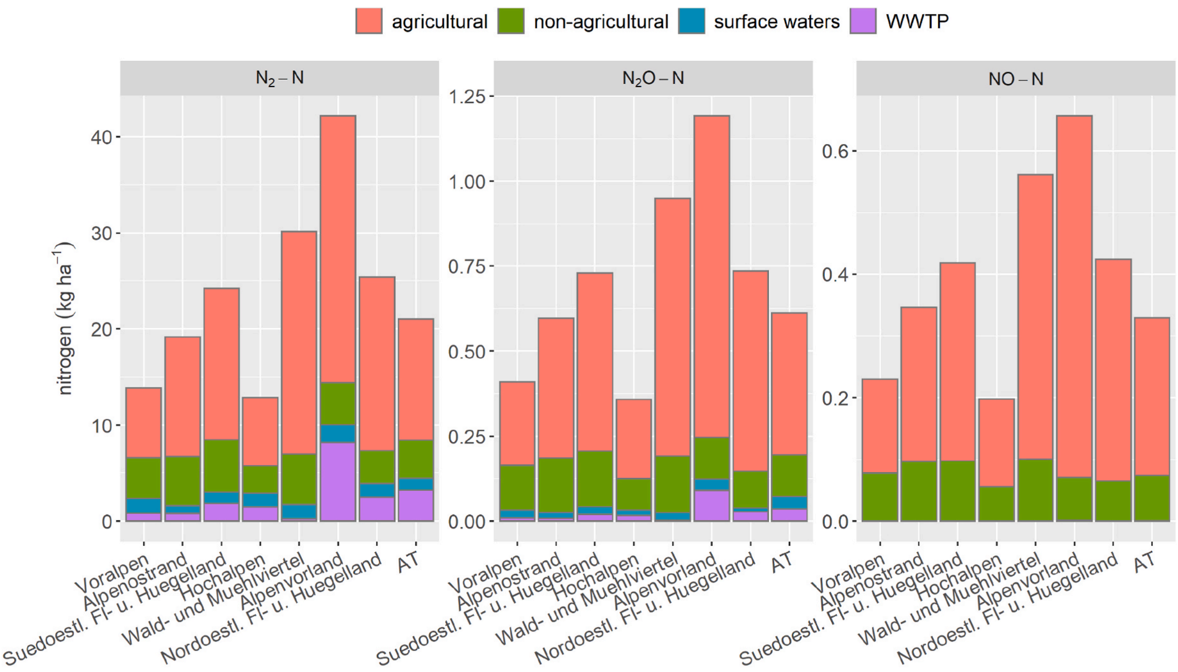

Fig. 5. Nitrogen amounts embedded in N_2, N_2O, and NO releases into the atmosphere per cluster area and their origins. The categories "agricultural" and "non-agricultural" both include soil and groundwater situated under these soils.

concerning N_2.

The most contrasting among all regional clusters are Alpenvorland with the highest volatilization of all considered N forms, the cluster Nordoestliches Flach-und Huegelland with the lowest NH_3 emissions from both sources, and the two alpine clusters Hochalpen and Voralpen with the lowest releases of N_2, N_2O and NO from all sources.

The reason for the highest N emissions in Alpenvorland are the likewise highest N inputs into agricultural soils, the high share (62%) of agricultural area, and the large amount of applied manure mainly causing losses of NH_3. Furthermore, WWTP also considerably contribute, in particular to the release of N_2 and N_2O in Alpenvorland since these emissions from WWTP are the highest among all clusters.

The low emissions of N_2, N_2O, and NO in the two alpine clusters Hochalpen and Voralpen have different reasons. In Voralpen, the reason is probably a combination of moderate N inputs via fertilizers and a low share of agricultural area in the total cluster area, resulting in a low area-specific impact of agricultural releases on the overall N volatilizations. In contrast, the low N_2, N_2O, and NO releases in Hochalpen are a result of the overall low N inputs, especially in agricultural soils. The low absolute amount of manure application can directly be linked to the low LSU density which in turn also causes the second lowest absolute NH_3 emissions among the clusters. Nevertheless, since 47% of the total cluster area is agriculturally used, the releases of N_2, N_2O, and NO are rather enhanced compared to a cluster with a lower share of agricultural area, such as Voralpen.

The cluster Nordoestliches Flach-und Huegelland has the lowest LSU density and, hence, the lowest amount of manure applied in agricultural area resulting in the lowest NH_3 emissions. Mineral fertilizer application results in higher N uptakes by plants which in turn leads to a lower amount of N available for denitrification. This effect is partly counteracted by the large contribution of agricultural N releases to the overall N volatilizations per cluster area due to the high share of agricultural area in Nordoestliches Flach-und Huegelland (Fig. 5).

4.2. *Nitrogen use efficiency*

4.2.1. *Plant production systems*

Fig. 6a depicts NUE for plant production systems for single years from 2012 to 2017. It includes exemplary target values for NUE, N output and excess N for cropping systems according to Oenema et al. (2015). The target values do not include permanent grassland and are generally highly dependent on the respective site conditions such as crop type, climate and soil type which are also not considered here. Therefore, the values only serve as an approximate orientation. NUE in the graph can be seen by the proximity of the points to the target values (Fig. 6a, dashed lines). A system with high N inputs and a high NUE will be found in the upper right corner of the graph.

Nationally, NUE reaches a value of 55%. In the non-alpine clusters, NUE ranges between 44 and 64%, except for Nordoestliches Flach-und Huegelland with distinctly higher values of up to 87%. All alpine clusters reveal lower NUE of 35–55% with the distinctly lowest NUE values throughout the years in the high-alpine cluster Hochalpen. The reason for the differences in NUE, particularly between the alpine and the non-alpine clusters, are the differences in production potentials on agricultural soils, fertilizer types and application rates. This is a consequence of the different climatic and topographic conditions in the alpine compared to the non-alpine clusters which in turn influences land use options.

The typical production system in the alpine clusters, which is particularly visible in the high-alpine cluster Hochalpen, is dominated by grassland use with significant proportions of alpine pastures in combination with ruminant livestock production (including mainly beef and dairy cattle; Table 1, Tab. A3, Appendix). This leads to a high proportion of manure returned as fertilizers to the soils in these clusters. In the cluster Hochalpen, the lowest N outputs via crops and relatively

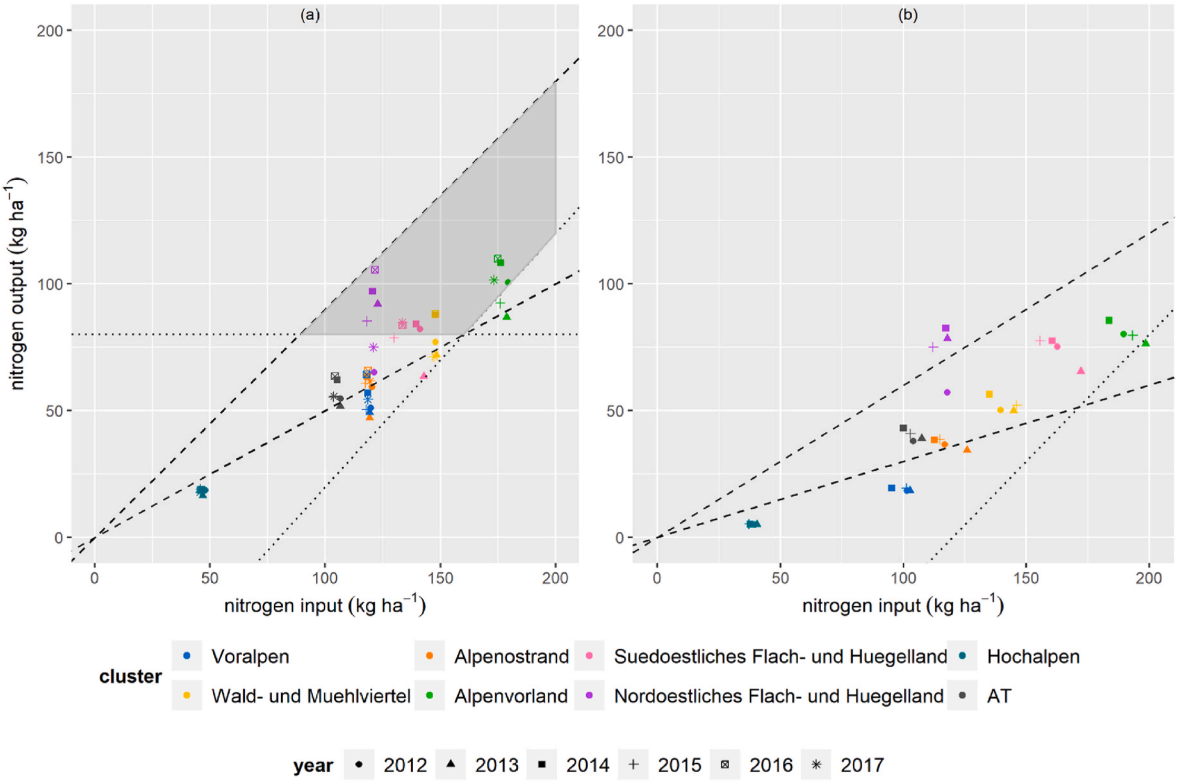

Fig. 6. Relationship of N inputs and outputs indicating NUE of plant production systems (a), and plant-livestock production systems (b) at the national and regional level. Dashed lines: upper and lower exemplary target values for NUE of 90% and 50% (a), 60% and 30% of crop-livestock systems with 1 LSU ha^{-1} (b), diagonal dotted line: suggested maximum surplus of 80 (a) and 120 kg N ha^{-1} yr^{-1} (b) agricultural area, horizontal dotted line: suggested minimum productivity of 80 kg N ha^{-1} yr^{-1} agricultural area (a), dark gray area: overall suggested range of all parameters (a), according to Oenema et al., 2015).

high N inputs result in the by far lowest NUE among all clusters throughout all considered years. The highest NUE in Nordoestliches Flach-und Huegelland, which is also significantly higher than in the other non-alpine clusters, can be explained by a low manure application and a low N surplus in combination with a high uptake of N by arable crops and thus high N amounts in harvested produce compared to N inputs by fertilizers. The highest NUE values of this cluster are in the range of 72–87% in the years 2013–2016 and are thus close to the upper target value of 90% according to Oenema et al. (2015). An exceedance of the target value of 90% points to a risk of soil N mining, whereas a NUE below 90% increases the risk of N losses. Thus, a NUE close to 90% implies the most sustainable N usage concerning N as a resource, soil conditions and environmental impacts.

A comparison of the surplus of the regional clusters to the exemplary target value of 80 kg N ha^{-1} agricultural area shows only an exceedance in Alpenvorland in the years 2013 and 2015. This is due to high N inputs, mostly via manure application on agricultural soils but also via deposition on non-agricultural soils that lead to the highest N losses among all clusters. The overall suggested range in respect to NUE, N surplus, and productivity (Fig. 6a, dark gray area) is solely achieved in the non-alpine clusters Alpenvorland, Nordoestliches Flach-und Huegelland, and Suedoestliches Flach-und Huegelland for most of the years. For the cluster Wald-und Muehlviertel, the suggested range is met in two years with NUE values of around 60% In the alpine clusters, the values are outside the suggested area which is mainly caused by the lower N outputs. Another reason is the exemplary NUE target value of 50%, which applies for cropping systems but not for permanent grassland. Since the alpine clusters are dominated by grassland, this target value is probably less suitable for these clusters.

Fig. 6a also indicates the influence of weather conditions on NUE. Particularly in the two alpine clusters, Voralpen and Alpenostrand, nearly constant N inputs result in substantially different N outputs for the period 2012 to 2017. This points to a dependency of NUE on climate conditions in these clusters. Apart from that, all regional and national clusters, except Nordoestliches Flach-und Huegelland and Wald-und Muehlviertel, show the lowest NUE across the years with reduced N outputs but unchanged N inputs in the year 2013. This year was one of the hottest and driest years in Austria, especially during the summer months with a 20% lower precipitation amount than on average (ZAMG, 2022). It probably lowered the harvested N and thus the N uptake by crops. The influence of large-scale climatic conditions on NUE is also stated by Oenema et al. (2015).

4.2.2. Mixed plant-livestock production systems

Fig. 6b indicates NUE for a mixed plant-livestock system with lower target values of NUE in comparison to the plant production system, namely between 30 and 60%. The reasons are stated in chapter 3.2. The presented results only cover the years 2012–2015 (see chapter 3.2.2). The mean NUE across the years is 39% on the national level. In the non-alpine clusters NUE reaches values of 27–47% except for Nordoestliches Flach-und Huegelland, which shows a mean value across the years of 63%. In contrast, NUE values in the alpine clusters are significantly lower, especially in Hochalpen and Voralpen with values between 12 and 20% respectively.

A comparison of NUE among the clusters shows a similar picture as for the plant production system. The lowest NUE appears in the high-alpine cluster Hochalpen, but also in the alpine cluster Voralpen through all years, and the highest yearly NUE in the cluster Nordoestliches Flach-und Huegelland with values above the upper suggested target value for crop-livestock systems in the years 2013 and 2015. The two alpine clusters Hochalpen and Voralpen both show the highest share of cattle among total LSU (Tab. A3, Appendix), and the highest share of grassland in agricultural area with considerable proportions of alpine pastures (Table 1) pointing at a high relative competitiveness of cattle production compared to alternative farming systems. However, livestock farming is very vulnerable to N losses, particularly during the storage and application of manure. With an average of about 10%, the N recovery in cattle farming is the lowest among all types of livestock (Sutton et al., 2011). The manure management and N recovery of cattle further lower NUE compared to the already low NUE when considering only the plant production system. The typically low achievable NUE of systems dominated by cattle production implies low potential for improvement (Klein et al., 2017; Hutchings et al., 2020). The opposite applies in Nordoestliches Flach-und Huegelland, which shows already high NUE values for the plant production system and also the lowest influence of livestock on NUE for mixed plant-livestock production systems among the clusters. The latter is due to the significantly lower LSU density. The LSU further primarily consists of pig farming (Tab. A3, Appendix), which reveals the second highest NUE among all livestock types (Leip et al., 2011a; Godinot et al., 2015; Groenestein et al., 2018). Obviously, NUE is limited by the potentially achievable NUE of the respective type of livestock and is influenced by the LSU density and thus the extent of the impact of the livestock production on NUE of mixed plant-livestock systems. To conclude, the results rather show the impact of livestock production on NUE than the goodness of the performance of a region within its predefined boundaries set by the type and share of livestock production.

The maximum suggested N surplus of 120 kg ha^{-1} for crop-livestock systems is once slightly exceeded in Alpenvorland in the year 2013. This is probably a result of the high LSU density and thus high manure application combined with high N losses from agricultural soils due to less suitable weather conditions in 2013 leading to lower N uptakes by crops. The suggested range of NUE is reached in all non-alpine clusters and also in the alpine cluster Alpenostrand, except for the year 2013. The reason for compliance probably is the already higher NUE for plant production systems, which also applies for Alpenostrand with a mean NUE of 50%. Additionally, the higher percentage of pig farming in livestock types in Alpenostrand compared to cattle production in Hochalpen and Voralpen could also result in a higher NUE.

5. Discussion

This chapter compares the results of the MFA with literature values. Furthermore, the uncertainty of the N flows of the MFA and its relevance to the results, as well as the most important insights of the study are discussed.

5.1. Comparison with literature values

The total area-specific N flows into agricultural soils of all non-alpine clusters coincide with the mean European input in 2010 of 145 kg N ha^{-1} (De Vries et al., 2021). In regard to the single N flows, higher N inputs via both fertilizer types, but less via atmospheric N deposition, and less via N biological fixation are found in the study by De Vries et al. (2021) for all EU countries. The European studies by Häußermann et al. (2021) and Worrall et al. (2016) agree with the findings presented here (Fig. 3b) that the main N output from agricultural soils is attributed to crop harvest (mostly as fodder crops) and N leaching into groundwater. All gaseous N output pathways from agricultural soils are higher in this study compared to the European studies by De Vries et al. (2021) and Sutton et al. (2011). The study by Kasper et al. (2019) reveals a range of N_2O emissions from agricultural soils for the two Austrian regions Marchfeld and Grieskirchen (0.1–0.8 kg N_2O–N ha^{-1}) similar to this study. The leaching values of Kasper et al. (2019) of 25–63 kg N ha^{-1} for the years 2006–2011 also agree with the ones presented here. The agricultural surplus values, defined as the sum of N losses into atmosphere and water presented in Fig. 3b (all pathways except “marketable crops” and “fodder crops”), are also in good agreement with the findings from other studies. De Vries et al. (2021) at the European level and Leip et al. (2011a) for Austria found similar values compared to the ones of the national and regional clusters. The Austrian Federal Environmental Agency (2019) reported a national N surplus value of 40 kg N ha^{-1} for agricultural land from the years 2013–2017 which agrees with the surplus of the national cluster of 48 kg N ha^{-1}.

Regarding the N emissions entering surface waters, 77% of the emissions stem from diffuse pathways at the national level. Sutton et al. (2011) found a similar share of diffuse and point emissions based on modelling results for the Danube basin. The total atmospheric inputs of N_2O and NH_3 also show good agreement with the study from Sutton et al. (2011), while the N_2 amounts are lower, but still comparable. The amount of N_2 released from WWTP coincides with the Austrian study by Amann et al. (2021). The prevalent forms of N released into the atmosphere which are N_2, followed by NH_3 via manure storage loss and via volatilization during field application in the national and all regional clusters also agree with the modelling results of Sutton et al. (2011) for Austria in 2000. The largest source of N_2, N_2O, and NO release is groundwater, particularly groundwater situated under agricultural soils in combination with the agricultural soils themselves. These results are in agreement with the findings of Leip et al. (2011a), who also identified the agricultural sector as the main source of N_2O (contribution of 73%), and of reactive nitrogen in general.

A comparison of NUE of plant production systems with literature values reveals a higher value for the national cluster of 55% compared to the global mean of 42% and the European mean of 52% in 2010. The non-alpine clusters with NUE values between 44 and 64%, except for Nordoestliches Flach-und Huegelland with values of up to 87% are in good agreement with a study of Quemada et al. (2020) for arable farms in Europe. Quemada et al. (2020) estimated a NUE of 45–75% for half of 195 exemplary arable farms in Europe and a maximum NUE of up to 80%. Another study by Oenema et al. (2015) shows similar values with a minimum of 48% NUE for cropping systems in the EU-28 countries from 2004 to 2011. The mean NUE of mixed plant-livestock production systems on the national level of 39% coincides with the mean NUE estimated for 182 mixed dairy farms in 5 European countries from 2006 to 2016 (Quemada et al., 2020). Furthermore, it is in line with the NUE values of 20–50% with a mean of 38% for 16 grassland-based dairy farms during 2010–2013 in the Netherlands (Oenema et al., 2015). This compliance could be explained by the influence of the two alpine clusters Hochalpen and Voralpen which are characterized by a high share of cattle farming (Tab. A3, Appendix) and together account for 52% of the national agricultural area.

5.2. Data uncertainty

The uncertainty of 75% of all calculated N flows of the regional clusters lies under 23%. The value of 75% correspond to the 75th percentile of the distribution of all uncertainty values. Only the N flows pertaining to the domestic waste, N_2O from groundwater, N_2O and NO from non-agricultural soils, as well as NO and N_2 from surface waters reveal uncertainties above 40% representing outliers of the total uncertainty distribution (Fig. A4, Appendix). The highest uncertainty and thus the lowest reliability is calculated for gaseous N_2 release from surface waters at both national and regional levels. This flow is estimated as the difference between the total gaseous release and the released amount of NO and N_2O from surface waters. Generally, values derived as differences between estimated values such as N_2 release from surface waters or domestic waste, and most of the flows representing the gaseous releases of N_2, N_2O, and NO into the atmosphere show the highest uncertainty. This is primarily linked to the difficult estimation of these flows at the regional and national levels. The most reliable results are the values derived from statistical data on nitrogen flows, such as food, animal products, and sewage sludge. Further reliable results are the ones derived from the MONERIS model applied to Austria (e.g. industrial discharge, treated wastewater) and the EMEP simulations (atmospheric deposition).

The relevance of the uncertainty of single N flows in respect to the entire N balance depends on the amount of the respective flow but also on the focus of consideration. The uncertainty of large N flows regarding the total N input of the balance has a potentially large influence on the N balance. The following analysis refers to the regional cluster Alpenvorland which reveals the highest N flows and N surplus among the clusters. Large N flows of the cluster with a proportion of more than 10% in the total N input of the balance are riverine output, N_2 from groundwater, atmospheric deposition on agricultural soils, leaching from agricultural soils, animal products, marketable crops, fodder crops, mineral fertilizer, manure and industrial feed (Fig. A5, Appendix). These N flows reveal low uncertainties between 6 and 15%. Thus, no substantial influence is expected on the entire N balance. Higher uncertainties only appear for N flows with smaller proportions in the total N input. These are the gaseous releases of N into the atmosphere and the domestic waste whose values should be interpreted with caution. The highest uncertainty of 122% of the N flow N_2 from surface waters stems from its estimation and thus does not have an influence on the other N flows of the balance. The uncertainty values of the other flows with higher uncertainties are comparable lower ranging between 23 and 50%, except for N_2O from non-agricultural soils with an uncertainty of 67%. Since the focus of this study is not on the gaseous N emission into the atmosphere, these uncertainty values should not affect the results of the entire N balance substantially.

6. Conclusions

The analysis of the MFA results shows the importance of comparing agricultural production systems at a regional level using the two methods of NUE and surplus. Austria as a mountainous country, shows large spatial differences in agricultural practices and in N balances which are closely connected to the given environmental conditions. Particularly regions dominated by mountains and therefore restricted in the choice of agricultural practices have very different N balances than the more diverse cropping systems found in the non-alpine, low-land regions. The formulated hypotheses of low N inputs causing the low area-specific N surplus, and of low area-specific output and thus a more inefficient use of N, bear out for the high-alpine cluster. This cluster is predominantly characterized by alpine pastures with cattle production at low livestock densities. Vast areas of alpine meadows are grazed without any additional fertilization. In this region food production per unit of nitrogen is limited and other functions of agricultural activity, such as landscape conservation, biodiversity maintenance or carbon sequestration in grassland soils, may grow in importance. For the non-alpine, low-land clusters two different situations appear. The region specialized in arable crop production with a low livestock density, reveals almost as low N surplus values as the high-alpine region but at much higher area-specific nitrogen in- and outputs with the consequently highest NUE in Austria. Despite the high NUE and low N surplus, the region is affected by a widespread exceedance of the threshold of nitrate concentration in groundwater due to low groundwater recharge rate, caused by low precipitation levels. The other non-alpine cluster characterized by a high livestock density, has similarly high area-specific nitrogen outputs as the first non-alpine cluster, but distinctly higher N inputs resulting in the highest N surplus among all Austrian regions. The high surplus leads to several groundwater monitoring stations exceeding the nitrate concentration threshold even though NUE values reach the suggested values of more than 50% or 30% for cropping or crop-livestock systems, respectively.

Overall, the presented differences of the regional clusters reveal the following: firstly, a sufficient NUE of an agricultural system can still lead to failures in achieving water quality targets such as nitrate concentrations of groundwater. If NUE is already high, further possible improvements are limited. This is particularly relevant for agricultural funding programs focusing on enhancing groundwater quality by acting on agricultural N management. Secondly, the maximum achievable NUE is constrained and largely determined by large-scale natural boundary conditions which cannot be modified easily. Consequently, the agricultural N management in less favorable environmental conditions, such as in high mountainous regions, cannot be assessed with the same criteria as in regions better suited for agricultural production. It requires adapted targets, such as relative nitrogen efficiencies which take into account yield gaps defined as the difference between potentially achievable NUE and actual NUE within specific framework conditions (Godinot et al., 2015; Rattalino Edreira et al., 2021). The dependency of NUE on geographic and climatic conditions is also evident concerning large-scale weather patterns affecting NUE across regional borders.

The findings of this study demonstrate the importance of regional N balances to identify and understand the causes and consequences of different characteristics and the relationships between N balances, NUE, and environmental effects. The different regional circumstances constrain the scope and efficiency of N management strategies and this aspect should be considered in the assessment of regional N managements as well as in the design of N management policies, such as planned by the Farm to Fork Strategy as part of European Commission's European Green Deal. Given the demonstrated importance and clear added value of regional balances, it would be important to improve the availability and harmonization of data at the regional level to reduce the uncertainty of the estimations presented here and to transform such balances into robust tools for policy and management support.

CRediT authorship contribution statement

Eva Strenge: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Ottavia Zoboli:** Conceptualization, Data curation, Methodology, Supervision, Writing – review & editing. **Bano Mehdi-Schulz:** Conceptualization, Funding acquisition, Project administration, Writing – review & editing. **Juraj Parajka:** Data curation, Writing – review & editing. **Martin Schönhart:** Validation, Writing – review & editing. **Jörg Krampe:** Resources, Project administration. **Matthias Zessner:** Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Validation, Writing – review & editing.

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

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2023.119023.

Appendix

Tab. A1

Natural characteristics of the clusters. Precipitation values from SPARTACUS for the years 2012–2017 (Hiebl and Frei, 2018), air temperature for the years 1990–2005 (Merz et al., 2011). Natural landscape classification and their grouping in this study.

	Natural landscape	group	elevation m a.s.l	precipitation mm yr^{-1}	air temperature °C
Alpenostrand	Central Alps and basin	alpine	908	1053	7.2
Alpenvorland	Alpine foothills	non-alpine	459	1025	9.0
Hochalpen	Central Alps	high-alpine	1589	1405	4.0
Nordoestliches Flach- und Huegelland	Plains and hills	non-alpine	258	580	10.0
Suedoestliches Flach- und Huegelland	Alpine foothills	non-alpine	360	874	9.8
Voralpen	Alps	alpine	826	1479	7.3
Wald- und Muehlviertel	Highlands	non-alpine	616	757	7.7
Austria			948	1145	6.8

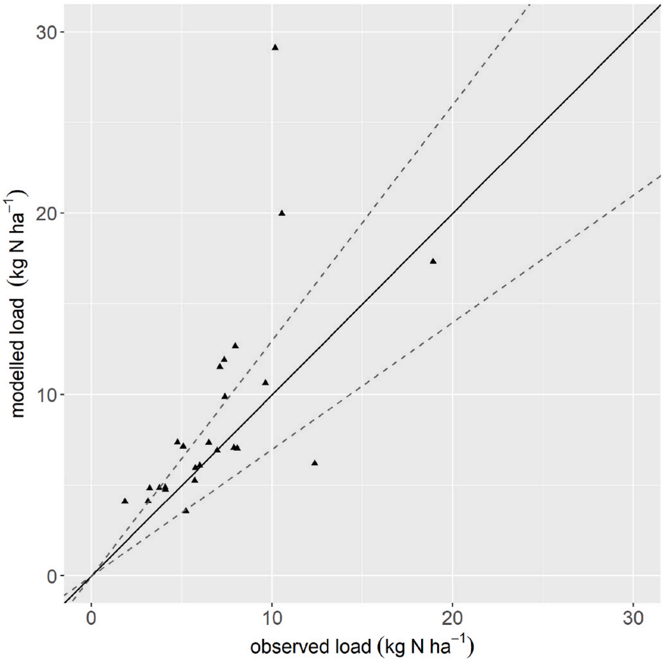

Fig. A1. Validation of the model MONERIS in terms of modelled to observed DIN-N river loads.

Tab. A2

MONERIS calculations of the concentration of dissolved N in the leachate, amount of denitrification of N in groundwater, amount of leached N from agricultural and non-agricultural soils as a yearly mean of 2012–2017 at cluster area.

	leachate concentration	denitrification in soil and groundwater	leaching from agri soils	leaching from non-agri soils
	mg N l^{-1}	kg N ha^{-1} cluster area	kg N ha^{-1} cluster area	kg N ha^{-1} cluster area
Alpenostrand	7.4	15.7	14.2	6.3
Alpenvorland	13.4	17.2	24.1	4.2
Hochalpen	1.6	9.6	10.0	4.4
Nordoestliches Flach- und Huegelland	32.8	19.8	17.9	3.4
Suedoestliches Flach- und Huegelland	12.8	16.4	15.5	5.7
Voralpen	4.7	7.8	9.6	8.4
Wald- und Muehlviertel	15.9	26.8	25.9	6.1

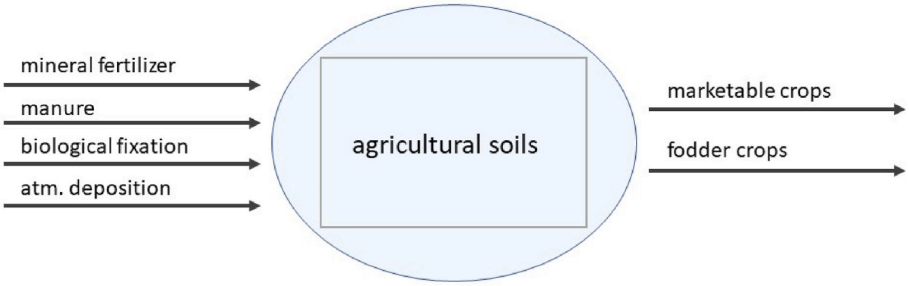

Fig. A2. Concept of a plant production system used for the NUE.

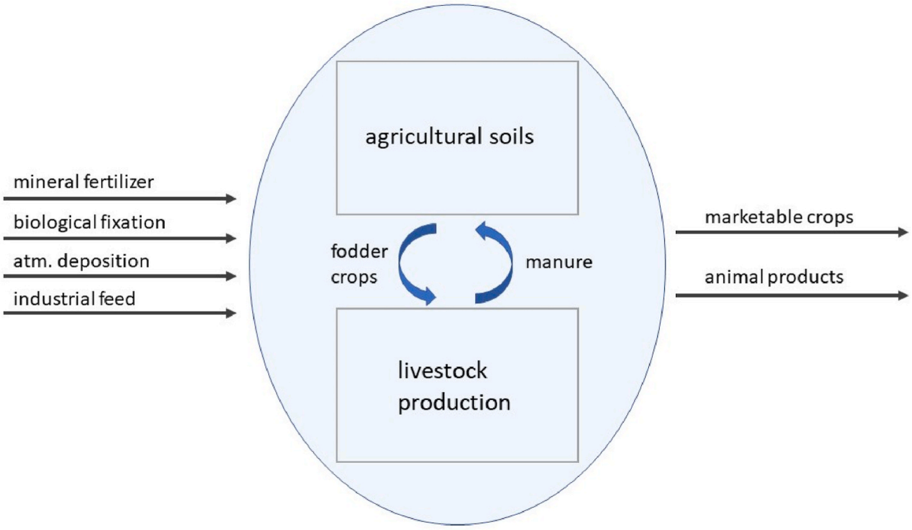

Fig. A3. Concept of a mixed plant-livestock production system used for the NUE. The flows "fodder crops" and "manure" are internalized.

Tab. A3
Share of livestock types in LSU of each of the clusters (derived from Loishandl-Weisz et al., 2020).

	cattle[c]	pig	poultry	sheep	horse	Others
	%	%	%	%	%	%
Alpenostrand	85	8	2	3	2	1
Alpenvorland	67	27	2	1	2	1
Hochalpen	89	1	0	6	4	1
Nordoestliches Flach- und Huegelland	35	54	2	2	5	1
Suedoestliches Flach- und Huegelland	44	45	5	3	2	1
Voralpen	87	4	1	4	3	1
Wald- und Muehlviertel	87	7	1	2	2	1

[c] Cattle includes beef and dairy cattle.

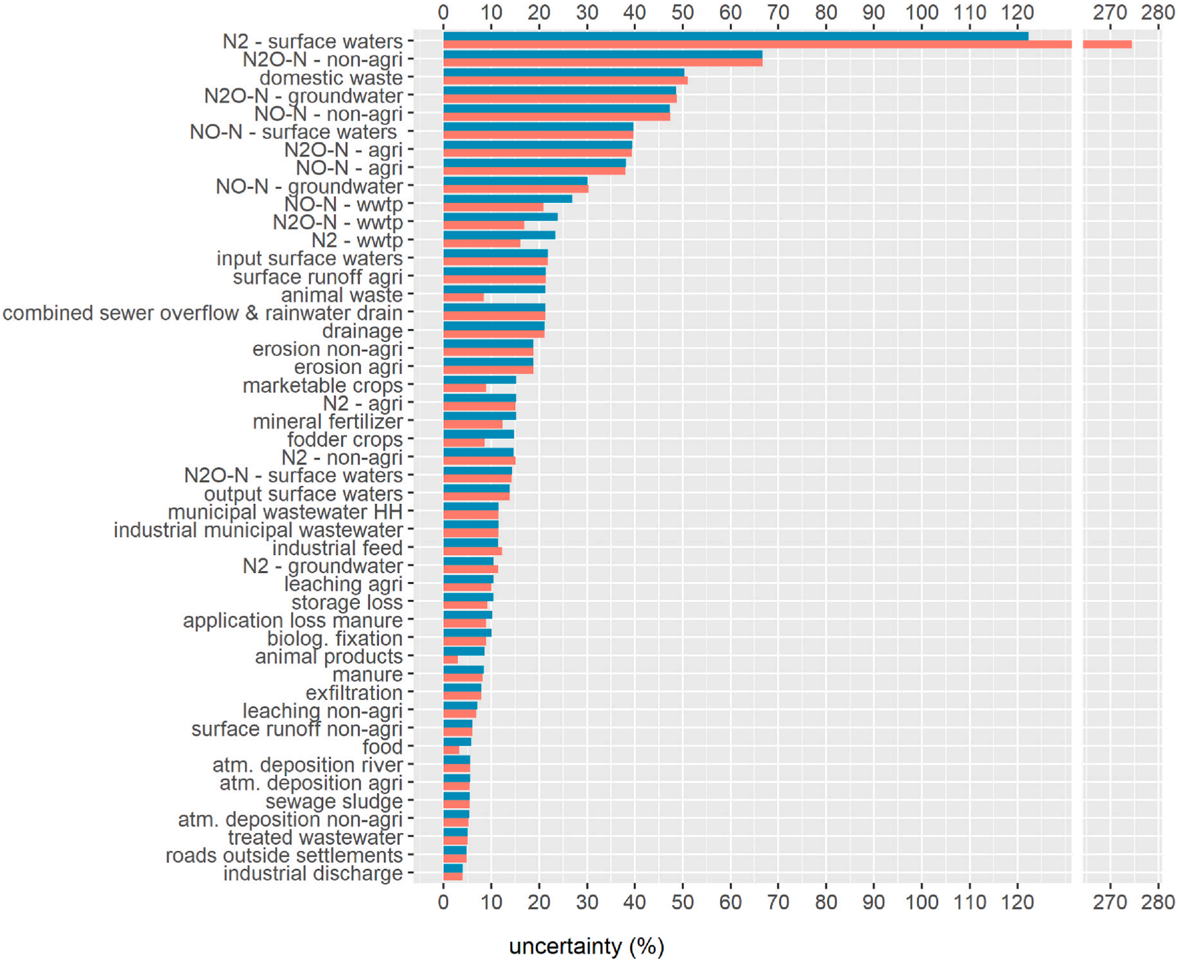

Fig. A4. Final estimation of the data uncertainty of the flows of the MFA at national and cluster level. The red bars represent the national cluster, the blue bars represent the regional clusters. X-axis break according to Xu et al. (2021).

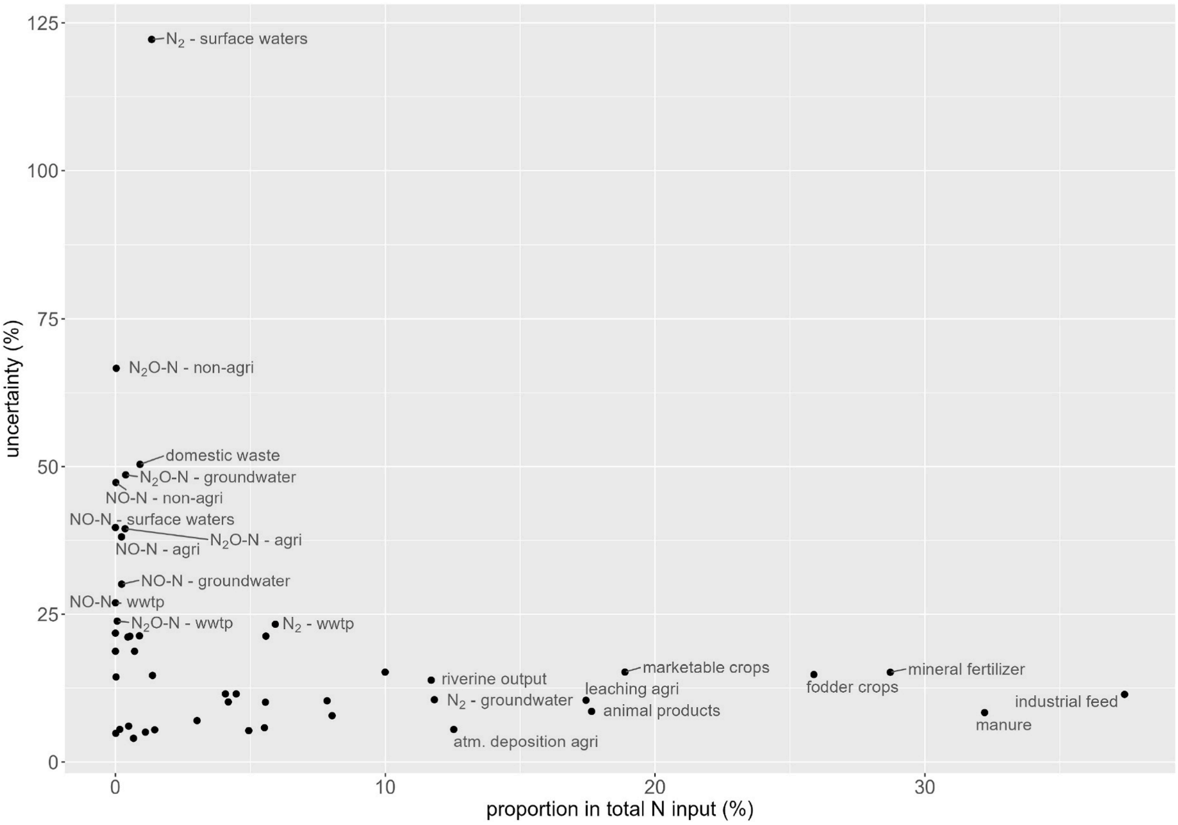

Fig. A5. Comparison of the uncertainty of the MFA N flows to the proportion of N in the total N input of the MFA, exemplary for the regional cluster Alpenvorland. The names of the N flows are only displayed for N flows with a proportion in total N input ≥10% or with an uncertainty >23% (referring to the 75th percentile of all uncertainties).

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