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Can nitrogen balances support the sustainability assessment?

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Introduction

A nutrient balance depicts nutrient flows going in and out of a defined system during a defined time (Oenema et. al., 2003). The nutrient balance approach is often used as a tool for tracking changes of nutrient surpluses over time and as an agro-environmental indicator at national, regional and farm level (OECD, 2019; Häussermann et. al., 2020; Einarsonn et. al., 2020; Quemada et. al., 2020), where the surplus calculation ($N_{surplus} = N_{input} - N_{output}$) represents an estimated amount of nutrients that could potentially be lost to the environment and therefore entangles information on how sustainable the farm management practises are.

The nutrient balance approach can also be used to support the transition to a more sustainable food production. Hill introduced a possible sustainable transition pathway (1985) and distinguished between two types of sustainability: the "shallow" sustainability, which includes the so called *efficiency* and *substitution* stages and the "deep" sustainability, which contains an additional stage called *redesign* (Hill, 1985 & 1998). For example, if a farm substitutes certain inputs with others to become more efficient, the farm is considered to have gone through a "shallow" sustainable transition. A *redesign* of the farm is essential for a deep sustainable transition, because the subsequent switch from curative to preventive solutions leads to long-lasting sustainable and resilient food production (Hill, 1998).

Intensive agriculture combined with other human activities affect the nutrient cycles on earth, in particular for nitrogen and phosphorus (Sutton et. al., 2013). Nitrogen (N) is an essential plant nutrient and therefore crucial for food production (Novoa and Loomis, 1981). In 2015, 184 million tonnes of N fertiliser were applied globally and approximately 46 kilotons of mineral N fertiliser in Switzerland (FAO, 2019; Heldstab et al., 2013). The large amount of N inputs ensure high crop production but also influence the global N cycle because large amounts of the N inputs are lost to the environment (Fowler et. al., 2013).

This synthesis report, explores the strengths and weaknesses of the nitrogen balance approach and data availability for Switzerland. In the second part, the nutrient balance of two contrasting farm systems are sketched and suggestions for a transition towards sustainable production are illustrated. In order to discuss N cycle and evaluate N balance as an indicator for sustainability, the system boundary was set at the farm-gate, allowing to define the relevant inputs, outputs, surpluses as well as the internal cycles.

Results

At the Swiss level, N balances have been calculated on a yearly basis according to the guidelines of the OSPAR (Convention for the Protection of the Marine Environment of the North-East Atlantic) or the OECD (Organisation for Economic Co-operation and Development) since 1975 and 1990, respectively and therefore possess a certain consistency in data acquisition and access (Spiess, 2011; OECD, 2020). At the farm level, data access for N flows becomes much more difficult and complex, especially when completeness of flows is aimed (Fig. 1). Indeed, quantifying N flows at the farm level remains challenging, as some flow dynamics change over time, depending on climate variability, such as soil moisture, temperature or changes in agricultural management (Cameron and Moir, 2013).

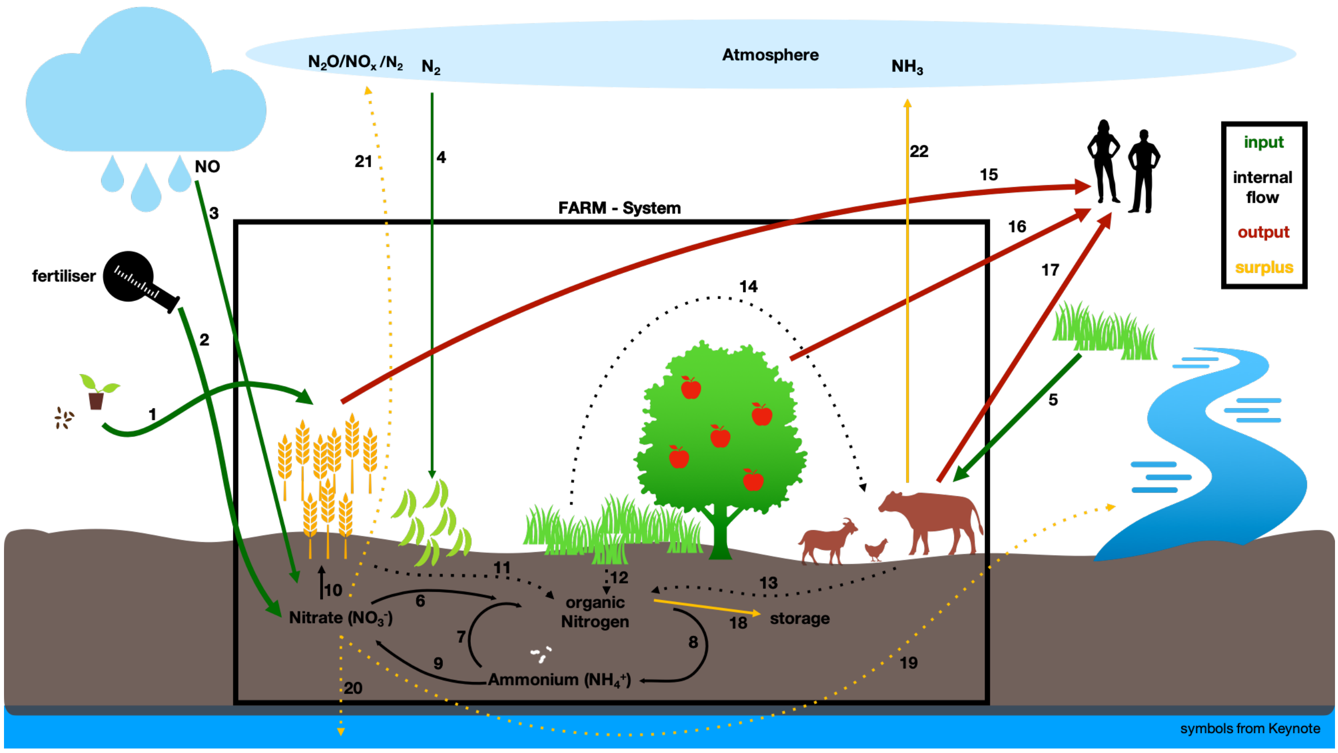

Figure 1. The farm gate nitrogen balance flow size. The flows are indicated according to how well they can be quantified (well quantifiable shown as thick arrows, approximately quantifiable in thinner arrows and estimations as dotted arrows). The shown flows are: (1) seeds and seedlings, (2) fertiliser, (3) deposition, (4) biological nitrogen fixation, (5) feed import, (6/7) immobilisation, (8) mineralisation, (9) nitrification, (10) nitrate consumption, (11) residuals, (12) litter, (13) manure, (14) internal feed, (15) crop and vegetables harvest, (16) products from perennials, (17) animal products, (18) storage of nitrogen in the soil, (19) run-off, (20) leaching, (21) denitrification, and (22) volatilisation.

Farmers usually have measured N content values for single livestock or cereal products (e.g. milk or wheat) and can estimate the N content of other exported products based on the quantities that are exported (Tab. 1). Imported products, such as seeds and mineral fertilisers usually also have a relatively transparent information on N content, but otherwise, most N flows are based on functions (with several variables) or estimations based on standardised values. This results in different quantification strengths for different flows (Tab. 1)

The differences in flow quantification possibilities and size influence the robustness of the single flows and subsequently the balance result. Nevertheless, when the results are interpreted over time, trends can be identified and approximate comparisons between farm types can be made. The N surpluses indicate a possible deviation of a system from sustainability, but for an appropriate transition towards sustainability, detailed flow quantifications are essential (Hill, 1998).

The nitrogen balance of two farms and their transition towards a more sustainable production

Two farms differing in size of N pools and flows are compared (Fig. 2). The arable farm is specialised on annual crop production and thus N pools are the soil and the crop itself within the farm-gate boundary (Fig. 2a). Fertiliser (mostly imported in mineral form) display the main input.

Tab. 1. Nitrogen flows levels and quantification strength characterisation.

	# of flow in Fig. 1	Flow name	Assessment level	Quantification	Recording
Input	1	Seeds and seedlings	Farm	Strong	Purchase information, farm-gate
	2	Fertiliser	National (field)	Strong	Purchase information, farm-gate
	3	Deposition	Regional	Strong	Measurement, interpolation
	4	Biological nitrogen fixation (BNF)	National (field)	Medium	equation
	5	External feed	Farm	Strong	Purchase information, farm-gate
Internal	6/7	Immobilisation	Field	Medium	Equation
	8	Mineralisation	Field	Medium	Equation
	9	Nitrification	Field	Medium	Equation
	10	Nitrate uptake	Field	Medium	Equation
	11	Residuals	Field	Weak	Estimation
	12	Litter	Field	Weak	Estimation
	13	Manure	Field	Weak	Estimation
	14	Internal feed	Farm	Weak	Estimation
Output	15	Crops and vegetables	National (Farm)	Strong	Sales information (national or farm-gate)
	16	Products from perennials	National (Farm)	Strong	Sales information (national or farm-gate)
	17	Livestock products	National (Farm)	Strong	Sales information (national or farm-gate)
Surplus	18	Storage in soil	Field	Medium	Equation
	19	Run-off	National	Weak	$N_{surplus} = N_{input} - N_{output}$
	20	Leaching	National	Weak	$N_{surplus} = N_{input} - N_{output}$
	21	Denitrification	National	Weak	$N_{surplus} = N_{input} - N_{output}$
	22	Volatilisation	Field	Medium	Equation

The N which cannot be taken up by the plant is probably lost to the environment (leaching into the groundwater, run-off into lakes and rivers and denitrification into the atmosphere). Such surpluses are expected to be rather high because monocropping systems are less efficient in taking up nutrients than perennial and pastoral systems, which are usually a combination of several plant species and root systems (Chen et al., 2017). Internal flows (especially the soil turnover) are assumed to be low due to the limited quantity of organic material left by the crop in the field. The crop yield usually is the largest output.

The second farm includes annual as well as perennial crops like pasture, trees and livestock (Fig. 2b), and is therefore considered a mixed farming system. The pool sizes within the farm-gate boundary are larger compared to the arable farm. Besides the addition of mineral fertilisers, there are additional input flows including BNF through legumes (i.e. as crop or in the pasture or in the crop rotation scheme) and animal feed import. Compared to the arable farm, surpluses are expected to be lower because N is added in multiple forms and taken up more efficiently from the diverse plant species. Nevertheless, N can additionally be lost to the environment via volatilisation from livestock. Since N is added in multiple forms, internal flows in the soil are assumed to be greater compared to the arable farm. Additionally, the pasture could serve as feed for the animals leading to a lower import. The output includes, annual crop, feed, fruits, timber and livestock products.

When evaluating the two farms with respect to sustainability one can conclude that the mixed farm is more sustainable and more resilient than the arable farm (Fig. 2). N flows are more diverse, multiple N pools are present and potential N losses are lower.

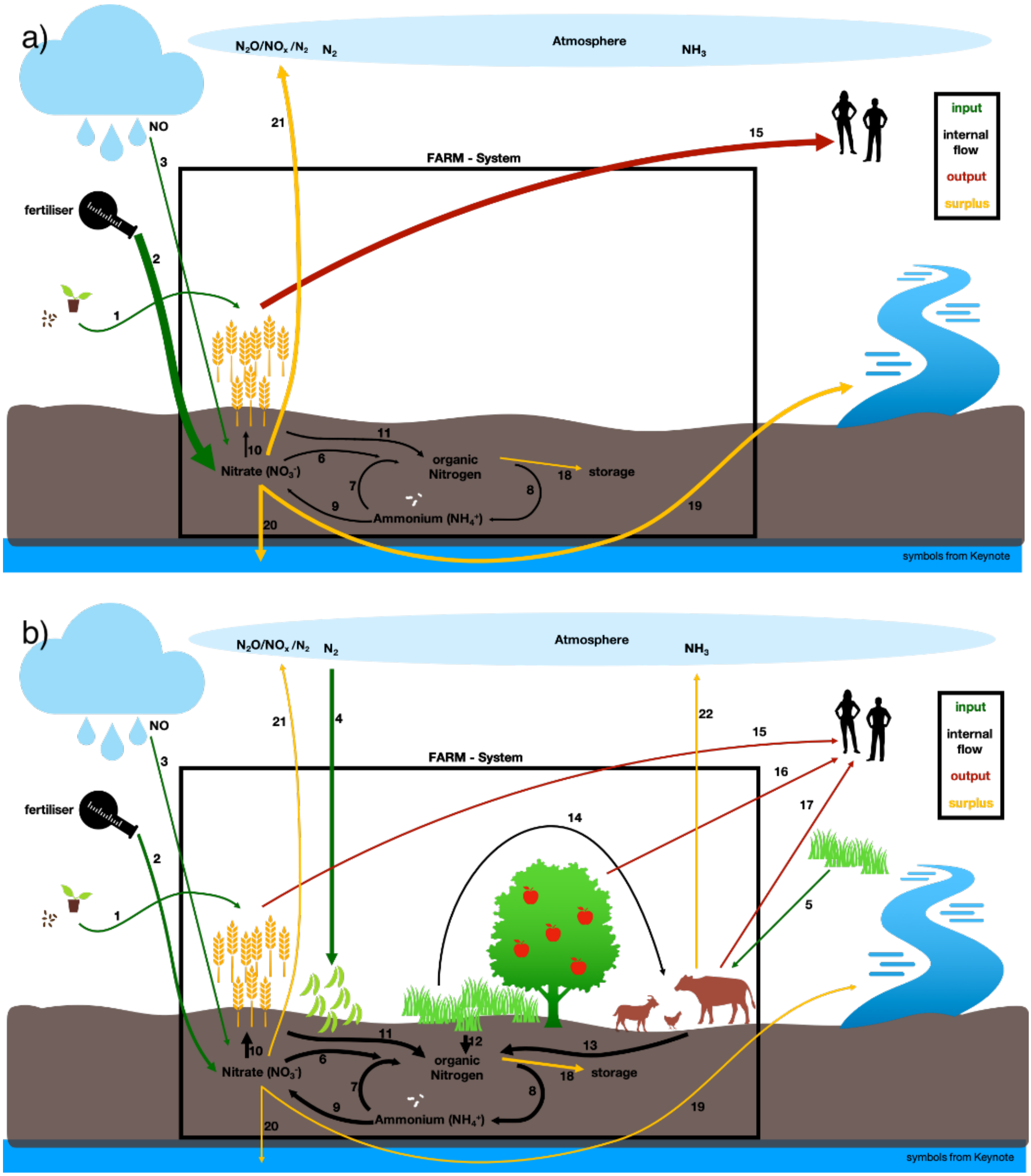

Figure 2. The nitrogen balance of (a) an arable farm and (b) a mixed farm. The importance/magnitude of the different flows are visualised with the arrow thickness. The names of the flows indicated with numbers refer to Figure 1.

According to Hill's sustainability concept, the arable farm would need to go through both the "shallow" and the "deep" sustainability stages.

In a first stage, the arable farm's *efficiency* could be increased with the reduction of mineral fertiliser inputs. However, if the main input flow is reduced, the risk of yield losses might increase. Alternatively, the farmer could *substitute* fertiliser inputs with other N input sources, such as BNF. Most farmers in Switzerland follow a defined crop rotation. This already helps reducing the N surplus and increasing the on-farm biodiversity. The final and important stage towards more sustainability would include the redesign process of the whole farm in order to minimise N surpluses and balance out N inputs and outputs. With respect to the concept towards sustainability from Hill (19985), the mixed farm could be seen as the result of a thorough arable farm *redesign*, in respect to the N balance. Nevertheless, N surpluses might be unavoidable also in mixed farms, as the N pools might be saturated. This is particularly challenging in regions with high livestock production or of imbalanced distributions within a farm and shows that sustainable production remains very dynamic and has to be continuously developed (Sun et.al., 2019; Recous et.al., 2019).

In contrast to the here suggested diversification of a farm, actual farms in Switzerland and developed countries in general become more and more specialised (Zorn, 2020). To still reach sustainability, the concept could be up-scaled to a regional level. Thus, different specialised farms in a distinct region could built together a diversified landscape with enhanced sustainability.

Conclusions

Nitrogen balances uncover the potential negative environmental impact of a certain management at a defined scale. In order to build such a balance, the borders of the system need to be defined. Whereas the promotion of sustainable intensification should be implemented at the regional level, it should be encouraged and sustained at the national level. This way, it could be possible to ideally combine bottom-up and top-down approaches, both with the aim of sustainable intensification (inspired by Pretty, 1997).

Through national balances, states can monitor the development over time, but because of the uncertainty of some N flows at the farm level, pin pointing at the exact source causing the surplus remains challenging. Legislations can steer the amount of external N inputs into a system, whereas it is more challenging to induce a deep sustainable transition, as transforming agricultural production remains a process of learning, trial and error and can therefore not be fully imposed (Pretty, 2018).

Nevertheless, the nutrient balance approach helps reveal and quantify flows of a given system, and it is important that monitoring and comparison occur on different scales.

Efficiency and s*ubstitution* are not "strong" enough to actually solve the problem of N surplus and its harm to the environment. Therefore, the transition towards a more sustainable crop production requires some rethinking and should include a thorough *redesign* of the current farming systems. Improvement can be achieved on the farm but also on a regional level, where interactions between farms can be pursued. Ideally, each sub-region and region in Switzerland could coordinate the production together towards more sustainability, and finally increase the over-all biodiversity and robustness of Swiss agriculture.

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