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Research article

Real-farming emissions of reactive nitrogen – Necessities and challenges

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ABSTRACT

Reactive nitrogen (Nr) is both a principal factor regulating growth in biological systems and a significant pollutant for the environment. The objective of this paper is to reflect on the challenges of the nutrient management related to and priorities needed to clarify how Nr is employed appropriately whilst striving to mitigate emissions at the same time.

To create orientation, valid data are needed reflecting the real-farming emissions (RFE) from individual farms to assess what is needed to balance partly contradicting goals, and to bridge the gap between current and envisaged levels. Furthermore, knowledge is required of which tools and measures are at the farmer's disposal to mitigate Nr emissions. Finally and of utmost importance, the farm management is in need of action knowledge, i.e. knowing how to select the most appropriate and cost-effective tools and measures for the specific conditions on each farm, while taking the possible impacts of their implementation on the balance between Nr-related productivity and threats into account. Dealing with such a complex issue requires a systemic approach, considering the farm system not only as a one-compartment model (1st scale) with quantifiable Nr inputs and outputs at the farm gate but as divisible into sub-systems (2nd scale). The Nr-flow through the sub-systems: feed, livestock, manure and utilised land area, represents an inner-farm Nr-cycle. Each sub-system can be further subdivided into sub-sub-systems (3rd scale) such as feeding groups within livestock, which could be differentiated in individual animals (4th scale). This approach enables to determine where (and to what extent) nutrients may be allocated more effectively and more cost-efficiently. The allocation of Nr resources between sub-units within the respective sub-systems determines the efficiency in the use of Nr and thus the proportion of Nr contributing either to an increase in productivity or to Nr-related environmental pollution. Quantifying the N-flows through sub-systems of a farm on the 2nd scale is the starting point for benchmarking; providing orientation for the regulation of processes both inside and outside the farm system. It creates target figures for the farm management while identifying the gap between the current ranking level of the farm and its potential rank. Improving the recycling of Nr throughout the whole farm system and increasing the efficiency in the use of Nr on the 3rd and 4th scale are seen as major opportunities for the farm management to balance the trade-offs without comprising productivity.

It is concluded that the lack of benchmark RFE values in relation to the amount of food and feed produced can be seen as one of the main barriers in the fight to mitigate environmental Nr emissions from agricultural processes. If benchmarking has not been established, the farm management lacks orientation regarding the target figures it should aim at. Without target figures it is not possible to formulate concise working hypotheses regarding the most effective and cost-efficient use of means that are to the farmer's disposal as well as strategies for an improved allocation of resources in a farm specific context.

1. Introduction

Reactive nitrogen (Nr) is of utmost importance for the production of human food, being one of the primary limiting factors in the growth of plants and animals. At the same time, Nr emissions contribute to climate change and is responsible for a considerable level of soil-, surface- and ground water-, and air-pollution. No other chemical compound exhibits this ambivalence to such a degree. Optimizing the availability for Nr as a key human resource while minimizing its negative consequences and developing strategies to decrease N-containing waste is thus of essential importance (Galloway et al., 2008). The century since the Haber-Bosch invention in 1908, has seen the rapid growth in the use of industrial fertilizers in agriculture and of energy in industry and transportation resulting in a 3-fold increase of total Nr production in the EU27 (van Grinsveen et al., 2013). According to Rockström et al. (2009), human processes convert around 120 million tonnes of N_2 from

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the atmosphere per year into reactive forms; more than the combined effects from all Earth's terrestrial processes. The authors have formed the hypothesis that at the planetary scale the safe boundary for anthropogenic nitrogen emissions has already been exceeded by a factor of approximately 3.5 and significantly perturb the global cycles of Nr. Circulation of anthropogenic Nr in Earth's atmosphere, hydrosphere, and biosphere has a wide variety of consequences; magnified with time as Nr moves along its biogeochemical pathway. The same atom of Nr can have multiple effects on the atmosphere, terrestrial ecosystems, freshwater and marine systems, and on human health. This sequence of effects is called the nitrogen cascade (Galloway et al., 2003). In succession, Nr molecules can: increase ozone concentrations in the troposphere, increase concentrations of airborne particulates, increase soil and surface water acidity and hypoxia in coastal waters (Erisman et al., 2007; Galloway and Cowling, 2002; Galloway et al., 2008). They also influence air quality due to ammonia emissions and have a considerable impact on the amount of greenhouse gases (GHGs) (Dolman et al., 2014) due to emissions of nitrous oxide, the most potent GHG emitted from agriculture. Modern agriculture is the major cause of environmental Nr pollution (Foley, 2005; Galloway and Cowling, 2002). The only ways to reduce Nr release into the environment are to reduce the import of Nr into the farm system and to increase organic binding of Nr in microbes, plant and livestock products.

Agricultural production in Europe is heavily dependent on external inputs; especially on energy-consuming synthetic fertilisers and protein-rich bought-in feedstuffs for the production of livestock products which already have negative environmental impacts during their production. The introduction of synthetic fertilizers made the Western world's food system what it is today. Kuokkanen et al. (2017) argue that this transformation has become an irreversible self-feeding process referred to as food system lock-in, which threatens planetary boundaries of nitrogen and hence our future food security. A system in a lock-in state can undermine its own existence by reducing the capacity to cope with upcoming crises of resource scarcity and environmental instability. Based on region-specific global models including emissions accounting modules, population growth and dietary trends towards emissions-intensive animal-based foods (in particular in developing countries) are expected to further increase the GHG emissions from agriculture by up to 80% by mid-century (Springmann et al., 2016). The authors estimate that in 2050, food-related GHG emissions could make up half of the total permitted emissions for global warming to remain below 2 °C. Thus, reducing the GHG emissions related to food and specific types of livestock production will need to be a critical component of policies aimed at mitigating climate change (Ripple et al., 2014). Despite the fact that agriculture is responsible for more than a quarter of all GHG emissions, most of which are related to livestock (Tubiello et al., 2014; Vermeulen et al., 2012), it has long been excluded from comprehensive climate policies in many European Countries. This is amongst others due to difficulties in monitoring agricultural emissions (Snyder et al., 2009), the lack of cost-effective technical mitigation options (Smith et al., 2007) and concerns about the potential impacts on production costs and food security (Golub et al., 2013; Havlik et al., 2014). Most of the agricultural emissions are related to the intrinsic characteristics of food production, and are therefore difficult to address without substantial effects on agricultural output. Pricing Nr emissions at source (as is usually envisaged for climate policies in the energy sector) can be expected to incentivize emissions reductions across the nutrient cycle. To prevent that taxing Nr at source evokes relevant negative implications for productivity would require detailed farm-level measurements.

The objective of this paper is to reflect on the challenges related to the ambivalence in the use of Nr while striving for appropriate mitigation measures. The necessity to assess real-farming emissions in an appropriate manner and the ambivalent role agricultural science plays in this matter are addressed. Furthermore, options to balance the partly contradicting goals within a systemic approach by an adequate allocation of resources are shown.

2. The ambivalence of reactive nitrogen

Intensification of agricultural production processes and the enormous increase in output in plant and livestock production per production unit is closely linked to the availability of Nr compounds in the form of fertilizers and/or feedstuffs. In line with technological developments, the availability of Nr has drastically increased the availability of human food on a global scale. At the same time, market prices for food have decreased in relation to general purchase power; at least in the Western World. However, the pay-out prices for animal products have become volatile and often drop below real costs of production for many farmers. Farmers have few options to directly exert influence on the pay-out prices within the current market conditions. This results in even greater competition between farmers where they reduce production costs, primarily by increasing performance and production capacities to achieve economies of scale. By increasing production volume of food over demand, they simultaneously help to increase the pressure on market prices and jeopardize their own livelihood. When considering options to mitigate the negative impacts of Nr, the driving forces concerning the use of Nr in agriculture under the current market conditions is necessarily a matter which has to be taken into account.

It has been demonstrated by various studies, reviewed by Bleken et al. (2005), that the higher the input of Nr into a farm system, the higher the probability that it will increase productivity and the higher the chance that a larger part of the Nr input will be released into the environment. Focussing primarily on minimizing the release of Nr into the environment is costly. It does not only compromise the productivity but requires yet more resources to achieve this goal (van Grinsveen et al., 2017).

If the conflicts which arise with the increased input of Nr into a farm system are considered more precisely, an area can be assumed where Nr is used in a way and to a degree which increases productivity without increasing the level of Nr released in relation to the amount of products sold. Addressing and then expanding this intersection area becomes a new production goal. It encompasses two partly contradictory goals, involving a conflict which if not resolved, creates imbalance. Striving for a balance is a different production goal and much more challenging than just going for an increase of productivity. It cannot be a clearly outlined goal due to uncertainties in assigning effects to the different sub-goals. A clear allocation is even more difficult because of a general lack of precise data. Additionally, the trade-offs between both goals are expected to be highly context dependent, i.e. the external context in which the farm management operates and that of the specific internal farm conditions. Thus, trade-offs vary considerably between farm systems, contradicting any attempts to generalise and predict possible outcomes. Indeed, it means striving for the internalisation of external effects within the boundaries of a farm system while trying to minimise external effects. This approach requires that the boundaries of the systems and sub-systems are clearly defined. When individual private interests and community interests have to be weighed up, measurements have to be carried out, based on the comprehensiveness of at least these two different perspectives, requiring a superordinate (meta-) level, from which the interactions can be surveyed and brought into balance.

Internalisation of external effects can have impact upon economic competitiveness due to costly investments or a lower productivity in comparison to other farms which increase productivity using Nr (fertilizer and/or feedstuffs) from external sources without considering the external impacts. Thus, externalising the impact of N use/emissions can strengthen a farm business's competitive advantage. Those farmers who rightly try to reduce Nr release to a minimum then face unfair competition, at least when viewed from the perspective of common goods. The internalisation of external impacts by reducing Nr emissions is only economically justified if the cost of external Nr inputs is high or when the availability of Nr is limited; such as in organic agriculture where mineral N fertilizer is banned. With this in mind, it makes sense to prevent Nr losses as far as possible while making sure that the Nr retained is recycled within the system most efficiently (Sundrum, 2002).

While the output of farm systems in terms of products sold is essential for the farmer's income and the livelihood of the farm, negative side effects of the production processes can be easily disregarded. This is particularly the case when these are not directly visible and when there is no institution with the power to monitor and strictly regulate the negative side effects. Although, it may be argued that EU legislation has forced the legislative institutions in the Member states to take measures in order to keep water and air pollution below certain thresholds. Concerning EU legislation, policies have focussed strongly on separate areas of interest, in particular targeting and reducing N leaching to the aquatic environment and reduction of Nr gases to the air. This is done primarily via monitoring inputs and manure management, disregarding the important links between the different types and areas of losses. Instead, an integrative approach is called for, where effects of co-benefits or drawbacks of different management options are incorporated (Dalgaard et al., 2017). As the circulation of anthropogenic Nr in Earth's atmosphere, hydrosphere, and biosphere does not respect boundaries, handling the challenge of protecting the common goods of water and air via separate legislative approaches does not seem promising. Addressing ecological assets and single areas of emission separately largely disregards the fact that Nr mitigation measures in one area can lead to problems in other areas, and even increase overall emissions. In contrast to other industrial processes, however, environmental Nr pollution from agriculture is characterized by non-point and highly variable sources of emissions. This makes it difficult to assess and monitor Nr emissions. The concentration of nitrate in the ground water, for example, can seldom be traced back in quantitative terms to Nr released from a specific farm. Consequently, it is hard to make the polluter pay the penalty and be held responsible. The polluter pays principle is ineffectual here and the general perception of this type of law as a blunt sword in the fight for justice is perpetuated.

3. Real-farming emissions

According to the general figures gained by national inventory assessments, Nr emissions from agriculture have not changed substantially in some of the European Countries over the past few decades (UBA, 2016). In contrast, Denmark has been successful in cutting nitrogen losses to marine waters by 50% since 1990 (Kronvang et al., 2017), while nitrogen losses to groundwater have decreased over the same period in the Netherlands (van Grinsven et al., 2016). The reasons for the lack of success in some countries are manifold and not easy to grasp. As outlined above, there is a need for economic incentives to aid farm management in the substantial reduction of Nr emissions which are able to counteract a one-sided focus on productivity. These incentives are not immediately apparent. On the contrary, there is a high incentive for ignoring possible negative impacts. Facing these might not only by very costly but also very challenging, thus questioning the traditional approach and way of thinking; possibly requiring a thorough re-orientation. Correspondingly, there really is an urgent need for valid data on Nr emissions from agriculture which reflect the real-farming emissions (RFE) from each farm. These are not only relevant for gaining an overview of the variation in Nr emissions between agricultural enterprises and to put the polluter pays principle into force. Measures to mitigate Nr emissions would also be considered and even implemented if cost estimates for the adverse effects of Nr emissions could be used to internalize these costs and to charge producers and/or consumers of Nr intensive products.

RFE data would also provide orientational knowledge for the farmers showing where they stand on Nr emissions in relation to other farms. Data from a representative number of farms could be used to create a scale ranging from very high to very low Nr emission rates per farm unit and giving the farm management an idea as to whether the farm belonged to the high, middling or low emitters. Incentives can emerge from a transparent classification of farms which improve RFE in order to escape being high emitters or by honouring actions which reduce environmental damages for the benefit of common goods. An example might be agricultural direct payments. As long as RFE data are not sufficiently solid and as long as the farm management can largely disregard them, there is no external pressure to face and to alter the situation, e.g. in terms of social or political pressure or pressuring using figures which point out penalties when recommended values are exceeded.

Furthermore, a valid assessment of real-life farming emissions is an essential criterion for the identification and implementation of appropriate measures. Currently, farmers seldom have the adequate information. However, even now farm managers can better form priorities for resource allocation if the need to balance partly contradicting goals would be made as explicit as possible. Besides external incentives and/or pressure that might prompt changes, the intrinsic motivation either for changing or maintaining the status quo usually seems to dominate the sphere of action. Potential internal incentives to mitigate Nr release into the environment meet potential barriers that reduce or block the willingness to improve RFE and to act responsibly towards possible peers, the immediate or the general community. The more believable the data, the higher the motivation for change is expected to be. The more accurate the RFE are, the easier it is to find and dismantle barriers to obtain a balance between the benefits and disadvantages of mitigating emissions.

Both the farm outputs (products sold and Nr emissions) addressed here emerge from very complex processes which take place in subsystems, embedded in hierarchical organized levels. Focussing on single aspects without taking both the context, and the conflicts between achieving productivity and the mitigation costs of Nr emissions into account does not allow any generalization of results and can be said to be overly narrow. Large variations in the outputs of farm systems, i.e. output of Nr via products sold on the one hand and Nr emissions into the environment on the other leaves ample room for improvement. Optimization of this relationship to the benefit of both farmers and society requires access to reliable farm-specific data and an overview of levels of N-flow through the various compartments of the farm system. Thus, a major question is how to increase the availability of valid data and on how to create an overview that can support decisions regarding an efficient allocation of available N sources.

The appropriateness of measures to maintain production at a competitive level and simultaneously implement measures to mitigate Nr losses in a cost-effective way is not only highly contextual but also relies on a function of margin utility. This applies to the intensification occurring with increased use of Nr inputs in form of fertilizers or bought-in feedstuffs as well as to the use of resources to mitigate Nr losses from the farm into the environment. Thus, identifying the optimum balance for each farm has to rely on farm specific RFE data characterising the internal conditions of a farm system. Additionally, the conditions outside the system boundaries (in terms of the price of products sold, availability and price of resources needed to restrict emissions, and also the cost of penalties to be paid when limits are exceeded) have to be taken into account. Cost-benefit relationships also depend on the status quo for both productivity and RFE data, and on the gap between the status quo and the envisaged target figures, respectively. Thus, without detailed productivity and RFE data on the specific farm system, it is not possible to identify the optimum balance between the goals of productivity and environment protection in a farm specific context.

4. Orientation, disposal, and action: know how to mitigate Nr emissions

Whether it is intrinsically motivated or forced by law to improve the current situation regarding Nr release into the environment, the farm management needs to know, and thus needs orientation, as to where to direct its efforts. The EU Nitrate Directive (Monteny, 2001) and the national emission reduction commitments based on the EU Directive (2016) addressing atmospheric pollutants contain limiting values for the concentration of Nr pollutants in ground water and air. They reasonably do not provide clear legal guidelines for farm management on how to contribute to achieve these values. In contrast, farm specific RFE data could actually provide guidance for management, supplying a picture of the status quo in relation to target figures. Farm specific RFE target figures can be deduced from the average levels obtained from assessing a sufficient number of comparable farms or an estimate of the optimum in the balance between Nr related productivity and Nr related threats. The current lack of orientational guidelines for farm management on how to balance the conflicting aims of increasing productivity and reducing Nr emissions highlights one of the major problems regarding the mitigation of emissions from agricultural processes.

Traditionally, agricultural research focuses on the impact of individual processes (for example, the uptake of Nr by crops or feed utilization by animals) rather than on the efficiency of nutrient resources in the whole system. However, exclusive focus on improving individual processes one by one may shift losses from one process to another; for example, reducing the loss of ammonia from manure storage can increase the loss during application on the field (Bleken et al., 2005). Besides orientation, the farm management is in need of tools and means that are able to achieve the envisaged target figures or at least a significant reduction in environmental Nr emissions. Different disciplines of agricultural science (e.g., animal nutrition, animal breeding, agricultural process engineering, etc.) hold various specialised scientific information (disposal know how) as well as tools and strategies ready for implementation. Environmental Nr emissions can be reduced by adopting technical developments and practices, such as improving storage and application methods of manure, feeding practices, or implementing specific housing techniques. Many scientific disciplines are engaged in identifying tools and measures to mitigate the negative side effects of production processes. However, agricultural science seems no less ambivalent than the use of Nr itself. Some scientific disciplines are involved in intensification processes intended to increase performance in plant and animal production by increasing the total amount of Nr used in form of mineral and organic fertilizer and feedstuffs. Other disciplines are focussing on the negative side effects of these intensification processes. Different agricultural disciplines seldom work together to find strategies to stabilize contradictory goals and to deal with the uncertainty regarding their effects. Specific framework conditions would be needed to make this happen, for example incentives by funding bodies to help to overcome the barriers preventing collaborative research work and provide alternatives instead of supporting people to gain a scientific reputation by becoming a specialist and focussing on single areas; thus losing sight of the whole picture.

Knowledge about chemical, biological or physiological regularities that are valid nearly independent of the context in which they take place can be assigned to disposal know how, available in the literature. Based on this knowledge, many measures and technical tools that have been proven in scientific studies to mitigate environmental Nr emissions under standardised conditions belong also to the disposal knowledge. They represent means to an end and are at the farmer's disposal when reflecting about options to pursue a certain target. However, the real effects following the use of measures or tools have to be proven (validated) to be effective not only in general, i.e. under standardised conditions, but under the given farm specific conditions. This includes their suitability in contributing to balance conflicting aims between productivity and mitigation of Nr losses on the individual farm. The context in which tools and measures are intended to be used vary considerably from farm to farm. Amongst other things, a farm's situation is characterized by the local and structural conditions, the availability of resources (nutrients, labour capacity, technical equipment, investments, information, skills, etc.), and the current level of productivity and Nr release and the gap between the envisaged target and the status quo. Currently, there are only minor incentives for farm management to implement adequate tools and means. These must not only be effective in the farm context but should simultaneously enclose a good cost-benefit relationship.

Because agricultural scientists have specialised rather than integrated the entire system, it is difficult to demonstrate the overall economic and environmental consequences of management decisions at the whole farm level (Kohn et al., 1997). Thus, it is legitimate to ask whether the focus of the various experts on their respective topics has led to a dissociation of the agroecosystem. It may be that the separate improvement of the single components has increased the total production but not the efficiency of the resources used, due to an unintentional dis-organization of the components of the agroecosystem (Bleken et al., 2005). The authors conclude that the re-integration of the subcomponents into a well-functioning whole requires an enforced interdisciplinary effort, focussing on the performance of the whole system rather than on the separate optimization of the individual components. Yet this is easier said than done.

To achieve significant real-farming emission reductions, it is important to ensure that emissions of farms are assessed in a meaningful manner while the tools and means, intended to mitigate Nr related threats have to be assessed in context; whether they work effectively and whether they provide a good cost-benefit relationship. Scientific investigations conducted under standardised conditions only provide "disposal knowledge" about the possible impacts of using such tools and means. Being only valid for the specific conditions under which it has been proven, disposal knowledge functions as a working hypothesis for "action knowledge" when implementing measures in a specific farm context which differs from the standardised conditions under which the disposal knowledge has been developed. Regarding the impacts that might occur in the use of generally recommended tools and means, an additional external validation is necessary via a scientific approach to assess whether the tools and means deliver what they promise. Currently, an external validation of the means in relation to the envisaged end seldom takes place in agricultural practice, let alone in relation to the balance between Nr related productivity and Nr related environmental pollution. Without external validation, individual tools to mitigate environmental Nr release seem to be an end in themselves rather than a means to an end. On the other hand, the previous discussion should have made it understandable how difficult it is to develop an assessment concept which provides valid data for Nr emissions from agricultural processes.

5. Systemic approach

Output from a production unit in terms of products sold and Nr emissions are the result of complex interactions between numerous variables and can be seen as an emergent property of a system. Regarding the general urgency to mitigate environmental impacts generated by agricultural processes, there is a need to understand the flow of nutrients through the inner-farm nutrient cycle better, as well as the reason behind the emergence of quantitative figures and the possible impacts of management operations on areas in- and outside the system. Understanding the underlying *modus operandi* is also an essential prerequisite to identify the most cost-effective leverage points. As biological processes follow a function of margin utility, it would be highly beneficial to obtain a reliable estimation of the optimum marginal utility in the use of Nr in a farm system, both in relation to the effects on N-related productivity and N-related threats. We are currently far from being able to assess such functional developments in a defined context. Nevertheless, as these evaluations would need to provide essential criteria for dealing with trade-offs and for developing strategies for the mitigation of environmental Nr pollution in a cost-effective way, we have to develop appropriate methodological tools further.

Taking this step also means to agree upon a procedure to define the boundaries of the system in which the trade-offs and actions to balance them interact. This is more difficult than it seems. It requires a systemic approach to overcome a reduction of complexity on the one hand and simultaneously prevent an overly complex approach that is difficult to realise. A system is defined as an integrated whole (distinguished by an observer) whose essential properties arise from the relationships between its parts (Ison, 2010). Thus, systems are not only very different in size and in what they encompass, they vary also considerably in their ability to allow for the exchange of substances between the inner and outer areas of the systems. What is outside a system is simultaneously part of (and hence inside) a superior system as systems are embedded in a hierarchical structure of sub-systems (Conway, 1987). Systems theory holds that the behaviour of higher systems in such a hierarchy cannot be simply discovered from a study of lower systems, and vice versa. This implies that each level in the agroecosystem hierarchy has to be analysed separately and both developed in its own right and in relation to the levels above and below.

In contrast, much of the previous research on nutrient management in agriculture has focused on altering the impact of specific farm subcomponents such as manure management, soil conservation, crop production, herd density, or animal nutrition in order to improve the overall efficiency of nutrient utilization and to reduce losses. Because agricultural scientists have become more and more specialised, there has been limited discussion on the relative importance of different methods to control nutrient pollution in relation to the entire system and the extent to which improvements in nutrient management are feasible, let alone reflections on the overall economic and environmental consequences of management decisions at the farm level. Unlike industrial enterprises, where it is comparatively easy to locate and measure emissions from waste pipes or chimneys, agricultural enterprises are characterized as open systems where the emissions emerge as the output of chemical and biological processes from non-point sources. A well-known example of how to assess the output from a biological system is the farm-gate balance sheet, defined as the difference between the amount of nutrient that enter the farm and the amount that leave it via the farm gate. While this approach gives an overview of the size of input and output figures, it does not provide any information about the internal farm processes and the variation between the various compartments (sub-systems). Thus, no clue is given of how to improve productivity while simultaneously reducing emissions. This approach neither considers the function of margin utility in the use of nutrients nor the recycling rates of nutrients in the internal-farm cycle, and also disregards the stocks of nutrients in the soil, in the feed or dung store of a farm. Thus, there is a demand for more appropriate and useful criteria, measurement tools and yardsticks by which effects within a specific context (defined by the boundaries and the process level) can be assessed. In practice, one can observe a farm but not the entire farm system. This means that subdividing a farm into subsystems seems an appropriate way of dealing with the complexity of a farm system. First steps into this approach were described by Kohn et al. (1997) and Watson and Atkinson (1999). Before this approach is clarified below in further detail, it is essential to introduce a key figure for nutrient management: the efficiency in which Nr is used within a sub-system.

6. Efficiency in the use of Nr

In general, efficiency is the capacity to avoid wasting materials, energy, labour, money, and time in doing something or to produce a desired result. Efficiency is a measurable concept, quantitatively determined by the ratio of useful output to total input. In this context, it is a measure of the extent to which Nr input is suitably employed for an Nr output in terms of envisaged sales products and adverse environmental emissions. Striving for high efficiency in the use of Nr means facing several restrictions; limitations in the availability of resources being but one. Limitations not only concern the choices for the input of N-rich production tools such as fertilisers and feedstuffs, but also the greater limitations of resources within the farm system, e.g. in terms of land area, high quality feed, labour and storage capacities. Finally, the environment has to be taken into account as a resource for the uptake of Nr waste. Other limitations of Nr management concern the need to achieve competitive productivity. On the one hand, the management cannot afford measures and investments for the mitigation of environmental Nr emissions which do not pay off in the long run. On the other hand, measures by the management which disregards the external impact of Nr emissions can exploit a competitive advantage by avoiding the effort and cost of mitigation, thus reducing production costs at the expense of fair competition (for those farmers who do the right thing by reducing Nr emissions). In contrast, efforts to only mitigate environmental Nr pollution, e.g. by reducing the amount of external Nr input, e.g. in form of bought-in feedstuffs, may work against enhancing productivity.

Efforts to reduce Nr input into the farm system while keeping productivity on a competitive level, can include Nr being substituted from other sources, i.e. nitrogen fixation by legumes, and increasing the efficiency in the use of on-farm residues. While this measures will reduce the purchased input of Nr, the inner-farm sources of Nr are also the origin of Nr losses, requiring further assessments about the fate of Nr within the farm system. An important (though often neglected) internal farm source of Nr is the nutrients recycling process. From a system perspective, animal excreta represent a return-flow of nutrients from a higher (animal) to a lower (plant) trophic level. Exporting animal manure means that the N which would have been available to crops on the farm must be replaced by inputs through either synthetic fertilizer or biological fixation in order to maintain the same yield level, while exported manure still contributes to ammonia evaporation and N leaching elsewhere. Flows of Nr within the system occur in a number of processes at various times and locations on the farm, for instance; accumulation and mineralisation of soil organic matter, assimilation by plants, harvesting, feed storage and processing, animal feeding and grazing, and through collection, storage, distribution, and incorporation of manure in the soils. All processes are associated with Nr losses, the relative rates depending on the relationships between the components.

However, Nr compounds only generate emissions when and insofar as they cross the boundaries of the farm system. An N-conservation approach in one component may be enhanced by other factors in the system. For example, when the dietary intake of N is reduced in the feeding regimes of dairy cows, less N is excreted in form of urea while milk production is maintained, which, in turn, reduces the quantity of N flow in the other components and can improve the overall N efficiency on the farm (Dou et al., 1996). An approach that conserves ammonia during manure handling and storage, however, would only effectively conserve Nr if the manure is applied in such a way as to prevent Nr from volatilization after field application. In certain circumstances, when crop acreage is insufficient for spreading all of the manure, manure Nr loss via volatilization in the air may be an undesirable way of reducing potential Nr leaching into water bodies. As these examples demonstrate, controlling the Nr flow by smart allocation and by influencing the boundary conditions in which mineralisation and organic binding of Nr take place, means that emission rates can be influenced considerably. Thus, an Nr-conservation approach, reducing the highly volatile mineral forms of Nr and promoting the organic binding of Nr (proteins are the most relevant organic N compounds) is an important strategy for enhancing the recycling process and reducing Nr emissions into the environment. From an economic perspective, however, recycling only makes sense when Nr input sources are limited; as is the case for organic farming or when sources are become more expensive, e.g. due to tax, and/or when the Nr emissions into the environment are subject to financial penalties high enough to be effective and not to be ignored.

It is obvious that it is more feasible to improve recycling processes within mixed farming systems than within specialised enterprises. Since herbivorous animals are at a higher trophic level than plants, the production of beef and milk proteins is much less N efficient than the production of plant proteins (Smil, 2002). The negative impacts for global N eutrophication of the disassociation of livestock from crop production, brought forth by an intensification of animal production in restricted areas and by gross transport of feed from "animal-free" regions have been pointed out by several authors (Granstedt, 2000; Tamminga, 2003). Livestock farming practices in Europe range from near complete self-sufficient feeding practices to feeding regimes with a very high purchase of concentrates. The amount of N in feed products imported into countries with intensive livestock production systems is often larger than the N amount applied as synthetic fertilizer (Olsthoorn and Fong, 1998). Feed is often imported from remote regions (Bouwman and Booij, 1998), completely disrupting the recycling of manure. On the other hand, feed protein produced for intensive livestock production is not just decoupled from recycling in remote regions. This is even the case within countries with intensive livestock production. For example, 40% of arable land in Germany is decoupled from the application of organic fertilizer (Destatis, 2011). Due to the high levels of livestock production in combination with stricter application of standards, about half of the manure produced in The Netherlands must be disposed of by livestock farms, half of which outside the Dutch border. Not surprisingly, the manure disposal costs per livestock farm tend to increase, currently constituting around 5% of the total production costs (van Grinsveen et al., 2017). The aspects outlined on the efficiency in the use of Nr compounds both inside and outside the farm system suggest that it is imperative to distribute animal production more evenly, both in relation to the amount of feed that can be produced locally and the amount of manure that can be used efficiently for plant production, if aims to reduce environmental Nr pollution are taken seriously.

7. Application of systemic approaches

Efficiency rates in the (re-)use of Nr and ways of increasing them can be only identified in a sound manner in the specific context and not in general terms. A systematic investigation is required to determine where and to what extent nutrients may be managed more efficiently. A first step in the application of a systemic approach in nutrient management was developed by Kohn et al. (1997). The authors created a model of nitrogen management for the application on a dairy farm, based on the four compartments: feed, animal, manure, soil. They performed sensitivity analyses in order to estimate the efficiency in the use of N and the relative importance of manipulating herd nutrition, manure management and crop selection in reducing nitrogen losses from the farm. The importance of N input to the farm via purchased feed, legume fixation, inorganic fertilizer and imported manure was investigated, and the potential to reduce N losses from dairy farms was evaluated. Related efficiency coefficients were set to reference values representing common management practices. Total farm N efficiency (animal product N per N input), and N losses per product N were determined for different situations by solving a set of simultaneous equations. Results revealed that there was more than a fivefold difference in N losses per animal product N between the most extreme scenarios, suggesting a considerable number of opportunities to reduce N losses from dairy farms.

It took some time before this approach was picked up and modified for the use in a surveillance program. In light of the negative side effects of agriculture processes on the environment, politicians in the Netherlands introduced and implemented the Dutch Minerals Policy Monitoring Program (LMM). The concept relies on the four compartments, suggested by Kohn et al. (1997), to compare efficiencies of N utilization and balances of inputs and outputs between the sub-systems and as a planning tool for N management to minimise potential N emissions to the environment (Daatselaar et al., 2015). Data on nutrients are collected and processed using the Annual Nutrient Cycle Assessment (ANCA) tool. Farmers can use the ANCA tool to calculate the outcomes for their own farm. Additionally, the average results of the corresponding group of LMM farms according to soil type and class for milk production ha^{-1} are presented to the farmer as a benchmark. A detailed description of the nitrogen inputs and outputs (for the calculation of the N use efficiency) is given in the yearly derogation monitoring report which is one of the products of the monitoring program. The previous findings showed that considerable differences in nitrogen use efficiency exist between farms of the same soil type and with the same level of milk production ha^{-1}. In most cases, both the nitrogen soil surplus ha^{-1} and the nitrogen use efficiency were higher if the milk production ha^{-1} was higher. By exporting manure off farm, intensive dairy farms avoid losses during application of this manure. The nitrogen use efficiency (as calculated by the ANCA tool) includes the import of nitrogen in animal manure from another farm on the input side. Accordingly, nitrogen in animal manure exported off farm is part of the output. Describing the underlying processes such as the conversion from available nitrogen in harvested feed into animal products (milk and meat) or the conversion from nitrogen, available in manure, into nitrogen added to the soil can provide useful additional information. Considerable variations occurring within the different groups offer various opportunities for farmers to improve the nitrogen use efficiency. The benchmarking is often the starting point, followed by suitable improvement measures. The setting up of study groups of farmers to discuss the benchmarking results is recommend by Daatselaar et al. (2015), since farmers take up more from their colleagues than from others.

8. On-farm assessments of N-efficiency

Parallel to the previously described ANCA concept, our working group also created an assessment concept for use on dairy farms. The study objective was to develop a methodological approach for quantifying and monitoring the N-flow through dairy farms' sub-systems to assess how efficiently N is being employed and how to develop a concept that helps to identify possible farm specific solutions. The N-efficiency concept (NEC) is based on Kohn et al. (1997) four compartment-model. In this respect, it is comparable to the ANCA concept but goes beyond this approach. To capture N cycling within farm systems and to get access to the levels of N input and output, farm systems were structured into the four separate, yet directly linked sub-systems: feed storage, livestock, dung storage and agricultural area utilised. Fig. 1 illustrates the N flow between the four sub-systems, and indicates which sources of information were used to provide Nr input and output data and to create a comprehensive picture of the Nr flow through the sub-systems of a farm. N input and output were quantified in comprehensive data sets of on-farm parameters in relation to each subsystem and by employing various equations to estimate quantities. This applies also for the estimation of gaseous emissions during storage. For further details concerning the methodology and the possible sources of data acquisition see Machmüller and Sundrum (2015, 2016). The quantifiable portion of N output from each sub-system which does not leave the farm system via products sold or estimated N losses serves as the N input into the following sub-system, creating a virtually closed cycle. Nr efficiency of the Nr flow through the respective sub-systems results from the quotient of Nr output in relation to Nr input.

The NEC approach was applied on 36 dairy farms, based on extensive operation records regarding annual Nr turnover. The farms were representative of the range of different farm structures, sizes and locations in Germany. Quantification of N-balances and N-mass flows revealed a high degree of variability between farms. This also applied to N-efficiency in the different sub-systems, both within and between the farm systems. The N-surplus on farm balance sheets amounted to 146 ± 65 kg N/ha. The total farm-N-surplus was determined initially using the farm's harvest yields and fertilization management. N-export

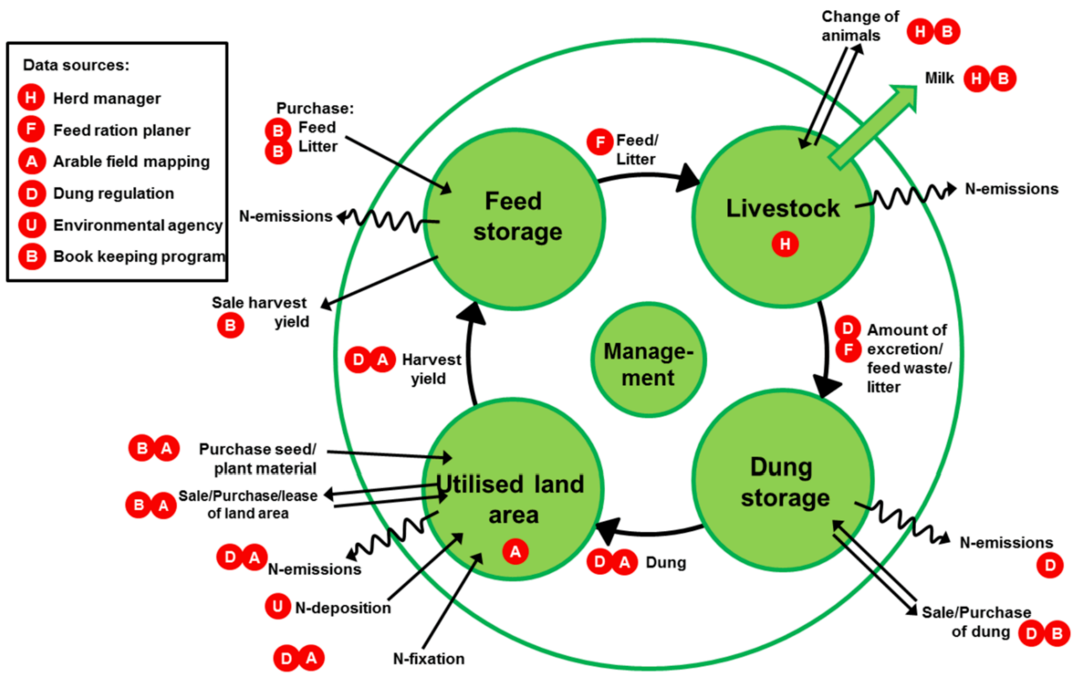

Fig. 1. Distribution and (re-)cycling of N across sub-systems and the data sources used (modified according to Machmüller and Sundrum, 2015).

from plant and animal products sold was approximately 44 ± 18% of the N imported onto the farm. With 45.8 ± 14.5%, mineral fertilizer accounted for the highest portion of N-input, followed by bought-in feedstuffs (33.7 ± 14.4%). Milk sold covered 25.1 ± 9.1% of the farms' total N-output. The amount of farm-N surplus was mostly determined by the farm's harvest yields and fertilization management. For further details of the results see Machmüller and Sundrum (2016). Efficiency in N-use differed considerably between sub-systems, indicating that each farm should rely on its own scheme to improve N-efficiency based on a continuous monitoring to assess the variation over time. A software programme can aid data sampling and documentation. The authors concluded that quantifying the N-flows through a farm's sub-systems offers an appropriate approach for assessing the level of N-emissions from dairy farms. The results indicate that many of the farm-N surpluses and their inherent environmental damage tend to be considerably underestimated when assessed only on the 1st scale. Each individual farm had various options at its disposal to increase efficiency in the use of Nr and to decrease costly N-input via mineral fertilizers and/or bought-in feedstuffs without necessarily compromising productivity.

9. Assessing allocation of Nr between sub-units

The NEC approach provides useful information for the farm management as it provides orientation as to where special attention should be directed to improve N efficiency; thus being more able to balance trade-offs. However, orientational knowledge cannot be equated to implementation and action knowledge. Thus, it is very useful for working out possible intermediate steps, based on the knowledge of the gap between the current state and the envisaged levels for the efficiency of Nr use in superordinate and/or sub-systems, but it does not provide knowledge on the most effective and resource efficient way of achieving this.

Structuring a farm system into sub-systems does not only facilitate the collection of data on the relationship of output and input quantities, but also quantitative data concerning the availability of Nr in the respective sub-systems. The allocation of Nr resources between sub-units within the respective sub-systems determine the efficiency in the use of Nr and thus the proportion of Nr contributing either to an increases of productivity or to Nr-related environmental pollution. A well-balanced allocation of resources between sub-units requires estimations about what can be expected in the farm specific context when the Nr resources are distributed in various amounts to the different feeding groups or agricultural areas or by differentiating between individual animals (e.g. dairy cows) or single plots of a farm system. The vertical arrangement of sub-systems on different scales within a dairy enterprise is illustrated in Fig. 2. The 1st scale comprises the whole farm and corresponds with the level applied in farm balance sheets. The Nr flow between the sub-systems on the 2nd scale is already illustrated in Fig. 1. Sub-divisions of the four sub-systems and their arrangements on the 3rd and 4th scale represent the specific structuring of a farm in various sub-units and thus can vary considerably between farms. In general, all sub-systems on the different scales are accessible for the quantification of Nr input and output, albeit differing in the efforts needed to obtain these data and in the accuracy level. In contrast to the 1st and 2nd scales describing the context of activities, the 3rd and 4th scale encompass the levels between which the allocation takes place and where "action knowledge" is required to enable the effective and cost-efficient use of resources and tools to balance the trade-offs between private and public interests. Necessary know how does not only encompass the quantities of resources available but also estimations on the current efficiency rates in the respective sub-systems.

The sub-units shown in Fig. 2 demonstrate the various areas which the farm management can focus on to improve allocation of available resources. In general, nutrient requirements of plants and animals differ considerably within a farm system between plots and individual animals. Knowledge about the requirements is essential to adjust fertilization and feeding regimes, therewith increasing efficiency in the use of Nr compounds and reducing Nr losses into the environment. While the impact of some measures are evident and they can be quickly and cheaply implemented (such as altering diet formulation to reduce nutrient losses), many management strategies face practical barriers to being adopted, i.e. costs as well as labour and capital investment (such as the construction of additional dung and/or feed storage facilities). Thus, there are not often enough real opportunities to promote them in the field under current market conditions. To persuade farmers to undertake practices that will simultaneously help the environment and lift a farmer's bottom line by improving allocation strategies and

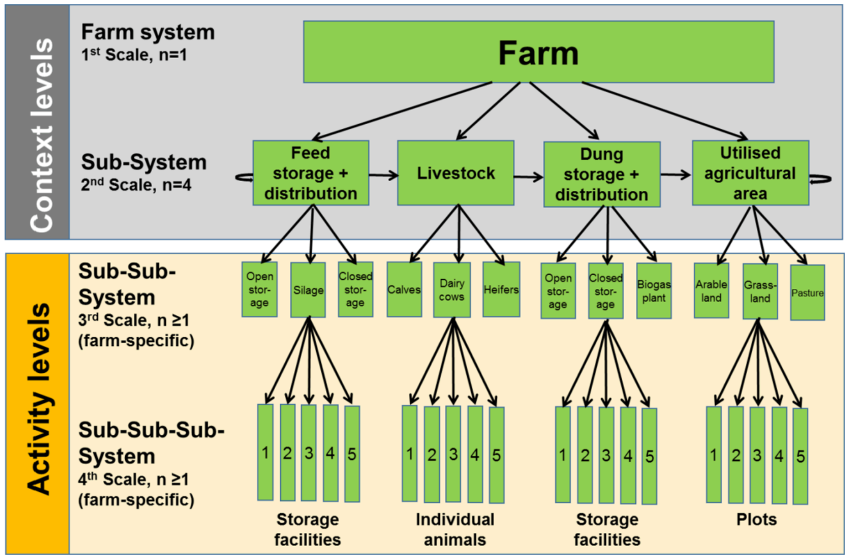

Fig. 2. Distribution of Nr across sub-systems and distribution of Nr within sub-systems between subunits on the 3rd and 4th scale of a dairy enterprise (modified according to Machmüller and Sundrum, 2015).

application methods requires appropriate incentives so that the farm management take public interests as well as their own into account.

Furthermore, the allocation of Nr and other resources should be based on appropriate data monitoring. However, comprehensive data sets are not always directly available to a farm enterprise. Data availability differs considerably between countries and even more between single farms. According to the knowledge of the author, the implementation of the Annual Nutrient Cycle Assessment in the Netherlands (Daatselaar et al., 2015) is currently the most widely used data acquisition concept in relation to environmental issues in dairy systems. The N-efficiency concept (NEC) introduced here shows that data acquisition can be significantly expanded by including data from the 3rd and even the 4th scale. Due to the large heterogeneity of farm structures, data acquisition on the 3rd and 4th scale cannot follow a fixed procedure, which would be applicable only on selected farms, but has to be adjusted to the respective circumstances. Consequently, accuracies of data varies between farms. The NEC approach does not only deliver figures of N efficiency for the respective sub-system, but also enables improvements of the consistency and plausibility of the data used to be checked and validated from the input and/or the output perspective on the 2nd scale and from the aggregated values obtained from the 3rd scale. A continuous monitoring will help to estimate whether variation of data over time is due to changes in the nutrient management or due to inaccuracies in the internal flows calculation.

Data acquisition is elaborately and often not attractive to farmers, especially if they cannot see possible monetary benefits. Consequently, farms differ in their preparedness to collect data, in the availability of data and in the use of software programs, already offering data, e.g. concerning animal stock and exchange, performance, feeding regimes or distribution of manure. In cases where detailed information is missing, aggregated data can be used, often at the expense of accuracy and validity of data. However, they are helpful at least to gain an overview about the amounts of Nr flowing between the sub-systems. Surveys gained by data acquisition on the 2nd scale can be the starting point to identify the most crucial areas within a farm, which than should be illuminated by further in-depth analysis. To convince more farmers to make use of such data for one's own end and for the benefit of the environment as a common good, further incentives will be needed, either in the form of grants and/or penalties in the case of excessive Nr losses. In the future, the use and extension of big data in the context of agricultural processes will increase technical and software-based opportunities while efforts are expected to decrease. In light of the enormous amounts of Nr flowing through the sub-systems of a farm and representing also a kind of cash flow, advisory services might provide more assistance for the farm management in improving their nutrient management.

In the context of the data analysis conducted by Machmüller and Sundrum (2016), a separate case study was conducted on a dairy farm, based on the availability of comprehensive records about the N distribution between storage facilities and the single plots of arable and grass land. Assessments on the study farm showed that the distribution of N resources between the individual farm plots often deviate considerably from the estimated demands for the crops cultivated. Consequently, the areal N balance sheets varied significantly between the individual plots. While many plots were over-fertilised, others were under-fertilised. The figures for the latter plots levelled those of over-fertilised plots and created average values that were far from matching the real surplus figures of the farm. Average figures were misleading regarding the need for countermeasures and the areas which should be taken into account to mitigate Nr emissions. The comprehensive calculations on the farm revealed a net N surplus far beyond the previous estimations. In comparison to the detailed monitoring plan, the calculation method for farm balance sheets applied in Germany only recognised 12% of the net N surplus on this farm. Although it only referred to one case study, the results of the comprehensive monitoring can nonetheless question the validity of farm balance sheets, indicating that both farm-N-surpluses and their inherent potential emissions have been underestimated considerably.

10. Conclusions

As one of the main emitters of Nr compounds, agricultural farms are challenged to optimize their production systems. Politicians, agronomists and many agricultural scientists appear to have confidence in the ability of the markets and of agricultural science to drive technological changes which enable the economy-environment system to both satisfy increasing global food demand and solve problems of environmental pollution and GHG emissions. These assumptions, however, generally neglect the biological basics involved, amongst other aspects the ambivalent nature of Nr and the resultant trade-offs. Whether benefits of Nr use for food and feed production exceed the Nr-related threats is very dependent on the context in which agricultural processes take place and on the level with which the situation in question is being compared. The same is true for the possible ways of balancing the trade-offs between private and public interests in a cost-effective manner, thus contradicting the frequent (but often misleading) attempts to formulate general recommendations for the implementation of measures.

Many technical tools and measures that have been proven to mitigate environmental Nr emissions under standardised conditions are at the farmer's disposal and thus belong to the category of disposal knowledge. However, the way that agricultural science predominantly focuses on the development of disposal knowledge shows a failure to grasp the complexity of the challenges at hand. The degree of benefit or damage due to the use of Nr emerge from a very complex (and often confusing) interplay between physical, chemical, biological, sociological and economic rules. The outcome of the context-dependent interactions, including the possible effectiveness and cost-efficiency in the use of resources, is thus hard to predict. These are, however, essential for the farm management to decide on the allocation of resources. Thus, focussing primarily on disposal knowledge risks being overestimated in its ability to solve environmental problems.

Solving the issue of environmental pollution from agricultural processes cannot just be left to technological development. It also requires different kinds of regulation and the development of implementation and action knowledge to create strategies for sustainable resource management on the local level, considering trade-offs in resource flows through sub-systems. To deal with the challenges appropriately, the farm management is in need: i) of knowing the current state of Nr flow through the sub-systems on the 2nd scale and the related efficiencies in the use of Nr; ii) of an agreement on the boundaries that define a farm system and the sub-systems embedded in this hierarchical structure so that results are comparable within and between farm systems; iii) of an agreement on the methodology for assessing real farming emissions (RFE) of Nr; and iiii) of finding their place in a national benchmarking monitoring program for RFE data. The latter does not only provide orientation on the gap between the current and desired level, but also addresses the problem of unfair competition. Farms behave unfairly when they emit a high level of Nr into the environment while simultaneously externalising production costs at the expense of common goods.

Assessments already implemented in the Netherlands refer to the 2nd scale of farm systems, providing far more meaningful results than farm balance sheets on the 1st scale. Improving the reutilisation of Nr in the whole farm system and increasing the efficiency in the use of Nr in the sub-units on the 3rd and 4th scale are seen as the major ways in which the farm management can balance trade-offs without comprising productivity.

Nevertheless, it can be argued that RFE data on the 2nd scale are imprecise and do not equate to the real Nr emissions from a farm. The counterargument would stress that this approach enables at least an approximation of the real-farming situation which is expected to be far more target oriented (where mitigating Nr emissions are concerned) than the scientific approaches which primarily focus on the extension of disposal knowledge. Furthermore, benchmarking offers an appropriate methodological approach to deal with uncertainties in the assessment of RFE data, as these methodological uncertainties affect all farms; although not exactly to the same degree. The lack of benchmarking for RFE values in relation to the product quantity of food and feed can be seen as one of the main barriers in the fight to mitigate environmental Nr emissions from agricultural processes. As long as benchmarking is not established, the farm management lacks orientation regarding the target figures it should aim for. Without target figures, it is not possible to formulate concise working hypotheses regarding the most effective and cost-efficient means that are at the farmer's disposal as well as a strategy for the allocation of resources in a farm specific context. The question as to whether the corresponding implementation and action knowledge has proven to be effective and cost-efficient needs to be validated afterwards by further on-farm assessments. Know how for dealing appropriately with the allocation of resources can be generated by case studies. A relevant number of case studies need to be further reviewed via meta-analysis in order to identify more general patterns.

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