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Agricultural Land Use Systems and Groundwater Quality: Impact Assessment Using Nutrient Balances for Evaluation, Monitoring and Conservation of Natural Resources

Frank Eulenstein[a,b,g,*], Marion Tauschke[a], Uwe Schindler[a,b], Lothar Müller[a,b], Marcos A. Lana[a], Roland Schindler [d,g], Walter H. Mayer[c], Hartwig Drechsler[e,g], Nils Cremer[e,g]

[a]*Leibniz Centre for Agricultural Landscape Research (ZALF), Eberswalder Str. 84, 15374 Muencheberg, Germany*
[b]*Kuban State Agricultural University, 13 Kalinin Str. 350044 Krasnodar, Russia*
[c]*PROGIS Software GmbH, Postgasse 6, 9500 Villach, Austria*
[d]*NEW Niederrhein Wasser GmbH, Rektoratstrasse 18, 41747 Viersen, Germany*
[e]*Dr. Drechsler Ingenieurdienst, Hannah-Vogt-Str.1, 37085 Göttingen, Germany*
[f]*Erftverband, Bergheim, Germany*
[g]*DWA, German Association for Water, Wastewater and Waste, Theodor-Heuss-Allee 17, 53773 Hennef, Germany*

Abstract

This review presents the methods used to assess soil, pore water and groundwater nutrient levels on farms and agricultural fields. The purpose of this catalog of methods is to provide a basis for evaluating the efficiency of measures for the control of water catchment areas. A Zone monitoring model (ZMM) which is a basis for appropriate monitoring schemes in view of risks for the groundwater coming from agricultural lands has been developed. Based on this scheme, various methods to monitor nitrate concentrations at different unit levels, from the farm to the soil zone and on to the groundwater are described. At farm level, nutrient balances are mandatory to identify the potentially remaining concentrations of nutrients in the soil. Nutrient balances are incorporated in the latest information and communication technology (ICT) and farm management information systems (FMIS).
The methods at groundwater-level described here are groundwater sampling by means of a suction lance, soil sampling beneath the groundwater table, groundwater sampling using the direct-push method, sampling from observation wells, from multi-level observation wells and from production wells. These practices are the early-warning systems which can prevent the surface and/or underground drinking water from contaminating with unwanted chemicals.

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Keywords: agriculture; groundwater conservation; nutrient balance; groundwater quality; monitoring; farm management; information systems

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* Corresponding author.
E-mail address: feulenstein@zalf.de

1. Introduction

The importance of fresh water resources for the well-being in Europe's industrialized societies and the protection of groundwater are the main topics of the environmental concerns in the European Union. The European Water Framework Directive, which entered into force in December, 2000 (EU WFD 2000) should highlight its significance and urgency. The Groundwater Directive (EU GWD 2006) was subsequently developed in response to the requirements of Article 17 of the EU WFD, formulating the EU policy on groundwater protection. By the end of 2015, the EU WFD aimed to achieve a good quantitative and qualitative state of all European surface water and groundwater bodies.

The presented methods are based on a large number of scientific papers, which are summarized in an operating manual (DWA M-911 (2013)). The methods described are now standard in Central Europe. In addition, the methods were also scientifically tested and tested in practice (Eulenstein et al. 2008).

This review describes methods that have been presented (Eulenstein et al. 2014; Dannowski et al. 2014). The current review includes up-to-date information with respect to the tools used for optimizing nutrient cycles in managing farm for sensible environmental conservation.

2. Monitoring nutrient cycles to protect water resources

2.1 The zone monitoring model (ZMM)

The zone model of monitoring of nutrient cycles was shown (Fig. 1). The model consists of different vertical compartments: the soil surface (farm zone) where nutrients are applied, the root zone, the drain zone, and the groundwater zone. It refers to a typical geo-hydrological situation in Europe, but could be modified and refined to suit other geo-hydrological situations as well.

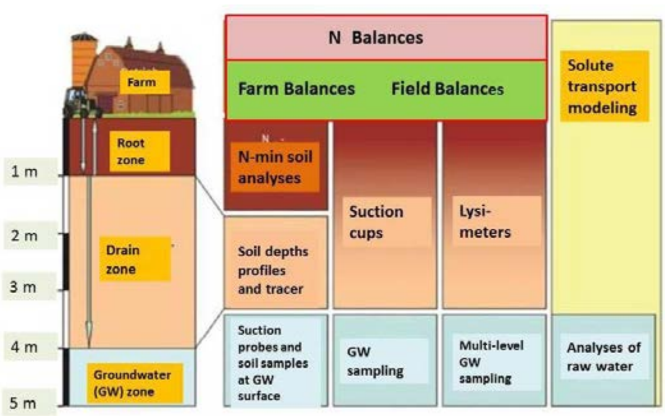

Fig. 1. Zone model of acknowledged methods for estimating agricultural nutrient surpluses for the purpose of groundwater protection, example of nitrogen. It demonstrates different monitoring levels and appropriate tools: the farm zone, the root and drain zone, and the groundwater zone (DWA M-911 (2013), modified)

Each zone is characterized by proven monitoring methods using analytical measurements and balancing calculations. Solute transport models enable an operator to analyze and predict nutrient flows over all these zones or even considering fluxes in all directions (Natkhin et al. 2013; Merz et al. 2009).

The following sub-sections of this chapter will focus on the farm zone above the soil, evaluating the performance of balances at field and farm level, and on sampling methods in the groundwater zone for monitoring purposes. These are not samples or repetitions, but are rather extensive surveys of individual areas and entire farms.

Methods applied to monitor the root and drain zone and the topic of solute transport modelling have already been characterized in concomitant papers (Schindler et al. 2015; Nendel 2015).

2.2 Nutrient balances at farm and field levels

2.2.1 Data requirements

Some direct and indirect methods of measuring, balancing and modelling nutrient cycles and recognizing harmful quantities of nutrients for water bodies are acknowledged (Eulenstein et al. 2006 and 2008; DWA M-911 (2013)). This chapter focuses on nutrient balances.

The nutrient balance, structured like an area balance sheet, is performed by calculating all of the nutrient inputs and those quantities that have been removed from the land. However, the accurate estimation of nutrient balances aiming at efficiency control and refined operational nitrogen management can be very complex, particularly in agro-ecosystems involving livestock production.

When the agronomic management of plant production (which is intrinsically associated with a flow of nutrients) is properly recorded and documented, it is easy to perform nutrient balances.

In nutrient balances, nutrient sources and sinks are compared in a system (Fig. 2). This can be carried out by completing operational balance sheets at farm or field level, depending on how detailed the available information is.

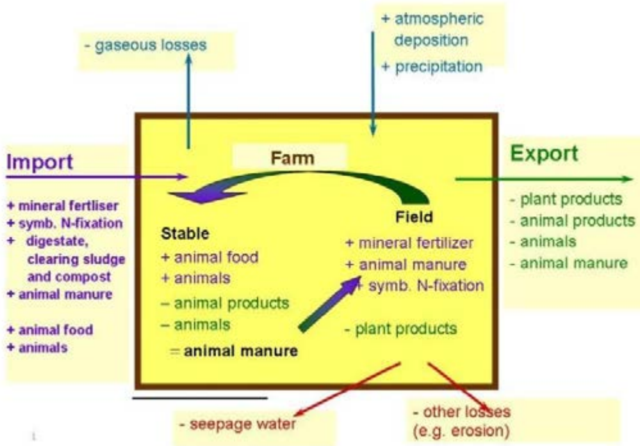

Fig.2. elements of nutrient balances.

Balances at farm and field levels should be based on regional specific data. They are available for many regions. Major elements of the nitrogen balance, such as leaching, were carefully studied in parts of Europe several years ago (see Eulenstein and Drechsler 1992; Mueller et al. 2001, 2005; Eulenstein et al. 2003; Schindler et al. 2008). Thus, water flow pathways and data, and orientation values of nutrients can be used for balancing procedures in specific regions. Nutrient balances as a part of ICT are suitable to support the circular flow of natural elements and economical values within agriculture (PROGIS 2015).

Many more innovations are in progress in this field of operational control on the use of land and water resources. As an example, a PF farming map can be sent via an office-based logistics system to mobile equipment (e.g. tractors with tablet PCs or smart-phones) to trigger sprayers with m² precision according to the map (Fig. 3).

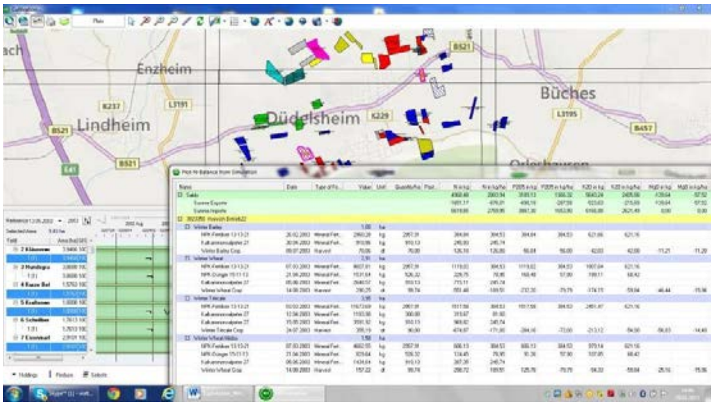

Fig.3 Screen shot of a nutrient balance sheet and a GIS map of related fields in the background (Figure of the PROGIS Company).

For smallholder farms, there is an additional need for ICT-equipped public or private advisors – one might serve up to 200 farmers, each with 25 ha = 5,000 ha or more, depending on the land use structure – with access to high-end expert knowledge supporting them in complex cases. Machine cooperatives providing the shared use of agricultural equipment and supporting additional social services enable the use of the latest technologies even for smallholder farmers. This will optimize the use of fertilizers and pesticides, thereby guaranteeing economic and ecologic benefits for them and also integrating the idea of groundwater protection.

2.3 Methods of in-situ groundwater quality monitoring

Schulenberg et al. (1990), Eulenstein & Drechsler (1992), Osenbrück, et al. (2000) showed a close relationship between the excess of nitrogen balance and the concentration of nitrate in groundwater.

2.3.1 Monitoring rules

In principle, any extraction well constructed and operated for drinking water supply or crop irrigation could equally be used for groundwater quality monitoring. However, drawing groundwater from these wells will provide mixed water of average quality for the related groundwater catchment, without the possibility of further temporal or spatial differentiation. Therefore, regular groundwater sampling at various places within a subsurface catchment will provide more detailed information. In the unconsolidated rock region this should be practicable at reasonable expense.

In the case of an allocated water protection area, as a rule, necessary data will exist, since the delineation of the protection zones is based on this information. For groundwater development projects whose water use permits have been granted recently, this data should also have been assembled in the course of the planning procedure.

2.3.2 Groundwater sampling by means of a suction lance

In regions with the depths to the groundwater of less than 6 m, information can be obtained at relatively short notice with respect to the impact of agricultural measures on groundwater quality by taking samples from the near-surface groundwater (Fig. 4).

Benefits: This relatively simple procedure does not require any especially high material or personnel expenses. Depending on the depth to the groundwater and the texture of the substrate, up to six samples can be taken within an eight-hour day. Analyzing the obtained water samples, compared with the analysis of soil samples, is much simpler and less time- and cost-consuming. The impact of land use and agricultural protective measures on groundwater quality can be assessed at a relatively early stage.

Disadvantages: In the case of depths to the groundwater of more than 4 m, the procedure takes more time; at depths to the groundwater of more than 6 m the technical low pressure will not suffice to abstract enough water for analysis. Occasionally, water must be filtered prior to analysis, which can lead to errors in determining particular substances.

Appropriateness for efficient survey: By taking water samples from beneath the water table, the quality of the recently constituted groundwater is examined. Thus, the results of water analyses can be related to matter inputs in the vicinity of the sampling point. Provided a reasonably fine sampling grid is established, hot spots of solute inputs can be identified within a groundwater catchment. The load balance of such matter inputs can be calculated from concentration, as long as the rate of groundwater recharge is known.

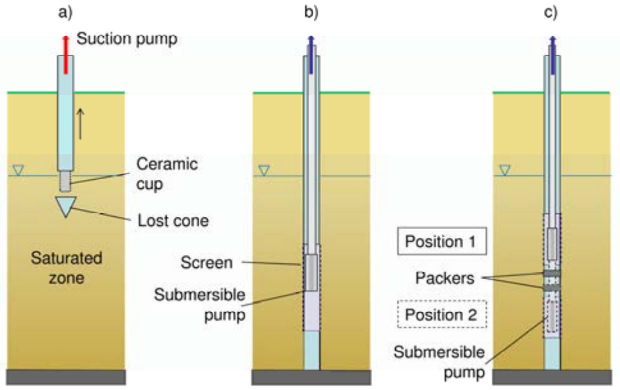

Fig. 4. Scheme of groundwater sampling methods. (a) Suction lance, (b) Monitoring well, (c) Multi-level sampling.

2.3.3 Soil sampling beneath the groundwater table

This method based on taking soil samples from the near-saturation zone also enables one to draw conclusions about the effect of agricultural measures on groundwater conservation.

Using a drill hammer with a push rod, the unsaturated zone is penetrated down to the water table. The substrate material is sampled in the notch of a trenched rod. Knocking carefully against the rod makes the saturated zone visible (free water will appear), and the uppermost section of about 15 cm is taken from the saturated substrate. This way, per inspected unit (e.g., per field block), four or five soundings are executed and the substrate material is collected in one homogeneously mixed sample

Benefits: Relatively simple soil sampling supports area-wide detection of nitrogen inputs at the groundwater table of a whole domain. By means of assembling mixed samples per inspected unit (field block), expenditure on analysis is minimized.

Disadvantages: At present, the application of the procedure is restricted to unconsolidated sediments and fine-grained substrates (silt, sand); coarse gravel material is out of its scope. At depths to the groundwater of more than 6 m, taking soil samples proves to become more and more time- and cost-consuming. In the case of a longer seepage period combined with higher recharge rates, the mean solute concentration of the recently constituted groundwater will tend to be under-estimated as a consequence of dilution.

Appropriateness for efficient survey: Because of the fact that water eluted from the soil samples originates from a certain range of depths (approx. 15 cm), results from chemical analyses represent the nitrate input into the groundwater averaged over a period of up to several months. Compared with Nmin soil analyses from beneath the root zone, they are less subject to short-term fluctuations caused by specific agricultural measures or weather events. Collecting mixed samples allows for the measurement-based detection of area-related nitrogen inputs into the groundwater. Just like taking water samples from the near-surface groundwater, usage of this procedure indicates the effects of protective agricultural measures on the groundwater quality at an early stage.

2.3.4 Groundwater sampling using the direct-push method

In areas sparsely equipped with monitoring wells, groundwater soundings have been progressively executed by means of the direct-push method in the recent years (EPA 2005; Hannappel and Braun 2010). This procedure allows groundwater samples to be gathered directly in the field and at specific depths. Likewise, an area-specific monitoring of the groundwater quality is feasible, even in the case of a deeper water table.

In the case of depth-specific groundwater sampling, the whole system is subsequently raised to the next position, and the sampling operation is executed as depicted before.

Benefits: As compared with conventional procedures, direct-push groundwater sampling allows the geologic and hydrochemical conditions underground to be surveyed faster and spatially more flexibly, combined with diversified local logging. Using lightweight automotive equipment makes sampling points accessible even on heavy terrain and supports fast relocation. Because of the groundwater observation points do not need permanent installation; no additional construction costs are incurred.

Disadvantages: As no regular groundwater observation wells are installed, the direct-push method only generates survey points for one-time usage. Repeated groundwater monitoring using the same installation is not possible.

Hammer-driven ramming for direct-push groundwater sampling is not feasible everywhere. Difficulties will occur depending on the conditions underground, especially for larger sampling depths and very deep water tables (> 20 m), as well as in the case of stony or strongly cohesive sediments. To estimate the depths approachable for sounding and sampling, previous knowledge is needed from well-informed and skilled staff that is familiar with the hydrogeological situation.

Appropriateness for efficient survey: Since the direct-push sampling method offers considerable mobility, it is especially appropriate for application at hydro-geologically well-perceived areas which nonetheless have an inadequate density of observation wells, and require extra area- or usage-specific investigations into the groundwater quality.

2.3.5 Groundwater sampling from observation wells

In the catchments of groundwater abstraction wells for the public water supply, as a rule, observation wells are deliberately placed in the vicinity of the production wells (Fig. 4). Based on those water level observations, or on pumping tests in the course of the pre-development phase of the well group, the shared groundwater catchment should have been delineated, the hydrogeological parameters of the aquifer should have been determined, and supervision of the hydrograph should be further ensured on a permanent basis. Such observation wells should also have been occasionally installed for the large-scale assignment of the subterranean catchment of a river or a canal. In addition, suppliers of potable water or water management authorities erect special observation networks to monitor the groundwater quality development, e.g. upstream of a well field or downstream of any polluters (Fig. 4).

These requirements are:

- Filter lining (screen) must be placed in the upper groundwater zone
- Short filter lines
- The related catchment area must be given a unique attribution

By systematic inspection of the results from observation wells, the effects of groundwater-protecting measures can be detected in the medium to long term. For this, the contributing subsurface catchment is to be attributed to the observation well according to the depth of the filter screen. This may be complicated in certain cases, and sometimes the catchment boundary may vary with time. To increase the trustworthiness of the efficiency assessment, if possible, several observation points should be used (Fig. 5).

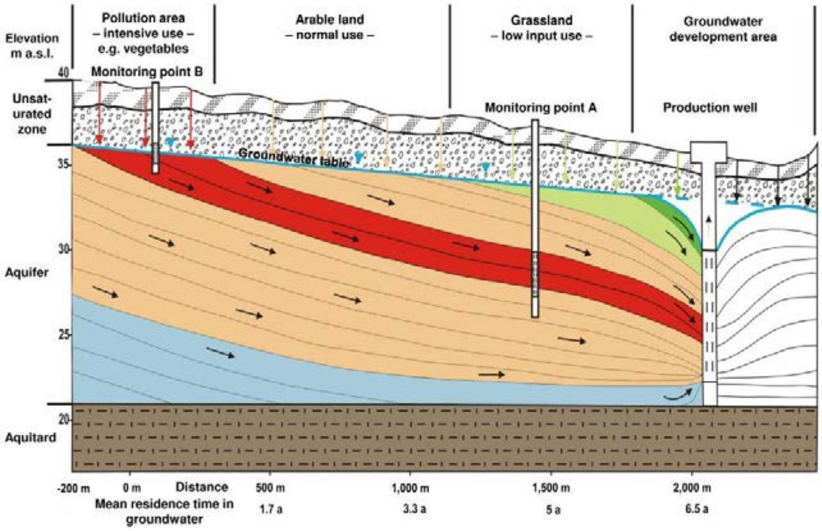

Fig. 5. Groundwater quality monitoring by means of observation wells in the upstream zone of a drinking water production well.

Fingerprint parameters of the groundwater age can make sense when interpreting the analyses. In many cases, the identification of so-called environmental tracers (2H, 3H, 3He, 18O, 85Kr, CFC, SF6) has proven to be useful for groundwater age determination. To examine the origin of nitrates and to explore the quantitative schemes of their decay, radioisotope-hydrologic measurements (15N-NO_3, 18O-NO_3, 34S-SO_4, 18O-SO_4) are also appropriate (Schulenberg et al. 1990, Stadtwerke Viersen GmbH 1999). Recently, these methods have increasingly been applied when examining the efficiency of agricultural measures to mitigate groundwater pollution (Osenbrück et al. 2000).

Benefits: At waterworks catchment areas, as a rule, a groundwater observation network is found for which long-term records of groundwater quality already exist. Optimizing this kind of network for the purposes of an efficiency survey allows the quality status of the upper groundwater layer to be captured at acceptable expense.

Disadvantages: The groundwater quality in the range of a well screen is dependent on a multitude of interacting factors, such as the spatial and temporal patterns of groundwater recharge, the flow velocity and solute transport across the aquifer, including dispersion, matter decay and transformation. Thus, the spatial and temporal attribution of groundwater quality data to the mostly non-point, distributed ('diffuse') sources will be relatively erroneous and complicated.

Appropriateness for efficient survey: Groundwater observation wells are principally suitable to evaluate the efficiency and impact of agricultural groundwater protection measures. To be used for relatively short-term information on groundwater quality, however, they should be compatible with certain conditions. Their filter construction (screen) should not be placed too deep below the mean water level, and they must not be biased by larger-scale effects from the catchment.

3.3.6 Groundwater sampling from multi-level observation wells

Multi-level observation wells (Fig. 4 c) are especially appropriate for the hydrochemical survey of thick aquifers or a system of aquifers hydraulically separated from each other by non- or semi-permeable confining layers. In general, they allow for the vertical differentiation of the hydrochemical conditions within one or between several groundwater-bearing units. In the context of the efficiency survey they are suitable for analyzing the dynamics of the vertical matter exchange even in the near-surface groundwater zone. In recent times, multi-level observation wells have been often supplemented by probes located in the unsaturated zone at various depths.

Disadvantages: Both the construction and operation of multi-level observation wells are very extensive and cost-consuming in comparison with regular groundwater observation wells. To avoid imperfections in groundwater sampling (evoking hydraulic short-circuits), only skilled personnel should be commissioned.

Appropriateness for efficient survey: Multi-level observation wells provide an important tool to evaluate the efficiency of agricultural groundwater protection measures, as well as being an instrument for the long-term prognosis of the hydro-chemical conditions in an existing drinking water protection zone. They are suitable for comprehensively analyzing and monitoring the hydro-chemical processes characterizing the pore aquifer. Combined with compatible observation equipment installed in the overlying unsaturated zone, the effects of agricultural groundwater-conserving measures can be studied in their temporal and spatial development.

3.3.7 Quality monitoring of raw water from production wells

The effects of agricultural measures on diminishing nitrate loads are often quantified from time series of the untreated groundwater quality at drinking water works, especially as this method offers a specified set of target variables which can easily be determined. Interpreting the time series of raw water quality data, the following conditions ought to be reflected (Fig. 5).

Benefits: Long-term records of untreated groundwater quality are already kept by suppliers of potable water, as regulated by law. These time series of critical substances, such as nitrates, pesticides or sulphates, are suitable for inexpensively assessing the effect of agricultural groundwater protection measures.

Disadvantages: Analyzing untreated groundwater samples from production wells does not allow for the intended hydraulically undisturbed, highly differentiated spatial or temporal attribution of observed water quality to agricultural measures of groundwater conservation.

Appropriateness for efficient survey: The evolution of substance concentrations in raw water from selected production wells can be used to evaluate efficiency under certain circumstances provided the substances are distinctly attributable to a particular groundwater catchment, and agricultural water protection measures have been practiced over a relatively long period of time. The duration of the monitoring period should be about one third of the average time of groundwater renewal (the quotient of the extractable groundwater volume and the annual recharge rate) in the developed aquifer, plus the mean transit time between the soil surface and the groundwater table. This method, however, will provide only rough information about larger-scale measures that cannot be locally and temporally differentiated.

4. Conclusions

On the basis of nutrient balance sheets, supplemented with data from soil analyses, farm managers can easily evaluate whether the field has been overcharged with nitrogen or phosphate in previous years or cropping seasons. The information generated can be used in agronomic decision-making, leading to the correction of management errors that could otherwise cause inefficient nutrient use or soil and water pollution and contamination. However, field balances are not recommended for large-scale analyses (e.g. entire water catchments) due to the large amount of work required for their parameterization and the potential lack of accuracy involved.

There are several methods of in-situ groundwater quality monitoring suitable for the checking the efficiency of agricultural groundwater protection measures. Besides their general characteristics, the benefits and disadvantages of each method were discussed and rated here under the summarized term "appropriateness for efficiency survey". The basics are outlined in the recently released German Technical Guideline DWA-M 911 (2013), "Efficiency of measures to control land use for groundwater conservation – the example of nitrogen", which was adopted for this contribution.

It can be stated that there is no individual method that would manage all the practical problems at low cost and at the same space and time. Instead, a thorough selection and/or a combination of methods are required, depending on agricultural, pedological, geological, climatic and hydrological site conditions. Some of the methods provide a relatively simple short-term indication of the local efficiency of specific agricultural groundwater protection measures. Others are more suitable for revealing and understanding the system behavior of an entire complex of groundwater units in spacious catchments under anthropogenic impact.

An efficiency survey should be carried out as close as possible to the actual agricultural area under reference to preclude incorrect or vague deductions. This will also raise the farmers' acceptance for conservation measures, since they are immediately informed and can understand the effect of their efforts on the groundwater resources under concern. The latest farm management information systems (FMIS) are also able to manage farms and fields with respect to other needs, such as logistics, precision farming, subsidies and more. They integrate cost calculation, possibly also CO_2 balancing, or even incorporate insurance or bank needs. Measures of precision farming help to save fertilizers, thus reducing nutrient surpluses. Their aim is to optimize both the farm economy and the ecology through land and water conservation measures. This is already under way on some projects and is the topic of ongoing work.

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