# New frontiers and perspectives in grassland technology

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**Abstract.** Grassland scientists and farmers are increasingly faced with emerging new technologies and information systems that have been primarily developed by engineering sciences in particular: precision agriculture, remote sensing, geographic localization and biotechnology. Whether the implementation of any of these technologies may be beneficial in economic and ecological respect is a challenging judgment call, especially for those who have to carry over that decision on their farm. Compared to arable land, new technologies have been applied on grassland only partially and with some delay. However, as we will demonstrate, there is place for a successful implementation of new technologies in various climate regions and for a wide range of applications. This paper presents the most significant and recent developments of new technologies in agriculture that have a potential for beneficial application on grassland. It defines the relevant terms and processes, provides examples of successful implementation and discusses future orientations and research needs.

**Keywords:** Grassland, new technologies, precision agriculture, remote sensing, biotechnology

## Introduction

The importance of grassland for global ecosystem functions and the delivery of ecosystem services are well documented and also well recognized by governments and consumers. In the face of increasing food scarcity, as reported by the FAO (2013), and the need for sustainable grassland production, scientists are called upon to present solutions on how natural resources on grassland can be used more efficiently for animal products and renewable energy. Managed grassland worldwide covers about twice the area of land that is under arable cultivation (Ellis and Ramankutty, 2008), however, it is often of marginal value. Such grassland is mainly found on rangelands and savannahs of the African and American continents or in the Asian steppe where inputs such as labor and agro-chemicals are limited, machinery is either missing or impractical and low-cost systems with only grazing prevail. On the other hand, in humid areas of the world, grassland is intensively fertilized and grazed or cut, thus supporting high productivity of animal husbandry. In such grassland, natural productivity can be further improved through the introduction of different types of technology. These systems are mostly found in the Northern hemisphere, Central Europe including Scandinavia, the UK, Northern America, some regions in Asia, coastal Australia and New Zealand. These regions harbor the highest cover of technology assisted grasslands. Most favorable growing conditions, such as soil fertility, moderate temperature, sufficient water, and market structure, as well as a highly developed agricultural and food industry, are decisive in where application of new grassland technologies is predominantly found.

In the present paper and in concordance with numerous scientific sources, the term grassland technology is used for approaches that: (1) rely on well-developed and applied principles of mathematics and natural sciences; (2) support the manipulation of grassland form and function for the benefit of productivity and sustainable production; and (3) are related to the management of grassland either in interaction with animals or when considering the entire farming system.

A wider, maybe even different, view on grassland technology is needed, as we should also consider any type of thoroughly planned, structured and controlled strategic process in the coupled grass-animal organization that may not necessarily rely on sophisticated techniques and Information Technology (IT). Further, the technology in question need not to be directly embedded into the on-site grassland management practices. Instead, there are many technologies that can deliver knowledge, data and facilities from outside the field and farm, as will be described later.

In grassland systems, the past increase in above ground net primary productivity (ANPP), the improvement of forage quality and the associated enhancement in animal production per individual animal and per unit of land area have been made possible through: (1) improved knowledge of scientists, advisors and farmers regarding biophysical and metabolic processes; (2) structural re-organization of farms through intensification and specialization of production, as well as (3) effective implementation of and high investment in agricultural and biological technology. It is difficult to disentangle the contribution of each of these factors but it is likely that grassland profited less than arable land from these technological developments.

In view of future technological developments on managed grassland, the focus of the present paper will be on: (1) the local applicability and possible use of technological developments; and, (2) the ecological impact and economic benefit of new technologies on grassland. By necessity, we will make a distinction between the extensively managed rangeland and steppes and the intensively managed grassland in temperate climate, as there are fundamental differences in the type of challenges that these systems are facing. We will, however, later emphasize that the introduction of new technologies should not be limited to intensive systems alone. In fact, the broad spatial scales of rangeland, savannahs and steppes in the world, including marginal lands, favor the introduction of some types of technologies, such as remote sensing (RS), which have a high potential for enhancing environmental quality and the efficient use of resources.

The aim of this paper is: (1) to review recent developments in technology dedicated to grassland; (2) to give an overview of technologies that are essential in the present and future management of grassland systems; and (3) to identify constraints that limit the application of technologies for ecological or socio-economic reasons. The structure and scope of the present paper is different from earlier ones on a similar topic (Frame 1995; Peeters 2009).

Through the survey of international peer reviewed scientific articles, we identified areas of new developments in agriculture that are currently under-represented. First, there are the perspectives and constraints of precision agriculture and the associated equipment on grassland as a suite of high technology that aims at improving productivity and efficiency of resource use. Second, we identified recent developments in biotechnology to improve the interaction of plants with beneficial soil microorganisms as equally relevant. Plausibly, we consider the interaction of microbiology, agronomy and agricultural engineering. We also focus on highlighting important links between these disciplines and the additional value that these links will bring about.

Due to the complexity of the topic, we decided to mainly focus on permanent grassland and to a lesser extent on grass crops and their mixtures with legumes or other herbs as a component of rotations on arable land. We will not review the state of the art of technologies associated with the processing of biomass from grassland to produce renewable energy or other secondary products as this relates more to process engineering (Prochnow *et al.* 2009).

## The role of remote sensing and digital image processing in grassland science

Technologies used on grassland are either simple and easy to handle such as standard machinery for mowing and fertilizer applications, or require skills and long-term experiences. The implementation of remotely sensed information, either from satellites or airborne imagery, into the decision making process is an example of the latter. With RS technology, farmers are confronted with highly complex information that needs to be translated before implementation.

A definition of RS that is generally accepted has been published by Jensen (2007), it is "the art and science of acquiring information about an object without being in direct contact with the object". This also includes, in principle, close range sensing (often referred to as proximate sensing) because sensor technology is mostly similar. However, the term RS is mostly used in context with airborne or satellite borne detection of the earth surface. The application of RS on grassland vegetation is not restricted to grassland science but is useful for a wider range of disciplines in natural and environmental sciences, such as geography, geology and ecology. This is important since grassland science benefits considerably from the progress in RS that has been made in other fields.

Applications of RS in agriculture extend beyond the needs of the individual farmer and also include land use classification for regional surveys and decision making. However, mapping of grassland vegetation and detection of phenomena that are related to management at large spatial scales has also been performed in many regions of the world (Adam *et al.* 2010; Kurtz *et al.* 2010). Investigations on standing biomass and canopy characteristics of grassland such as soil cover (Zha *et al.* 2003) and biomass production (Maselli *et al.* 2013), sward height and floristic composition (Feilhauer *et al.* 2013) have successfully been applied at different scales and using various sensors. A study subjecting floristic composition to Non-metric Multidimensional Scaling NMS as related to spectral reflectance revealed that spatial distribution of diagnostic species in an area can very well be identified and mapped (Schmidtlein *et al.* 2007). The progress made with this approach lies in the availability of color coded ordination maps where each color indicates similar species composition and gradual differences among pixels represents shift from one plant community to another. These maps can directly be analysed through GIS and thus inform us on which environmental factors explain elements like grassland quality, and give us unprecedented information on how to improve this.

Nearly as important as the identification of grassland types is the detection of their temporal variation which is a result of the mutual interaction of management with local environment conditions. There is a common understanding that management effects can be extracted, since the environment at test sites can often be well described. For instance, the temporal variation of the Normalized Difference Vegetation Index (NDVI) (Schmidt and Karnieli 2000) used as a robust spectral indicator of greenness of vegetation and nitrogen content (Ramoelo *et al.* 2012), soil cover and leaf area index, allows the recognition of the start of the grazing season and the rotation among paddocks. At larger scales, this approach has already been tested and has been applied for years in a project in Australia known as "Pastures from Space" (Hill *et al.* 2004). However, the spatial dimension of grazed land in many regions of the world is, compared to Southern Australia, too small to allow the application of earlier generations of satellite imagery due to their coarse spatial resolution. With the launch of new satellites that provide imagery at high spatial resolution and revisit time such as RapidEye®, the detection of spatio-temporal patterns at scales close to that of field surveys is made possible. That way, RS on grassland provides very useful information on its traits. Similarly important is, however, that RS data are implemented in GIS containing synchronized ground level information and spatial metadata (Yu *et al.* 2010) that are fed to simulation models thus allowing predictions at close to real time based on up-to-date status of the vegetation.

We conclude that conventional methodology of identification of type and state of grassland vegetation through sampling, analyses and visual assessment can in principle be augmented and partly replaced by application of RS technology, either satellite based or at close range near the object. However, RS technology still suffers from methodical deficiencies (*e.g*. spatial versus radiometric resolution, cloud cover and number of observations available). With optical sensors that are fully dependent on the "limited" energy provided by the sun, a compromise between spatial and spectral resolution has to be made. Either pixel size is too small as to provide sufficient reflected solar energy so the signal to noise ratio is not good enough, or pixels are too large for detecting phenomena on grassland that require better spatial resolution. Further, insufficient revisiting time of satellites is another constraint to the detection of dynamics of growth patterns and defoliation regime on pastures and meadows as well as impact of climatic events and natural hazards that evolve rapidly during the growing season. In order to solve these problems, synergistic blending of multiple co-located images provided by two satellite sensors of different characteristics on the same target area have led to virtual maps that mitigate or transcend the individual limitations of each contributing dataset (Gao *et al.* 2006; Hilker *et al.* 2009; Walker *et al.* 2012). A comprehensive review on current state of the art in grassland vegetation detection by RS is presented by Schellberg *et al.* (2008).

The boundaries between RS and near range sensing applied in Precision Agriculture (PA) in the application of information technology in agriculture are fluent. Often, the technique is basically the same and the physics of energy (either provided by an active source, *e.g.* RADAR, or by the sun) interaction with the object are well known. Near ground spectral measurements with handheld radiometers at plot scale resulted in classification of fertilizer levels, water supply and management intensity on grassland (Chopping *et al.* 2003; Clevers *et al.* 2007; Clevers *et al.* 2008). Moreover, due to a much better spatial and temporal resolution achievable near the ground (a few meters or less above the canopy), a wider range of features can be detected. The application of sensors in PA strives for detecting these features for several reasons, e.g. identification of individual species (Gebhardt *et al.* 2006), size and shape of gaps, and coverage of organic fertilizer. The extraction of the features in question is carried out by quantitative digital image processing (DIP). The complexity of the features such as leaf color and shape, overlapping of leaves and tillers leading to shaded leaves and varying soil color (Himstedt *et al.* 2012) is the major constraint in the application of DIP on grassland as compared to arable land, where phenotypes are very similar and soil background is moderately uniform.

In spite of these challenges, it has been demonstrated that species identification is possible even on grassland. The effort required to develop image processing tools on grassland is justified by the need to identify species for the purpose of site specific weed control. Such examples are given by Gebhardt *et al.* (2006) and by Van Evert *et al.*(2009), who developed routines to identify broad-leaved dock (*Rumex obtusifolius L.*) including its spatial reference in the grassland field. Although the application of pesticides is rare in grassland as compared to arable land, highly competitive weed species require severe measures to avoid species invasion, with the premise to eliminate emerging populations as early as possible. In such cases, maps of weed distribution allow site-specific control with minimum effort of pesticides and minimum environmental harm. The technique to apply pesticides site-specifically has already been developed for arable land (Gerhards *et al.* 2012). Considerable effort has been made to identify plant species and their position in grass stands with the intention to apply herbicides only locally, using the right pesticide and the most efficient dose. These technological developments already indicate that a strong link exists between RS and precision agriculture. This will be developed in more detail in the following section.

## Importance of Precision Agriculture (PA) to improve efficiency in variable grassland landscapes

The increase in yield and quality of products harvested worldwide from arable land during the past decades is mainly driven by technological development (Hejcman and Kunzova 2010) including improvement of crop rotations, tillage practices, provisioning of high quality seed and sowing techniques, pesticide and fertilizer applications, and harvesting techniques. Most of these advanced technologies have not been applied on permanent grassland, but they can be well used on temporary and sown grassland embedded in crop rotations.

### *Definition of Precision Agriculture*

PA is an approach that can best be described as the application of information technology in agriculture in a wider sense (Cox 2002). PA has its origin in the efforts to adapt management to the spatial variability within fields in order to minimize any kind of input to agricultural fields and to improve the use efficiency of resources. This is why the term "site-specific management" is often used synonymously to PA.

Today, PA includes a wide range of applications that improves the control on any type of agricultural activity and serves the decision support in the production processes on farms. These applications are not only related to plant production itself but also to natural conservation, restoration, and protection as well as landscape planning. Further, precision livestock farming (PLF) has developed as a discipline. It can be defined as the management of livestock production using the principles and technology of process engineering. According to Wathes *et al.* (2008), "processes suitable for the PLF approach include animal growth, the output of milk and eggs, some endemic diseases, aspects of animal behavior, and the physical environment of a livestock building, such as its thermal micro-environment and emissions of gaseous pollutants such as ammonia". Especially on grassland farms, application of techniques in the field and in animal husbandry can well be combined, as it will be demonstrated.

### *Detecting field heterogeneity*

As the management of heterogeneity in the field is a primary objective of PA on grassland, the detection of that heterogeneity remains a major challenge. As described above, RS strongly supports the detection of such heterogeneity. However, some of the field properties can better be measured or estimated using specific sensors as published by Bailey *et al.*( 2001) and Mertens *et al.* (2008). Methodology can close the gap between traditional soil sampling and the application of sensors. Recently developed penetrometers allow spatial monitoring of soil properties automatically, apparent electromagnetic conductivity (EM38), water content and penetration resistance. For instance, Sun *et al.* (2013) have tested a similar device on permanent grassland and found linear negative relationships between yield and penetration resistance and non-linear positive relationships between yield and volumetric soil water content within a 1.4 hectare mowing pasture on temperate grassland. In contrast to arable land, these devices can only be applied in handheld mode and not be pulled by a truck like horizontal penetrometers. However, some of the mapped soil information is quite easy to obtain, such as soil bulk density, and can be of considerable value for decision-making on spatial arrangement of plots, grazing areas, fertilizer zones, set aside land and placement of feeding and water points. For instance, Sigua and Coleman (2009) reported a strong linear decline in penetration resistance with increasing distance from the feeding point on an old pasture. Compared to bulk density analyses, this procedure is easy and saves time and money.

With reference to the spatially explicit management of nutrients and soil fertility on grassland, rapid and time-saving PA procedures are needed. There is still no practically feasible solution available that allows the derivation of fertilizer maps in species rich grassland swards. The conversion of yield maps into nutrient extraction maps and their subsequent translation into application maps for chemical-synthetic and organic fertilizer still requires the nutrient analysis from harvested plant material. Further, grassland farmers generally fail to calculate the correct nutrient extraction and balances at plot and farm scale since yield information is missing. Yield mapping technology on-the-go may help to solve this problem, if rapid parallel plant analysis of nutrients and moisture (for instance based on NIRS) could be installed on harvesters. Prototypes exist, but problems still remain, such as the mismatch between the windrow taken up in relation to the location of plant growth, calibration of sensors in species rich swards and the provision of homogenous and well defined portions of plant material to the sensor.

A promising way of determining fertilizer application maps is that of direct scanning of the crop by optical sensors, either at close range (Radtke *et al.* 2010) or by RS (Ullah *et al.* 2012). Following current state of system developments, two sensors are most interesting. First, the so called N sensor (Agricon 2013) derives information on vitality of the crop from the red edge of the spectral signatures, *i.e.* the steep increase in reflected solar radiation from red to infrared wavebands. The authors are not aware of any published testing of this system on grassland, but there is no good argument why the principles of this system should not be applicable.

Second, on pastures, the problem of yield estimation is likely to be solved with the rapid pasture meter (Farmworks ®, http://www.farmworkssystems.co.nz). On-the-go readings of an optical sensor are converted into dry mass per unit area via regression equations derived from calibration. The readings are transmitted via Bluetooth to an on-board PDA which creates digital maps of dry mass of the paddock. This system has been developed to support grazing management based on the temporal change of the amount of residual biomass during downgrazing. Besides mechanical, other systems like ultrasonic sensors have been successfully used (Fricke *et al.* 2011).

Guided by the premise that PA should preferentially support sustainable grassland management, the following criteria should at least be considered in the decision on if and which PA technology is practical and advantageous: (1) expertise of the farmer and his farm workers and the perspective of getting them trained and educated; (2) willingness, personal ability and motivation to prove whether applying PA technology is an option to improve productivity and sustainability and upon decision to carefully plan the implementation of PA; (3) available capital and the readiness to assume risk; and (4) farm conditions, such as field and farm size, facilities and machinery that can be upgraded.

## The functional trait approach and its role in integrated grassland technology

In accordance with the initially presented meaning of technology in the present paper, a characterisation of grassland features is essential. Traditionally, grassland scientists strived for understanding the response of vegetation to environmental conditions and management, like species abundance, their requirements and their ecological indicator value (Ellenberg *et al.* 1991). In ecology, however, theories have been developed, and put into practice, that are based on morphological, physiological and phenological properties of plants, the so called plant functional traits (PFT), rather than on taxonomy. Extensive descriptions of the role of PFT are given by various authors: Diaz and Cabido 2001; Lavorel and Garnier 2002; Cornelissen *et al.* 2003; Garnier and Navas 2012. Many of these plant properties are related to functions like productivity and responses to changes in the environment or processes like photosynthetic activity, tissue turnover and exploration of resources such as light capture and nutrient uptake. For example, chlorophyll content in leaves is a good representation of the capacity of the leaf to absorb photosynthetic active radiation (PAR) and at the same time is strongly correlated with the intensity of light reflectance and absorption. Consequently, a relationship (although non-linear) exists between green leaf area and remotely sensed rate of PAR absorption, which has been published as early as in 1984 (Asrar *et al.* 1984).

Such linkages have at least two important implications for future technologies in grassland science. The first one is that, in functional ecology, recent developments indicate that the functional trait approach also allows the linking of plant optical types with their individual role in the ecosystem (Ustin and Gamon 2010). As some traits significantly influence reflectance in well-defined spectral regions, any group of plants exhibiting certain trait combinations (*e.g.* pigments, water content, cell wall density) can be seen as an optical type. Although the principle of this relationship is not complicated, this methodology requires a different way of measuring grassland vegetation, which is focusing on functional traits. It is the composition of morphological, physiological and phenological traits that determine not only the optical type but also the functions of these types in the ecosystem. The detection of plant functional traits by RS can be extended beyond what is currently done. Ustin and Gamon (2010) consider the reflectance spectra as the presentation of so-called end-members. These endmembers can, for instance, be the PFT of plants contributing to the reflectance spectrum of the canopy. Spectral mixture analysis (Adams and Adams 1984) compute the fractional composition and reflectance properties of these endmembers based on best-fit criteria. Changes in these fractions will lead to explainable changes in spectral reflectance. As such, the linking of functional ecology with RS allows us to look at grassland vegetation with a different perspective. It supports developing an advanced understanding of functional relationships between plant communities, enviro-nmental conditions and management. The overall challenge of future research will be to identify these optical types and relate their optically detectable trait combination to functions in the plant community.

The second implication is that, once form and function of grassland communities become detectable, RS will allow surveys of ecosystem properties, functions and services across a wider range of spatial and temporal scales. It is generally accepted that the quantification and mapping of supplies and demands of ecosystem services is essential to support decision-making, *e.g.* yield prediction, degradation and erosion surveys and monitoring of land use intensity. Some research has demonstrated that the direct or indirect assessment of ecosystem services by RS is already applicable (Malmstrom *et al.* 2009; Ayanu *et al.* 2012), but only with a soft approach based on empirics and statistics. Bringing together RS technologies with functional ecology will open up new vistas in that the spatial and temporal dimensions of ecosystem services will become detectable and, more importantly, the underlying processes and functions at the desired scales. A key question in interlinked research of RS with functional ecology is whether the attributes that we detect are of predictive value.

The spatially explicit reference of remotely sensed canopy PFT to soil properties, altitude and climate laid out in GIS (some of which are also detectable by RS) goes even one step further. It gives an example of truly integrated research and shows the way towards a functionally guided research on grassland that primarily follows the premise of linking and understanding mechanisms across all organization levels within the entire system. These levels will range from molecules, cells and organs to plants and canopies.

Here we propose this way as the “functional holistic approach” that aims at optimizing mathematical procedures which integrate functional relationships at different organization levels. According to similar attempts in “holistic functional medicine”, we view the system as a whole and not as a collection of its parts, because it functions as a whole and therefore cannot be fully understood if we look only at functionalities within its components. In conclusion, RS and GIS cannot only be seen as supporting technologies that provide vegetation detection and data processing tools. If we succeed in establishing and operationalizing a framework that makes full use of the interfaces and synergies that these technologies offer, the chain of causes and effects will be easier to understand and grassland science will develop a better potential in solving problems on grassland related to environment, economy and feed supply. In Figure 1, we propose such a framework and focus especially on the links among disciplines.

## Technological challenges in stimulating positive plant-microbe interactions

As demonstrated in the previous section, PA emerged from recent developments in information technology, new sensors, and agricultural techniques to support management decision and sustainability of production. However, modern PA directions go even towards the integration of principles of soil ecology, plant ecology (such as PFT) and pest/natural enemy behaviour (Rains *et al.* 2011). Whereas past PA developments have been mostly technology driven, the incorporation of biosciences is relatively new. Here we will focus on soil biology, in particular plant-microbe interactions, as related to growth processes and their implication for management decisions on permanent grassland. We will see that there are unexpected links between well-established high-value agricultural engineering and biotechnology on microorganisms. We will begin with an introduction to microbe-driven soil processes and their relevance to grassland quality, and then we will point out the current and future possibilities to better take advantage

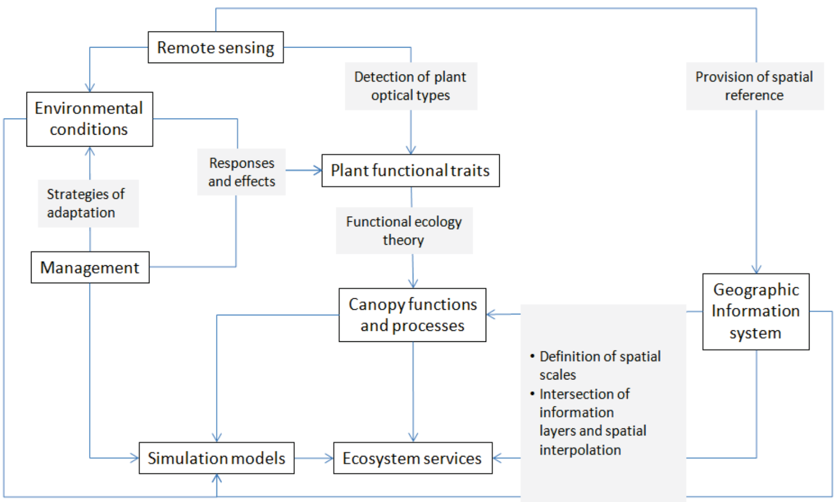


**Figure 1. A framework of a functional holistic approach of grassland science.**

of microbial services.

Plants interact with a plethora of soil microorganisms, spanning the continuum of positive (mutualistic) to negative (parasitic/pathogenic) effects on plant growth. On the growth-stimulating side of the spectrum, we find the major nutritional interactions with mycorrhizal fungi, among which arbuscular mycorrhizal fungi (AMF) are dominant in grasslands (Smith and Read 2008).We also find nitrogen-fixers such as rhizobia and, to a lesser extent, free living bacteria (Herridge *et al*. 2008). These organisms stimulate plant growth by a direct provision of growth-limiting resources such as nitrogen and phosphorus. Looser interactions such as those between plants and bacterial and fungal decomposers can also have a positive effect on plant growth by suppression of antagonistic microbes (Mendes *et al*. 2011) and increasing nutrient availability to plant roots or AMF hyphae (Bakker *et al*. 2012).

Increasing the reliance on beneficial microorganisms can be expected to result in a significant improvement in grassland quality. Direct improvement would include better nutritional quality of forage, but probably also higher productivity and soil quality. All grasses and legume species of significance in grassland are potentially colonized by AMF, and thus stimulation of their interaction will likely result in an increased improvement of plant nutrition (Lekberg & Koide, 2005). In contrast, colonization by rhizobia is restricted to the majority of legumes and one non-legume (*Parasponia andersonii*), which are the only species that can form the bacteria-containing root nodules responsible for N fixation. Apart from direct beneficial effects on plants, stimulating performance of these microorganisms can contribute to other services, such as soil carbon storage, which is important for mitigating climate change (Pachauri & Reisinger, 2007) and improving soil quality (Franzluebbers 2002). Evidence suggests that the potential of soils to store carbon is limited by nutrients, in particular N (Dieleman *et al*. 2012; Tian *et al*. 2012). Therefore, soil organisms that can stimulate N nutrition like rhizobia and AMF may be instrumental in soil carbon storage. For instance, stimulating the abundance of the legume red-clover (*Trifolium pratense*) has been shown to lead to increased soil N levels and soil carbon storage in grasslands (De Deyn *et al*. 2011).

For AMF, the relationship with soil carbon is harder to uncover because: (1) most plants engage in the symbiosis, thus complicating the establishment of a causal relationship, and (2) AMF do not increase total soil nutrient pools but only the fraction available to plants. Through increased plant assimilation and a qualitatively different soil carbon pool this is likely to stimulate soil carbon build-up and soil structure (Rillig & Mummey 2006; Verbruggen *et al*. 2013), although they may also stimulate plant litter decomposition which will partly negate the effect on soil carbon levels (Cheng *et al*. 2012).

### *Grassland management practices improving plant-microbe interactions*

With increasing knowledge on plant-microbe interactions, ways to shift them towards the positive side of the equation are becoming tangible. Soil microorganisms are generally found to be highly responsive to management regimes such as soil disturbance (*e.g.* tillage) and fertilization regime. The abundance of AMF decreases through tillage to a larger extent than other fungi (Schnoor *et al*. 2011), and they are found to respond strongly in abundance and species composition to fertilization (Verbruggen & Kiers 2010). Especially high phosphorus concentrations are known to suppress AMF abundance and potential species richness (Smith and Read 2008; Verbruggen *et al.* 2012). Evidence suggests that this is caused by a reduced reliance of plants on AMF for phosphorus, which is concomitantly dependent on N availability such that a reduced N:P ratio can suppress AMF (Johnson 2010). Thus, apart from a conservative fertilization regime, also controlling and optimizing relative proportions of nutrients can contribute to stimulation of symbiont abundance. For rhizobia, both tillage and fertilization regime have also been identified as key factors controlling their abundance, in particular through effects on soil nitrate concentrations reducing their abundance (Peoples *et al*. 2009). This further indicates that precision fertilization schemes can create a stable and functional AMF and rhizobia population, in combination with an absent or modest tillage regime. If this is achieved, N fixation will increase plant N:P ratio, further stimulating AMF abundance, and thus potentially producing a state of increased reliance on and status of soil microbial functioning.

Another important management practice that can significantly influence beneficial soil microbes is grazing intensity. Moderate to high grazing intensities (assessed by defoliation of plants) can in principle stimulate rhizobial N fixation to some extent (Menneer *et al*. 2003). For AMF, it has been found that grazing can both increase (Grigera & Oesterheld 2004) and decrease (Wearn and Gange 2007) their root colonization. However, soil compaction can also decrease AMF root colonization and AMF-mediated plant nutrition (Nadian *et al*. 1997) therefore, high abundance of feedstock may generally have negative effects.

### *Grassland diversity*

In order to enhance benefit from microbial functions increasing plant diversity could likely be an important tool. This is obvious for experiments where including legumes such as *Trifolium* will contribute to N fixation as well as plant and soil quality, but this of course is less so with merely increasing the diversity of grass species. However, even increasing diversity within plant functional groups can have positive effects. Microbial functions such as nutrient mineralization are generally positively influenced by plant diversity, and this even extends to $C_3$ grass diversity (*e.g.* Zak *et al*. 2003). Also, it is commonly found that AMF abundance is strongly and positively associated with plant diversity in grassland systems (Bingham & Biondini, 2009). Thus increasing plant diversity can also be expected to stimulate these beneficial fungi. However, these potential positive properties of biodiversity need time to take effect and are therefore not always apparent in the short term. For soil biotic activity (including microbial biomass production), plant diversity has been found to have a strong positive influence, independent of plant functional group diversity, but only in the longer term (>4 years) (Eisenhauer *et al*. 2011). At the same experimental site, with a focus on a smaller time window from the installation of the plant diversity gradient (< 4 years), only very modest effects were found (Habekost *et al*. 2008).

Potentially, some of these positive effects can be extrapolated to within-species genetic diversity. In theory, and with some empirical support (Hajjar *et al*. 2008), this should allow for better responses of the plant population to local soil environment and temporal variation. There is already strong evidence that crop genetic diversity can reduce yield losses due to fungal pathogens (Zhu *et al*. 2000), however, whether beneficial microorganisms respond to crop diversity, and in what direction, is not fully resolved while a promising avenue of inquiry (*e.g.* Verbruggen and Kiers 2010).

### *The importance of biotechnology in plant-microbe interaction*

Recent research has unveiled most of the major plant regulatory pathways responsible for nodule formation and downstream interactions with rhizobia ( Geurts *et al*. 2012). This opens up new possibilities to explore biotechnology-based opportunities to expand host-breadth of rhizobia-interactions to families currently devoid of nodule-forming members. In particular, research in the only known non-legume that can be colonized by N-fixing rhizobia, *Parasponia andersonii*, has revealed that this nodulation has evolved independently and may in principle also be possible in other plant families (Op den Camp *et al*. 2011). Moreover, because AMF and rhizobia share a remarkable similarity in genetic pathways leading to the plant-symbiont interactions, many of the genetic elements needed for rhizobial colonization are already in place in mycorrhizal plants (Geurts *et al*. 2012). Although promising, before transferring this trait to non-nodulating plant families, there are years of fundamental research ahead. In this respect, it has also been proposed that another N-fixing symbiosis termed "Actinorrhiza" (between plants and N-fixing bacteria of the genus *Frankia*), may even be a better candidate for genetic engineering research, as this interaction is less specialized, therefore less complex, and thus potentially easier to transfer (Markmann and Parniske 2009).

The plant genetic pathways of mycorrhiza formation and function are also getting resolved at a fast pace (Oldroyd *et al*. 2009). This understanding lays a foundation for future improvements of plant-AMF interactions, *e.g.* through genetic modification or traditional plant breeding . This might enable screening of novel plant varieties for subtle changes in genes required for optimal benefit from AMF, such as those responsible for pre-symbiotic recognition (Gough and Cullimore 2011) and efficient nutrient exchange (Javot *et al*. 2011). On the fungal side, less is known on genetic pathways that define the perceived benefit of the plant-AMF interaction (Lanfranco and Young 2012). However, one first step has been made in the genetic improvement of these fungi, as recombination has been shown to be possible for this tentatively "asexual" phylum (Colard *et al*. 2011), allowing for producing novel varieties of AMF and selecting for preferred strains (Sanders 2010).

### *Breeding effects on symbiotic interactions*

It has been argued that the common practice of breeding plants by testing their performance in sites with high nutrient levels, and the confounding lack of reliance on symbiotic microorganisms (and thus relatively higher costs of symbiosis than in more marginal but common habitat), might lead to loss of some symbiotic traits. Indeed, for soybean it has been shown that older cultivars rely more on nitrogen-fixing rhizobia than newer cultivars (Kiers *et al*. 2007). Likewise, some wheat varieties appear to have become less dependent on AMF through time (Sawers *et al*. 2008), and the same has been observed in breadfruit (Xing *et al*. 2012). However, a recent meta-analysis across studies published over a period of 20 years concluded the opposite: the authors concluded that responsiveness to AMF has in fact increased with the year since release (Lehmann *et al*. 2012). Thus, even though this does not seem to follow a readily generalizable pattern, taking plant-microbe interactions explicitly into account during breeding efforts has a high potential for increasing crop nutrition, defense against pathogens (Bakker *et al*. 2012) and effect on mycorrhizal symbionts (Ellouze *et al*. 2012).

### *Plant-microbe interactions in grassland technology*

In the previous section we explored multiple ways to improve service provision by beneficial soil microbes. However, the question remains how can this knowledge be used to inform current grassland farmers? For one, knowing the microbial feedback loops that are likely to be responsible for aspects of plant productivity and quality, can lead to more integrated management. If we can follow PFT in a low-cost manner, *e.g.* by RS, we can follow particular interventions that feedback on the microbial communities (such as sowing a mixture with high inter- or intra-specific diversity) over a longer time than currently is common. As indicated before, such longer-term monitoring is necessary to distinguish between immediate effects that may be smaller or even opposite to more long-term effects. However, we do acknowledge that the technological improvements we propose here mainly fuel the possibility of increasing our knowledge on efficiency of measures to stimulate soil- microbial service provision; they are still in the developmental phase.

## The use of simulation models

Integrating data and processes in different components and at different spatial and temporal scales of the grassland system is a major goal of simulation models. A large number of bio-physical models have been developed since the 1970s and have improved our understanding of plant and soil processes and their responses and feedbacks to human activities (McCall and Bishop-Hurley 2003; Trnka *et al.* 2006). However, some were restricted to pure stands of grasses such as *Lolium perenne* and thus are too unrealistic for their extrapolation to permanent grassland. Thereby, dynamic process-based models including the farm-scale level have received much attention (van Ittersum *et al.* 2008; Martin *et al.* 2012). Compared to the simulation of growth dynamics of arable crops in response to management and environment, the same simulation on grassland is challenging due to: (1) unpredictable species composition during continuous alteration; (2) multiple above and below ground interspecific competition; (3) disparate phenological development of species; and (4) the intricate multiple effects of sward conditions before defoliation on biomass accumulation and floristic composition during regrowth. It still remains a general problem that diversity within grassland swards is difficult to translate into robust mathematical algorithms. Recent model developments therefore concentrate on the functional composition rather than on species composition of the plant community. Following this approach, Duru *et al.* (2009) developed a grassland model in which plant species were grouped in plant functional types and where species of these types were assumed to respond similarly to environment and management. That way, the prediction of dry matter accumulation rate has been made possible, even when management practices were altered and when composition of plant functional types differed.

Apart from dynamic growth models, N cycling models have been developed to integrate the processes such as forage intake by ruminants, excretion, volatilization, atmospheric deposition and leaching (Yue *et al.* 2012). The coupling of N cycling models with dynamic growth model is most promising (Hutchings *et al.* 2007). However, the complexity of the dairy production system with its biotic and abiotic elements, such as animals, grassland, crops, soil and climate influencing each other in space and time, is not well understood. An important issue in this respect is the spatial and temporal variability of the different processes involved in N cycling, frequently associated with an asynchrony and a spatial mismatch of N supply and demand, leading to so-called “hotspots” and “hot moments” (Groffman *et al.* 2009).

It has been shown that models can be helpful tools in capturing the above mentioned complexity and in supporting decision making (Barrett *et al.* 2005). However, it is not yet well understood how the spatio-temporal variability in the turnover rates in plants, animals and soil has to be considered in models in order to capture the complex process interactions in the overall N cycling on farms. Existing models have used coarse time steps of a month or a year (Brown *et al.* 2005; Groot *et al.* 2003).

An important step forward in the integration of expert knowledge and secondary information into models has been accomplished with decision support systems (DSS). DSS are complex tools that collect and analyze data supporting decision making and development of strategies. As one example of a successful application, NGAUGE (Brown *et al.* 2005) simulates the flow of N on farms and works out recommendations for policy makers and researchers by taking into account optimization procedures that reduce environmental impact while maximizing N use efficiency.

## Research perspectives

In a recent publication on redirecting technology on farms, Rains *et al.* (2011) pointed especially to the potential of new sensors for early detection of stress and diseases. They propose to use these sensors in a more holistic and dynamic way following a management concept that strictly respects the rules of sustainable agriculture. In contrast, PA is mainly technology-driven instead of on-farm philosophy. We, as researchers, are fascinated by innovative technologies that are provided by the industry, and we almost immediately realize the potential that these technologies have for the development of highly productive and labor-saving cropping and farming systems. However, criticism is justified in asking to which extent PA actually contributes to the efficient use of resources, improved production and reduction of side effects; the answers to which are not fully understood yet, especially with respect to drawbacks and tradeoffs. Furthermore, the authors are not aware of any published journal article on economic return of investments into PA on grassland although it is very relevant since PA technology can be considered expensive compared to other technology already existing on traditional farms.

In general on grassland, farm technology is less crucial than on arable land as far as production is concerned. This is based on at least three facts: (1) the limitation in management measures to cutting, grazing and fertilization of the sward and subsequent harvesting; (2) the non-invoking of techniques that is indispensable in arable crops, such as tillage and the control of pests and diseases; and (3) the fact that only one type of crop is to be managed, thus allowing a very specific required technique. Of course, on temporary grassland that is integrated into a crop rotation, the range of potential applications increases and so does the effort to arrive at a decision. Therefore, we have primarily reviewed relatively low-cost large-scale applications such as RS and coarse-scale modeling that could be easily modified for application on grassland.

As for the more labour intensive technologies such as breeding new varieties (and biotechnology) and highly precise on site measurements linking soil physical properties, PFT, microbiota, and remotely sensed information, we would recommend to integrate these in small-scale research trials as we do not yet know how these interactions can be scaled up to field-level processes and thus the potential gain. Another recommendation to optimize gains in comparison to costs is to adapt technology already used in high-yielding agriculture, rather than de-novo development of technology specifically for permanent grasslands.

## Putting technological development into practice

In the future, it will remain a permanent challenge to put science into practice especially as the rate of technological development will further increase. From a teachers’ perspective, education at universities has to keep up with transforming the curricula as well as providing access to modern laboratories, computer labs, technical equipment and field facilities and machinery. Especially the handling and interpretation of remotely sensed data on grassland vegetation requires teaching of underlying physical processes and biological drivers, which is more often conducted in cartography and geography than in agricultural sciences. The same holds for biotechnology, where grassland science benefits from education in biosciences.

Direct knowledge transfer into practical grassland agriculture requires an approach that should be mainly supported by agricultural schools and advisory services. Seelan *et al.* (2003) presents a nice example of how training, data delivery and application developments can be integrated in order to provide farmers with management tools derived from RS technologies. Also, sensitive guidance and skilled education will be needed to stimulate farmers to get involved in promising technological developments, as the time investment in getting familiar with new technologies may seem burdensome in the short-term to farmers regardless of later pay-offs.

As has been shown in previous sections, agricultural technologies not only include agricultural techniques in engineering but also newly developed laboratory methodology (PFT measurements, biotechnology) that allow to better understand and manipulate biotic and abiotic processes on grassland. Some of these technologies are directly relevant for practical decisions on farms, such as stimulation of rhizobia and AMF through balanced fertilizer application and defoliation regime, selection of (a variety of) cultivars or targeted removal of weeds, whereas other technological progress is of assistance in improving our understanding of biological, physical and chemical relations among plants and beneficial microorganisms as well as with the abiotic environment.

A good example of how these developments serve sustainable grassland production is the current trend towards low-cost systems of dairy production, that continue to be perfected mainly in Australia, New Zealand, Switzerland and Ireland (Thomet *et al.* 2011), and that are considered beneficial mainly due to lower environmental impairment and better animal health. The lower the management intensity of such a system, the higher the reliance for success will be on successful management of natural plant-soil and plant-animal interactions, and thus the need to maintain this service by modest fertilizer application and direct or indirect manipulation of soil biota. Consequently, the importance of knowledge on the impact of microorganisms on the functioning of the entire system is evident, and although technological input is comparatively low, such systems represent ambitious technological progression and education. Converting this technological progress into practice requires in-depth system knowledge and thinking rather than know-how to guide high-tech machinery.

Grassland scientists are confronted with an enormous knowledge hub beyond their core discipline and primary education which is driven mainly by information and biological technology. This makes high demands on them because of permanent upgrading of skills and sustained communication with other disciplines involved. Whatever decisions on introduction and upgrading of technology have to be made on the farm, the question of applicability and benefit remains central. In view of the increasing economic pressure on dairy and meat production on grassland, only those applications are acceptable that convincingly reduce production costs and reduce the risk of lower net income.

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