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The elusive role of soil quality in nutrient cycling: a review

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Abstract

Cycling of nutrients, including nitrogen and phosphorus, is one of the ecosystem services we expect agricultural soils to deliver. Nutrient cycling incorporates the reuse of agricultural, industrial and municipal organic residues that, misleadingly, are often referred to as 'wastes'. The present review disentangles the processes underlying the cycling of nutrients to better understand which soil properties determine the performance of that function. Four processes are identified (i) the capacity to receive nutrients, (ii) the capacity to make and keep nutrients available to crops, (iii) the capacity to support the uptake of nutrients by crops and (iv) the capacity to support their successful removal in harvested crop. Soil properties matter but it is imperative that, as constituents of 'soil quality', they should be evaluated in the context of management options and climate and not as ends in their own right. The effect of a soil property may vary depending on the prevailing climatic and hydrologic conditions and on other soil properties. We recognize that individual soil properties may be enhancing one of the processes underlying the cycling of nutrients but simultaneously weakening others. Competing demands on soil properties are even more obvious when considering other soil functions such as primary production, purification and flow regulation of water, climate modification and habitat provision, as shown by examples. Consequently, evaluations of soil properties and management actions need to be site-specific, taking account of local aspects of their suitability and potential challenges.

Keywords: Ecosystem service, nitrogen, phosphorus, nutrient cycling, residue, soil quality

Introduction

Human existence relies on diverse soil resources, and those affecting nutrient cycles are particularly relevant (Amundson *et al*., 2015). Limited natural availability of nitrogen (N) and phosphorus (P) in agroecosystems has been tackled by manufactured fertiliser inputs that are greatly dependent on energy (N) or mining (P) (Bouwman *et al*., 2013; Bodirsky *et al*., 2014). Anthropogenic activities dominate the global cycle of N and P (Delgado & Scalenghe, 2008; Bouwman *et al*., 2013). Losses of N and P from the systems, in which we produce, process and consume crops, have a negative effect on human health and the quality of ecosystems. In addition, these systems contribute to a continuous depletion of finite resources (Correll, 1998; Cordell *et al*., 2009; Erisman *et al*., 2011; Withers *et al*., 2015).

In this study, we use the word 'cycling' to refer to the circular movement of plant nutrients, particularly N and P, from field soils to consumers and back again including. Adoption of this concept of a circular economy can reduce losses, rates of depletion (European Union, 2015) and reliance on scarce resources (European Union, 2014). Cycling includes the recovery and reuse of nutrients in organic residues. However in Europe, large quantities of the nutrients in livestock manures, sewage sludge and food chain waste are not recovered for agricultural use, representing over 40% of the amounts of N and P currently used in the form of mineral fertilizers (Buckwell & Nadeu, 2016). Despite the considerable scope for better utilization, losses of nutrients are to some extent inevitable, in particular those for reactive N (Bodirsky *et al*., 2014). The sustainability of agricultural production therefore depends on regular use of

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supplements. This supplementation not only relates to inputs of N via either biological fixation or mineral fertilizer (Schröder, 2014) but also, where needed, to the application of amendments, such as lime. Supplements can also be instrumental in the optimal utilization of nutrients in residues. For example, use of fertilizer N can reduce the soil P surplus associated with the use of organic residues, when supplementary N helps to meet crop requirements and prevents nutrient deficiency, thereby leading to better growth and resource use (Spiegel *et al.*, 2010). Conversely, the nutrients in organic residues themselves, including micronutrients, can improve the utilization of mineral fertilizer N (Graham, 2008; Schröder & Sörensen, 2011).

Cycling of nutrients relies on the quality of agricultural soils, either directly through their capacity to receive nutrients and to convert them into or keep them in forms that are available to crops, or indirectly by governing the productivity and harvestability of crops and thereby the effective capture of nutrients from soils (Giller *et al.*, 1997; Karlen *et al.*, 2001; Brussaard *et al.*, 2007; Harris *et al.*, 2011; Keesstra *et al.*, 2016). The National Resource Conservation Service (NRCS) of the USA and the Soil Science Society of America (SSSA) defined soil quality as ‘the capacity of a specific kind of soil to function within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation’ (Mausbach & Tugel, 1995; Karlen *et al.*, 1997). The concept of soil quality is regularly criticized for several reasons: (i) it can be biased towards crop production, neglecting other soil functions, (ii) it may be biased towards organic agriculture, ignoring trade-offs in extensive forms of agriculture, (iii) the comprehensive and compounded ratings (‘indices’) are not always informative about required management actions, (iv) ‘more’ (i.e. a higher soil quality rating) is not always ‘better’, (v) the interpretation of proposed indicators or their values for function performance are not always clear and (vi) it insufficiently acknowledges that ratings lose justification if the appreciation of soil properties (‘S’) becomes too detached from the environmental aspects (‘E’, i.e. climate, weather, slope) and management options (‘M’), whereas it is the S × E × M interaction that is critical for the eventual function performance (Letey *et al.*, 2003; Loveland & Webb, 2003; Sojka *et al.*, 2003). In the context of sustainable food production, Schulte *et al.* (2014) defined soil quality as the capacity to sustain primary production, to purify and regulate water, to reduce and regulate the emission of greenhouse gases, to sustain biodiversity by providing habitat and to support the cycling of nutrients. Their concept has been further elaborated by Coyle *et al.* (2016) and in the European Horizon 2020 project LANDMARK (Schulte *et al.*, 2015). Each of the five main soil functions, defined by Schulte *et al.* (2014) and identified as ‘ecosystem services’ (cf. CICES, 2013) interacts with the other four. Listing and assessing separate functions acknowledges that soils are multifunctional and helps to identify the underlying determinants of each function and reveals trade-offs and synergies, as opposed to a single endpoint, such as soil quality, soil health or soil fertility. Schulte *et al.* (2015) argued that in addition to other criticisms the NRCS/SSSA definition also lacks the recognition that soil quality requirements should not be seen outside the context of societal demands for each soil function, demands which are not fixed in time and space. These criticisms indicate the need for a better practical application of the soil quality concept that starts with an in-depth understanding of the relationship between soil properties and each function. This study takes nutrient cycling in agriculture as the point of departure, disentangles the processes underlying effective nutrient cycling, and attempts to identify how soil quality and nutrient cycling are related and affect other functions.

Origin and fate of available nutrients

Figure 1 shows the generic response of a given crop in terms of the assimilation of nutrients after their application to soil. It can be helpful for understanding which soil properties determine the recovery of nutrients from soils and the complementary losses. Three features of this figure demand attention: (i) the inability of a crop to recover nutrients without at least some loss, (ii) the diminishing efficiency in the use of nutrients at increased application rates and (iii) the left-hand side of the figure. The latter refers to a part of the response that remains hidden in field experiments; that nutrients are harvested even from unfertilized control plots. The intercept on the *X*-axis reflects the amount of nutrients potentially taken up from, seemingly, free resources. These resources can be deemed truly free if they originate from natural processes such as weathering of soil particles, free-living N fixing micro-organisms or N-compounds formed by lightning. However, one cannot consider these nutrients free and durable if they are provided by reserves that have been built up, deliberately or not, through agricultural management, or derived from crop residues, organic manures or fertilizers applied in previous years (Schröder *et al.*, 2007). Nor are they free, if they are fixed from the air by symbiotic N fixers (e.g. Rhizobium associated with clovers) in return for photosynthesized carbohydrates, or if they are simply available due to an excessive use of nutrients outside the study area. Examples of the latter are ammonia-N deposited in regions with a large livestock density (e.g. Lekkerkerk, 1998) or the use of irrigation water containing large concentrations of leached N (e.g. Shapiro, 1999). As such, the value of the intercept is not informative about the intrinsic ‘soil quality’ *per se*, as it may simply reflect the amount of nutrients that have been applied outside the spatial or temporal system boundaries.

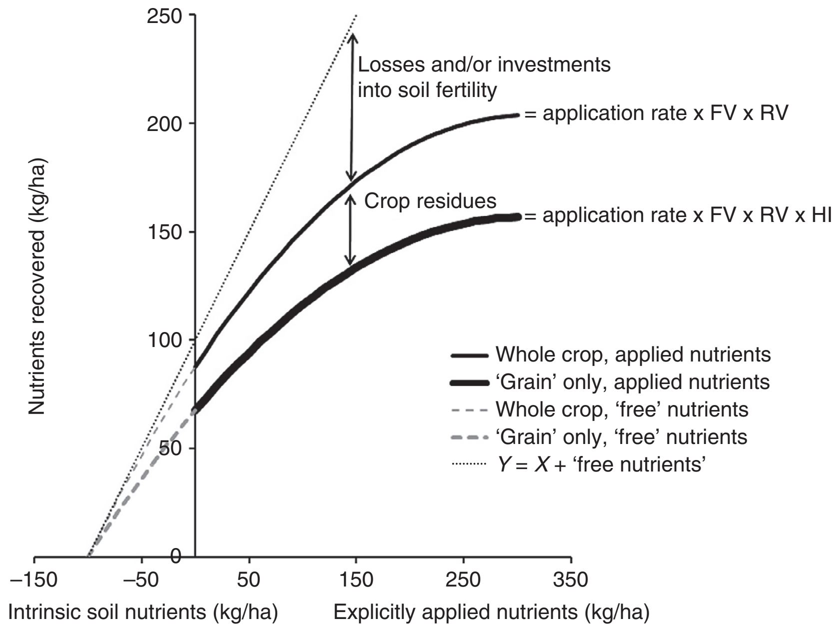

Figure 1 The nutrient uptake response of a crop (consult text for details).

For a given crop type, the slope of the nutrient uptake curve for the whole crop in Figure 1 is affected by the fertilizer value (FV) of each separate nutrient input source, by the crop recovery value (RV) of each nutrient input source once it has become plant available and by the harvest index (HI), which is the extent to which nutrients that have been recovered by the crop and are eventually allocated to harvested parts instead of crop residues. The total amount of nutrients taken up by a crop (NU, kg/ha/yr) then equals the sum–product of the nutrient input rates (NI, kg/ha/yr), their input type-specific FV (kg/kg) and the crop type-specific RV (kg/kg). The total amount of a nutrients harvested (NH, kg/ha/yr) equals NU × the crop type-specific HI (kg/kg). The total amount of nutrients that is lost and/or invested in soil fertility (Nloss, kg/ha/yr) equals NI – NH.

Note that FVs, RVs and HIs for a given crop may differ across nutrient sources, due to their chemistry and their sensitivities to E, M and, indeed, to S. Nutrient use efficiency (NUE) is generally defined as the ratio of the amount of recovered nutrients (*Y*-axis of Figure 1 minus the intercept, i.e. those additionally recovered) to the amount of applied nutrients (right-hand side of *X*-axis of Figure 1, so excluding the intrinsically supplied nutrients). Note that NUE decreases when increasing the nutrient application rate, regardless of the soil type. The eventual position and shape of the curve is, however, very much climate-dependent and soil-specific. Without a thorough analysis, it is therefore difficult to conclude whether an observed difference in NUE between systems (e.g. conventional versus organic) is merely the result of a difference in the nature of nutrient sources or the application rate and nutrient supplies built-up in the past (i.e. M-related), weather-related (i.e. E-related) or the result of truly soil-related differences in FV, RV and HI.

Before addressing the properties determining FV, RV and HI, it must be emphasized that the capacity of a soil to cycle nutrients must above all be judged on the basis of its capacity to *recycle* the nutrients from organic residues, often misleadingly referred to as 'wastes'. These 'wastes' are an inevitable by-product of the production, processing and consumption of crops (Schröder, 2014). They can serve as a resource for further agricultural production and include crop residues, livestock manures, digestates, biosolids, slaughter house wastes, and composts. In this case, the role of soil quality needs to be evaluated from the perspective of capability to recycle such residues.

Steps involved in nutrient cycling

The capacity of soil to cycle nutrients is a series of consecutive steps. These steps are (i) the capacity of a soil to receive and retain nutrients, the 'accommodation value' (AV), (ii) the capacity of a soil to make and to keep nutrients available for crop uptake, that is to ascertain the FV of the applied residue, (iii) the capacity of a soil to facilitate the recovery of plant-available nutrients, the RV and, finally, (iv) the capacity of a soil to support the successful collection and export of produce containing a portion, defined by the HI, of the nutrients acquired by the crop to a subsequent processor or consumer. Obviously, each step is not only affected by soil properties but also by climatic conditions and management options, which determine the impact of soil properties. In turn, soil properties affect the impact of weather and may influence the availability of management options.

Accommodation value

Residues rarely contain N and P, or any other nutrient, in ratios that crops need to cover their nutrient demand. Many residues have very low N-to-P ratios relative to crop requirements, indicating that P will accumulate in the soil and may eventually be lost to the environment, in situations where N requirements are provided by residues alone (Schröder & Sörensen, 2011). In general, nutrient cycling cannot be considered sustainable if more nutrients are applied than the amounts that crops can use according to their yield potential in the particular environment. This also illustrates that function performance is not merely determined by soil properties. Several studies have indicated that yield potential is dominated by climate conditions, regardless of soil properties (Boogaard *et al*., 2013; Tóth *et al*., 2013; Zavattaro *et al*., 2015). Obviously, climate impacts the nutrient cycling potential in terms of the AV. Soil properties, such as organic matter, texture and rooting depth, have a modifying effect on the impact of climate. The use of organic residues may not only be restricted by potential yields but also by the concentration of contaminants in them, such as arsenic, heavy metals, pharmaceutical residues, organic pollutants, pathogenic microorganisms and phytotoxic compounds (McGrath *et al*., 1994; Erhardt & Pruess, 2001; Motoyama *et al*., 2011; Peyton *et al*., 2016). Soils differ in their capacity to cope with these types of constraints, and therefore, soil quality also affects this aspect of the AV. Consequently, differences between soils in terms of this aspect of the AV are reflected in regulations (Spinosa, 2001). Many organic residues are relatively bulky and heavy due to their high water content. In these cases, their application can be difficult if the accessibility of a field is restricted by a lack of machinery bearing capacity (Schulte *et al*., 2012). The AV of poorly drained soils with shallow water tables may be reduced due to their relatively low nutrient attenuation capacity in the surface horizons. Soils may also have a relatively low AV where the composition of the organic residue requires incorporation into the soil to reduce the volatilization of ammonia-N, but where soil properties, climate or management make this impractical. This situation can exist where fields are stony, too steep, or where they lack workability due to seasonal droughts. The presence of soilborne organisms can have a positive effect on AV of soils via improved drainage or decontamination. Figure 2 gives an overview of attributes underlying the AV.

Fertilizer value

Nutrients in organic residues are generally partly present in an organic form and therefore need to undergo mineralization before plant roots can take up the nutrients. However, the mineralization dynamics do not always match crop demand, and this may contribute to losses. The inherent composition of residues can also stimulate loss processes such as the denitrification of nitrate-N and the volatilization of ammonia-N. Denitrification is stimulated in the presence of reactive carbon, including carbon in the residues themselves, and a small oxygen concentration in the soil (Heinen, 2006). Ammonia losses are most likely where alkaline residues are applied, such as digestates or human and livestock urine (e.g. Huijsmans *et al*., 2016). The capacity of soils to retain nutrients is also a crucial factor affecting the FV of residues and fertilizers. This retention is related to Fe, Al and Ca compounds in the case of organic and inorganic P and to the cation exchange capacity in the case of ammonium or potassium (K). Retention involves reduced losses to water and air but may on the other hand diminish the availability to crops.

As a consequence of the above processes, the FV of organic residues is, at least initially, smaller and more variable than that of industrially manufactured mineral fertilizers. The eventual FV depends on the ratio and nature of mineral and organic constituents (Schröder, 2005; Bhogal *et al*., 2015), on the method used for residue application (affecting the risks of ammonium and nitrate losses (e.g. Huijsmans *et al*., 2016)), on the climate-dependent length of the growing season (determining the extent to which mineralization patterns lag behind the crop uptake patterns), on weather conditions and on the application history (Schröder *et al*., 2007). That history determines to which extent farmers should account for the accumulated residual effects of applications in preceding years. Soil properties play an important role in many of the above processes. Texture, organic matter content and other factors determining the hydrology of the field and affect mineralization via the effects of soil moisture and temperature on microbial activity (Yue Li *et al*., 2014). In addition, clay content and pore size distribution play a role in the protection of organic matter against microbial degradation (Hassink *et al*., 1993; Lehtinen *et al*., 2014; McDonald *et al*., 2014).

Extreme pH values, related to acidity or sodicity, and shallow water tables (limiting oxygen transport) can hamper the decomposition of organic material by soil organisms, which leads to increased nutrient storage in organic matter, wet peat soils being a typical example. It is obvious that the presence of soil organisms interferes with nutrient cycling and can help crops to better recover nutrients. Conversely, it has also been shown that there can be competition for nutrients between soil organisms and crops (Kuzyakoc & Xu, 2013) and that the recovery of nutrients from organic residues can be increased by suppressing rather than by stimulating specific groups of soil organisms, such as urea hydrolysers or ammonium nitrifiers (Edmeades, 2004; Ruser & Schulz, 2015).

Stimulating soil biota may carry a price. First of all, soil organisms need to be fed if they are to be sustained,

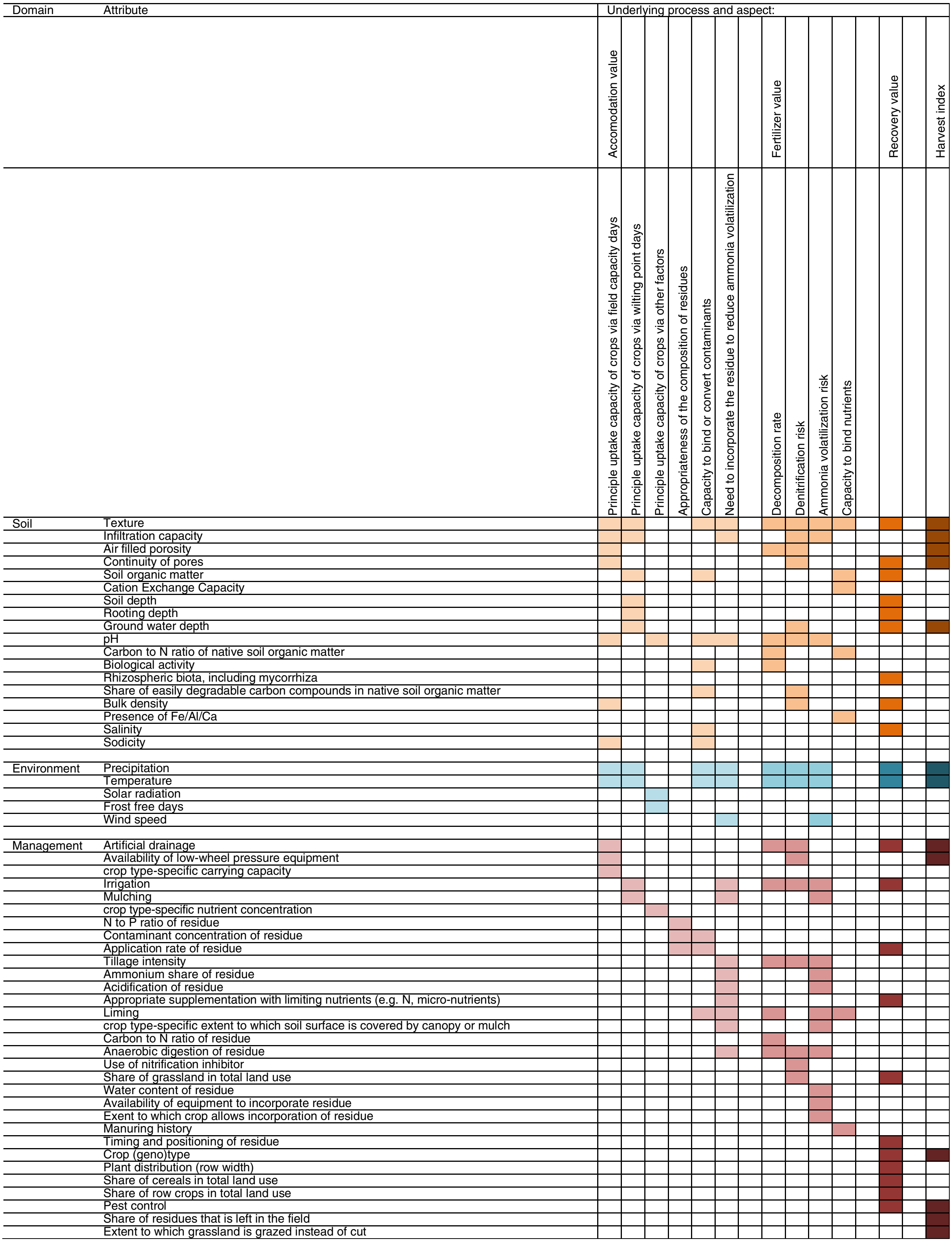

Figure 2 Attributes underlying the soil capacity to receive nutrients in the form of residues (AV), their fertilizer value (FV), the recovery of the plant-available nutrients by crops (RV) and the harvest index of nutrients recovered by crops (HI.)

implying that a part of the crop or growing season, which could have been dedicated to outputs for human use, needs to be sacrificed. Moreover, if soil biota has to be protected at any price, practices with a proven contribution to the FV of residues, such as the injection of livestock slurries, would have to be reconsidered (Huijsmans *et al.*, 2016). In conclusion, successful nutrient cycling has no simple proportional positive relationship with the presence of soil biota or mineralization. We will elaborate on this below. Figure 2 gives an overview of attributes underlying FV.

Recovery value

Reports on nutrient recoveries often refer to the fraction of applied nutrients that is harvested in addition to the amount harvested in a crop that has not received fertilizer (e.g. Schröder, 2005). This definition of recovery equates to the product of FV, RV and HI. Rather than how we defined it previously, in this approach RV simply pertains to the capacity of a crop to recover the nutrients that have become available as a consequence of the FV of the residue. From our concept, RV is a function of crop properties (root length density distributions and mobilization mechanisms of roots in time and space), the vertical and horizontal positioning of nutrients in the soil (De Willigen & Van Noordwijk, 1987; Lynch, 2007; Schröder *et al.*, 2015) and soil-related factors affecting the RV. These soil-related factors are basically the same as those governing the accessibility and workability of a field (see section on Accommodation Value) as they may determine the time lag between suitable spreading windows (e.g. on stubbles of preceding crops in late summer) and the establishment of a vigorously growing crop with large nutrient requirements (e.g. in the subsequent spring), and the accessibility of the pedon by plant roots, with or without cooperation with rhizosphere microorganisms. Implications of the accessibility of a pedon were demonstrated by Johnston & Dawson (2010), who showed that the soil structure mediated by organic matter rather than the material itself that improves the availability of P to crops and reduces the need for fertilizer P. Douglas & Crawford (1998) demonstrated how soil compaction of grassland negatively affects the recovery of intrinsically available and applied N. Likewise, change of soil pH also affects the RV together with other soil properties (Bákonyi *et al.*, 2010). Figure 2 gives an overview of attributes underlying RVs.

Harvest index

Nutrient cycling is not assured only by the effective AV and the uptake of nutrients in crops (FV and RV); it also requires effective harvesting and export of crops and their nutrient content for subsequent use by processors or consumers within and beyond a farm. A proportion of the nutrients ends up in non-harvested plant residues, whereas the amount of nutrients recovered in harvested products is a function of the HI. The major soil-related factor is the accessibility of a field around the time that the crop is ready for harvest. This is mainly determined by drainage and water-holding characteristics in interaction with climate and weather conditions (Schulte *et al.*, 2012). Note that the harvest index can be zero or small despite excellent accessibility to fields if a fraction of the crop is not removed owing to poor pest management or a deliberate decision to leave the whole production or residues unharvested. Relevant attributes are listed in Figure 2.

Biological N fixation and weathering

The demand for nutrients from finite resources is not merely determined by minimization of losses through efficient cycling of nutrients, as addressed in the preceding sections, but also by benefitting as much as possible from the intrinsic capability of the soil to make nutrients available to plants, that is nutrients derived from biological N fixation and weathering. Soil-related aspects affect, *inter alia,* the eventual availability of nutrients. Biological N fixation mainly occurs via the symbiosis of Rhizobium and leguminous crops. The presence of sufficient micronutrients is important for the efficacy of that symbiosis (Weisany *et al.*, 2013) as does the presence of crop-specific Rhizobium strains (e.g. Keyser & Li, 1992; Ledgard & Steele, 1992). Under N-fixing conditions, N remains available for non-N-fixing plants, either slowly by decomposition of senescing leguminous crops, by decomposition after their mechanical destruction (‘green manuring’), or after ingestion and subsequent digestion and excretion by livestock. The eventual transfer of that N into harvestable material (RV $\times$ HI) is influenced by the same factors as those governing the transfer of N from residues. The availability of nutrients from weathering is, as far as the soil-related properties are concerned, primarily determined by (i) the weathering process as related to parent material and pH, water regime and biological activity, (ii) the ability of the soil to store these released nutrients and (iii) crop rooting depth (Figure 2).

Synergies and trade-offs between soil functions

Soil properties or management decisions with a positive effect on a specific function may enhance other functions (‘synergies’) or reduce them (‘trade-offs’) (Power, 2010). One of the most obvious examples of a conflict between soil functions is the demand for the production of fresh water with a low concentration of nutrients, which is probably best served by set-aside land, and the demand for nutrient cycling through fertilized and transpiring crops which have received fertilizer applications. Figure 3a and b give more examples of synergies and trade-offs between nutrient cycling and

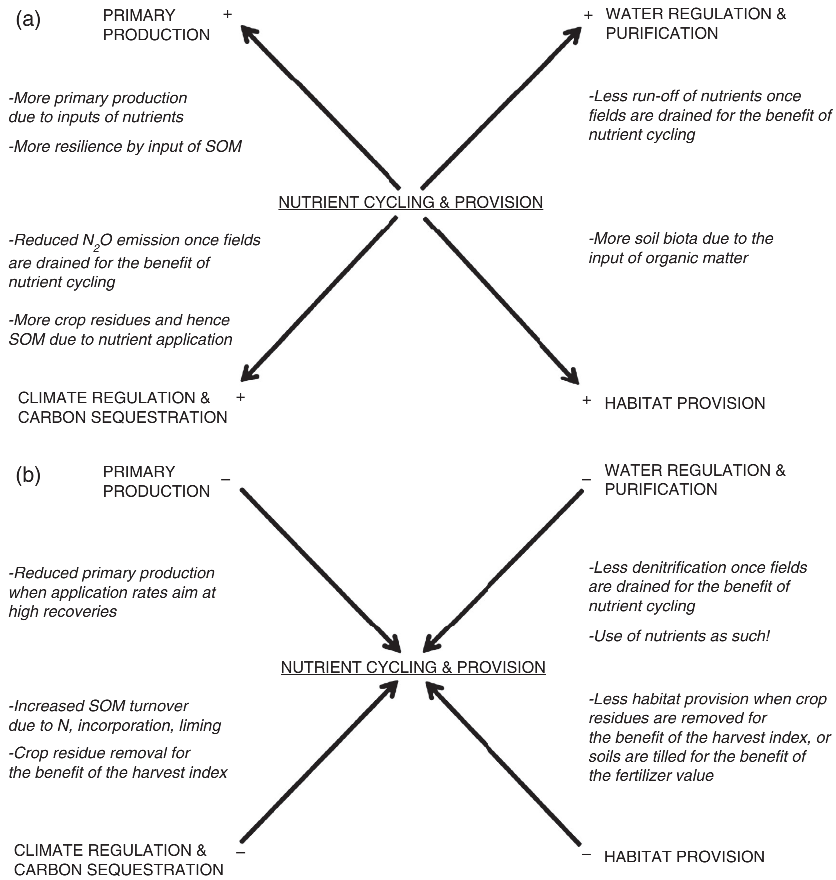

Figure 3 (a) Examples of situations where conditions or measures with a positive effect on nutrient cycling are supportive of the other four major soil functions. (b) Examples of situations where conditions or measures with a positive effect on nutrient cycling have a trade-off in terms of the other four major soil functions.

other soil functions. As far as management decisions are concerned, not removing cereal straw, for instance, provides a substrate for soil organisms (Fraser & Piercy, 1998), contributes to short-term sequestration of carbon, increases the water retention capacity of soils (Hudson, 1994) and may support primary production by soil organic matter (SOM)-induced disease suppression (Stone *et al*., 2004). At the same time, however, it slightly reduces the total amount of nutrients harvested and, hence, their potential for nutrient cycling according to the present definition. Tillage often increases yield and thus the amount of nutrients harvested (Palma *et al*., 1997; Rasmussen, 1999; Alvarez & Steinbach, 2009; Giller *et al*., 2009). The positive effects of reduced or no-till on biological and physical soil properties, including the retention of plant-available water (e.g. Spiegel *et al*., 2007; Hobbs *et al*., 2008; Lehtinen *et al*., 2014), is apparently not always reflected in increased yields and shows that what is beneficial for one soil function is not necessarily beneficial for all functions. As far as soil properties are concerned, well-drained light textured soils have a high potential for nutrient cycling in Atlantic climatic conditions. They allow field traffic all year round, allow incorporation of residues, are conducive to rapid mineralization and have relatively small denitrification losses. They also facilitate deep rooting and thus avoid nutrients moving beyond reach, provided that suitable crops are grown. In addition, their infiltration capacity can contribute to the recharge of groundwater and its purification via increased residence times compared to soil types that are conducive to surface run-off (Rivett *et al*., 2008). However, the same kind of soils may have a smaller carbon sequestration potential due to ample aeration and limited protection of SOM, are less able to buffer nutrients and water, less able to decrease the bioavailability of contaminants and less productive under dry conditions due to their smaller water retention capacity (Coyle *et al*., 2016). As for biodiversity, there are as many dilemmas. Soil quality, soil health and soil life are often presented as a trinity (e.g. Doran & Zeiss, 2000; Brussaard *et al*., 2007; Kibblewhite *et al*., 2008), and, indeed, the presence of soil biota is instrumental in nutrient cycling (e.g. Caldwell, 2005; Coleman, 2008). Mineralization of organically bound nutrients would be limited without the support of soil biota; that is, FV of residues would be greatly reduced. Moreover, rhizospheric microorganisms can have a demonstrable effect on the size and effectiveness of roots and thus increase the RV of plant-available nutrients (Lynch, 2007). Due to their effects on soil structure and the consequential drainage capacity (Bronick & Lal, 2005; Blouin *et al*., 2013), soil biota may also affect the suitability of fields to accommodate the reception of residues (AV). Laboratory experiments have further shown reduced mineralization rates when specific groups of soil biota were deliberately removed (Griffiths *et al*., 2000; Wagg *et al*., 2014). Field experiments have demonstrated an intricate interaction between specific types of residues and the kind of soil biota required for their decomposition (Rashid *et al*., 2013) or yield depressions in leguminous crops if the appropriate Rhizobium strain is lacking (Keyser & Li, 1992).

Giller *et al*. (1997) posed the question of which and how much soil biota is truly needed for nutrient cycling. This question is legitimate as the actions required to maintain soil biota in terms of diversity and abundance, carry a price, either because of the cost of the actions themselves or because of yield penalties. Tillage operations can have a negative effect on earthworm populations but, depending on the environment, crop yields can benefit from the positive effect of tillage on the accessibility of a soil to roots, on weed control and on the conservation of ammonium-N in manures. Likewise, refraining from pesticide use will undoubtedly have a positive effect on the on-farm biodiversity including soil organisms, but there is convincing evidence that it carries a price in terms of nutrient use efficiency, productivity and thus land consumption and off-farm biodiversity (De Ponti *et al*., 2012; Grau *et al*., 2013). It is evident that the use of pesticides can undermine the inherent capacity of soils to suppress pests and diseases. However, in general, there are no indications that the collateral damage to soil biota hampers the decomposition of organic residues in a significant way. Although some species have a key role in determining soil processes, soil organisms generally show strong functional redundancy (Setälä *et al*., 2005). Giller *et al*. (1997) acknowledge that these 'unemployed' organisms probably play a role in the resilience of production systems to perturbations. However, without more evidence of a broad applicability of this utility across many environments, there is as yet no reason to refrain from every activity that may potentially be harmful to soil biota. The generally observed positive relationships between the abundance of soil biota, N mineralization and crop yield are sometimes interpreted as an indication for a causal positive relationship between soil biota and yield, implying that soil organisms need to be cherished for the sake of yield formation. The enhanced mineralization is not necessarily the result of promoting soil biota, however. Instead, both mineralization and abundance of soil biota may simply be the consequence of improved conditions for microbial activity such as rewetting a soil after droughts (López-Bellido & López-Bellido, 2001) or resulting from greater inputs of organic matter, that is a substrate for soil biota. In line with this, a long-term experiment comparing conventional and organic cropping systems, differing in terms of soil organic matter inputs, has indicated that the recovery of both organic N and mineral N by crops is not significantly affected by the abundance of soil biota (Langmeier *et al*., 2002; Bosshard *et al*., 2009). Differences in mineralization rate are hence not *per se* indicative of the capacity of soils to sustain the FV or RV, let alone 'the soil quality', if differences between systems in terms of weather or of earlier organic material inputs cannot be excluded. Attribution of ecosystem service credits to systems with greater mineralization (e.g. Sandhu *et al*., 2015) becomes questionable.

Concluding remarks

Soil quality has no constant and ubiquitously applicable value for the function of nutrient cycling and even less so in view of other soil functions. This results, first of all, from the trade-offs between the ecosystem services that soils are expected to deliver and from interactions of soil properties with climatological conditions and management options. The same soil property can simultaneously strengthen and weaken the performance of one or more functions. Consequently, assessments of soil properties and recommended management actions will likely need to be site-specific, bearing in mind that the plasticity of the supply of functions and the demand for them, differ from one place to another.

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