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Assessments on the sustainability of soil use and management are based on the conservation and improvement of soil functions. A major problem in the use of soil functions in those assessments is the fact that no or few quantitative methods exist to characterize soil functions in the field. It is therefore important to define key properties or indicators that should be measured to characterize the state of soil functions. In this study soil functions which are important in the natural environment or in nature development sites were identified. Those were the habitat function, the C-storage and the filter, buffer and reactor function. Then physical, chemical and biological soil properties which characterize each of these soil functions were identified and the effects of soil management measures on each of these soil parameters were analyzed. Finally a list of soil properties that indicate the effect of nature management measures of soil functions was produced. Soil depth, SOM, availability of nutrients (N and P) and pollutants, structure, macro porosity. Biological activity, pH, CEC and BS are key properties for identifying the effect of measurements on the soil functions.

Trefwoorden: soil functions; soil properties, nature management, sustainable soil management

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Inhoud

Nederlandse samenvatting

In het natuurbeheer en natuurontwikkeling is het gebruikelijk om maatregelen te nemen, die ingrijpen op de bodem. De maatregelen hebben tot gevolg dat de abiotische omstandigheden beter aansluiten bij de gewenste toestand voor de natuurdoeltypen. Zo wordt bij voormalige landbouwgrond geprobeerd om door het afgraven van de bouwvoor de nutriëntenstatus te verlagen, of wordt via het opzetten van het grondwaterpeil of het bevloeien met oppervlaktewater de vochttoestand aangepast.

Hoewel de maatregelen in veel gevallen inderdaad leiden tot andere natuurtypen, wordt nu ook de vraag gesteld of deze praktijk als duurzaam bodemgebruik bestempeld kan worden. In eerdere rapporten over duurzaam bodemgebruik is duurzaam bodemgebruik gedefinieerd als het in stand houden of verbeteren van bodemfuncties, waarbij geen afwenteling naar andere functies, andere milieucompartimenten of toekomstige generaties mag plaatsvinden. Het is echter niet eenvoudig om in het veld te zien of te meten of bodemfuncties inderdaad verbeteren of in ieder geval behouden blijven. Deze functies zijn namelijk niet beschreven in termen van meetbare bodemeigenschappen.

In deze studie streven wij ernaar enkele indicatoren te geven waarmee de bodemfuncties kunnen worden beschreven en uiteindelijk kan worden aangegeven of bepaalde natuurbeheermaatregelen als duurzaam kunnen worden bestempeld. Hiervoor zijn de volgende stappen doorlopen:

1. Het identificeren van bodemfuncties, die van belang zijn in natuurgebieden of natuurontwikkelingsgebieden (uitgewerkt in hoofdstuk 2). Het resultaat van deze stap is dat de habitatfunctie, de filterfunctie, de bufferfunctie, dekoolstofopslag en de reactorfunctie verder zijn uitgewerkt
2. Bepalen welke fysische, chemische en biologische bodemeigenschappen deze bodemfuncties karakteriseren (uitgewerkt in hoofdstuk 3).
   De **bufferfunctie** wordt voornamelijk bepaald door chemische bodemeigen-schappen, zoals pH en CEC en de diepte van het bodemprofiel. Het kleigehalte en het gehalte aan organische stof zijn ook belangrijk, maar omdat die vooral een rol spelen bij het bepalen van de CEC, hoeven ze niet apart te worden gemeten.
   De **filterfunctie** wordt in hoofdzaak bepaald door de infiltratiecapaciteit, het watervasthoudend vermogen. Deze eigenschappen hangen af van de structuur en de diepte van het profiel. Textuur, pH, organische stofgehalte en bodem-biologische activiteit zijn zeer bepalend voor structuurvorming. Maatregelen die daarop effect hebben, hebben via die route ook effect op de filterfunctie.
   De **koolstofopslag** in de bodem is vrijwel geheel afhankelijk van de biologische activiteit. Waar het bodemleven wordt beïnvloed door maatregelen zal dit ook een effect hebben op de hoeveelheid organische stof die wordt afgebroken, of juist wordt opgeslagen in de bodem.
   De **reactorfunctie** wordt bepaald door biochemische reacties als gevolg van biologische activiteit, hoewel ook chemische evenwichten een rol spelen. Deze reacties worden mede beïnvloed door pH, vochtgehalte en zuurstof-beschikbaarheid. De biologische activiteit wordt bovendien ook nog bepaald door de kwaliteit van de organische stof, de basenverzadiging en de structuur.
   Zowel de koolstofopslag als de reactorfunctie vertonen een sterke relatie met de **habitatfunctie**, die weer wordt bepaald door de structuur, de dikte van het organisch profiel, de basenverzadiging, de aanwezigheid van verontreinigingen en de kwaliteit van de organische stof.
3. In beeld brengen van de effecten van maatregelen op de in hoofdstuk 3 genoemde bodemeigenschappen en de termijn waarop de veranderingen zullen optreden (uitgewerkt in hoofdstuk 4).
   De effecten van maatregelen op bodemeigenschappen zijn weergegeven in een tabel. Omdat er een verband bestaat tussen de eigenschappen en de functies, is in dezelfde tabel weergegeven wat het effect op de

bodemfunctie is. In enkele gevallen blijkt dat een verandering in eigenschappen kan leiden tot tegengestelde effecten op bodemfuncties. Daar kan het verschil tussen korte en langere termijn een rol spelen, of daar is de lokale situatie van groot belang en kan niet op basis van een theoretische analyse het uiteindelijk effect worden bepaald, of het effect op de bodemfuncties.

Tabel met effecten van maatregelen op bodemeigenschappen en bodemfuncties: B, F, H, R en C staan voor buffer-, filter-, habitat-, reactor- en koolstofopslagfunctie. Cursief gedrukte letters indiceren een afname van de functie, vetgedrukt een toename. Wanneer een functie niet vet of cursief gedrukt is, betekent dit dat de functie wel wordt beïnvloed, maar dat de richting van de verandering niet eenduidig is.

Maatregel →	Plaggen/afgraven		Bekalken		Vernatten	
Bodemeigenschap ↓	Effect op bodem-eigenschap	Effect op bodem-functie	Effect op bodem-eigenschap	Effect op bodem-functie	Effect op bodem-eigenschap	Effect op bodem-functie
Diepte profiel	-	*BFHR*			-[1]	*BFH*R
SOM	-	*BF*HR*C*	0/-	C	+	**BF***H*R**C**
Nmin	-	HR	+	HR	-	HR
P-beschikbaar	-	HR	-	HR	+	HR
Beschikbare verontreinigingen	-	**HR**	-	**HR**		
Structuur	-	*FH*	+/0[2]	**FH**		
Macroporositeit	-	*FH*	+	**FHR**		
Biologische activiteit	-	*FHR***C**	+	**FHR***C*	-	*FHR***C**
pH			+	**BFHR***C*	-	*BFHR***C**
CEC	-[3]	*R*	+	**BFH**		
Basenverzadiging			+	**BFH**		

Plaggen of het verwijderen van de bouwvoor heeft een negatief effect op alle bodemfuncties. De bufferfunctie en de filterfunctie worden direct minder, vooral wanneer de verwijderde bovengrond veel rijker is aan organische stof of klei dan de lagen die na afgraven aan de oppervlakte komen.

De habitatfunctie veradert ook, vooral wanneer na afgraven het moedermateriaal aan de oppervlakte is gekomen. De biologische activiteit is daardoor (tijdelijk) veel lager en als gevolg daarvan neemt ook de reactorfunctie af. De hoeveelheid koolstof in de bodem neemt door het verwijderen van de organisch rijke bovengrond direct af, maar als gevolg van een lagere biologische activiteit na het afgraven, neemt de mogelijkheid om nieuwe organische stof op te slaan wel toe.

Bekalken leidt over het algemeen tot een hogere biologische activiteit en pH. Daardoor wordt de reactorfunctie verbeterd, maar de mogelijkheid tot het opslaan van koolstof wordt kleiner. De buffer- en filterfunctie worden door bekalken verbeterd.

Door **Vernatten** neemt het volume van de onverzadigde zone af, waardoor de biologische activiteit daalt. Als gevolg daarvan worden ook het organische stofgehalte en de pH beïnvloed, wat vervolgens weer leidt tot een afname van de bufferfunctie. De opslag van organische stof neemt over het algemeen toe door deze lagere activiteit en de reactorfunctie af.

[1] De diepte van het bodemprofiel verandert niet direct, maar de dikte van de onverzadigde zone wel. Dat heeft groot effect op biologische activiteit, pH en chemie

[2] Positief effect (toename structuur) in kleigronden,, nauwelijks tot geen effect in zand.

[3] Afname in zandgronden, in kleigronden geen effect. Moeten deze drie punten/opmerkingen niet in het Nederlandse geschreven worden; dit is de Nederlandstalige samenvatting

Het opstellen van een lijst met bodemeigenschappen, waarmee het effect van beheermaatregelen op bodemfuncties kan worden gemeten in het veld (uitgewerkt in hoofdstuk 5).
In de tabel is uitgewerkt wat de te verwachten effecten van maatregelen op de bodemeigenschappen zijn. Deze eigenschappen zijn voor een groot deel complementair. Alle eigenschappen, die mogelijk veranderen als gevolg van de maatregel zouden daarom van belang zijn om te meten. Voor al deze eigenschappen zijn ook al meetmethodes ontwikkeld.

Meten van de effecten van plaggen of afgraven
Bij plaggen en afgraven spelen de eigenschappen van de bovengrond (de laag die wordt verwijderd) na de maatregel geen enkele rol meer. De eigenschappen van de 'nieuwe bovengrond' bepalen dan in welke mate de bodemfuncties zijn behouden of verbeterd. Voorafgaand aan de maatregel kan op verschillende dieptes worden bemonsterd en de eigenschappen van de bovenste en onderliggende lagen met elkaar worden vergeleken.

De biologische activiteit zal een van de eerste bodemeigenschappen zijn die na de ingreep veranderen, hoewel deze verandering zeer variabel zal zijn in tijd en ruimte

Meten van de effecten van bekalken
Bekalken heeft invloed op de pH en daarmee op alle eigenschappen die beïnvloed worden door biologische activiteiten? en chemische evenwichten. Structuur, macroporositeit en SOM worden door de biologische activiteit beïnvloed, de CEC, base-verzadiging en de beschikbaarheid van nutriënten en verontreinigingen hebben een sterke directe relatie met de pH. Deze eigenschappen kunnen dus allemaal veranderen, hoewel de mate waarin en de snelheid waarmee dit gebeurt afhangt van het bodemtype en de uitgangssituatie. De diepte van het bodemprofiel zal gelijk blijven, maar de dikte van de organische horizonten kan, net als het type humusprofiel, sterk veranderen.

Meten van het effect van vernatten
Vernatten en het verlagen van de zuurstofbeschikbaarheid in de bodem heeft al op korte termijn effect op verschillende chemische evenwichten en op de biologische activiteit. Het heeft effect op de beschikbaarheid van nutriënten en (indien aanwezig in het profiel) verontreinigen. Voor nitraat geldt dat vernatting via denitrificatie kan verdwijnen als N_2O, waardoor de beschikbaarheid in de bodem lager wordt, maar broeikasgasemissie toeneemt. Fosfaat wordt over het algemeen juist beter beschikbaar. De veranderingen in de beschikbaarheid van verontreinigingen zijn erg afhankelijk van het type verontreinigingen en de manier waarop deze aan de bodem gebonden zijn. Dat is niet in een eenvoudige tabel te plaatsen. Voor al deze chemische evenwichten geldt dat op basis van metingen voorafgaand aan de maatregel (op basis van modellen) een voorspelling kan worden gemaakt van de beschikbaarheid na vernatten.

De biologische activiteit zal veranderen en kan worden vergeleken door voorafgaand aan de maatregel en op verschillende moment na vernatten metingen te verrichten. Bij vernatting van (zure) veengronden zal de dichtheid van wormen zowel voor al na vernatten niet erg hoog zijn, deze moeten alleen gemeten worden in minerale bodems.

Het effect op de vastlegging van organische stof zal pas op lange termijn (meetbaar) veranderen. Hier moet gedurende een periode van zeven tot tien jaar voor worden gerekend. De veranderingen in microbiologische activiteit, die veel sneller reageren, kunnen wel een indicatie geven van de organische stof-opbouw.

1 Introduction

1.1 Soil functions in natural areas and nature development sites and sustainable management of soils

Soil management is an important instrument in natural areas in the Netherlands and even more so in nature development sites. Conditions in the latter, which are often formerly agricultural sites, are unfavorable for the development of an ecosystem rich in biodiversity. Often faced problems are a high nutrient content and a low ground water table. Soil management techniques are then used to improve the soil conditions. One of the most often used techniques is top soil removal. Fertile top soil is removed until the subsoil, which is low in nutrient content is reached. In combination with other measures this should result in a high natural quality. However, sometimes questions arise if top soil removal and other soil management measures can actually be qualified as sustainable soil management.

In order to assess the sustainability of soil management in natural areas Smit et al. (2007, 2009) prosposed to evaluate the effects of management practices on those functions of the soil which are of importance in such areas or in nature development sites.

In recent years public interest has increased to determine the consequences of management practices on the quality of soil relative to sustainability of soil functions in addition to plant productivity (Schoenholtz et al., 2000). Soil quality is considered as a key element of sustainable agriculture and forest management (Warkentin, 1995). Many definitions of soil quality have been proposed in the last years (Arshad and Martin, 2002). Karlen et al. (1997) defined soil quality as 'the fitness of a specific kind of soil to function within its capacity and 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'.

Due to De Kimpe and Warkentin (1998) and the Commission of the European Communities (2006) the following soil functions have been addressed as main factors in preventing soil degradation they have to be maintained to guarantee soil quality:

a. biomass production, including in agriculture and forestry;
b. storing, filtering and transforming nutrients, substances and water;
c. biodiversity pool, such as habitats, species and genes;
d. acting as carbon pool;
e. source of raw materials / resources;
f. physical and cultural environment for humans and human activities;
g. archive of geological and archeological heritage.

Part of these functions, notably b-d can also be used to describe the fitness of the soils regarding nature and nature development, an important ecosystem function.

In previous studies on sustainable use of soils in the rural area (VROM and LNV, 2006; Smit et al., 2007; Smit et al., 2008) assessments on the sustainability of soil use and management are based on the Thematic Strategy for Soil Protection. The reports of Smit et al. (2007, 2008) directly link soil use and management to the soil functions and state that sustainable use of soils is: conservation and improvement of soil functions.

A major problem in the use of soil functions to assess sustainable soil management is the fact that no or few quantitative methods exist to characterize soil functions in the field. One does not know whether the filtration function is large at one location and small somewhere else. Neither can the impact of management measures in e.g. nature conservation areas be quantified. Therefore it is important to define key properties or indicators that should be measured to characterize the state of soil functions. For soil chemical properties in forest soils there exists a monitoring program in different European countries (Pan-European Programme for Intensive and Continuous Monitoring of Forest Ecosystems (De Vries et al., 2002).

1.2 Concept of effects of management on soil quality

The goal of soil management is the restoration, maintenance or improvement of soil quality. Droogers and Bouma (1997) defined the concept of soil stability in terms of resistance and resilience of soil functions (Figure 1). A soil may exhibit a high resistance but a poor resilience with respect of a specific property, i.e. the resistance of the structure of a dry clayey soil due to compaction and its poor resilience in rebuild the structure of a compacted clay soil (Schjonning et al., 2004). Resistance and resilience are key factors that must be considered analyzing the effects of management on soil quality.

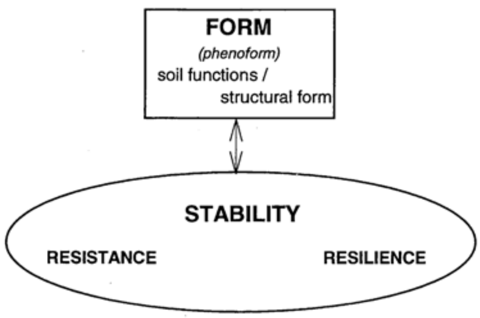

Figure 1
Soil stability in terms of resistance and resilience as related to the term form comprising soil functions as well as structural form (Schjonning et al., 2004).

Quantifying soil functions is complex and may even seem impossible. This problem has already been faced in many studies regarding soil quality assessment. Soil quality assessment typically includes the use of indicators of soil quality. Examples of such indicators are organic matter, topsoil-depth, infiltration, aggregation, pH, electrical conductivity, suspected pollutants and soil respiration. (Arshad and Martin, 2002, Kampichler et al., 2010). However, such indicators condense an enormous complexity in the soil (Schjonning et al., 2004). Doran and Parkin (1996) realized the weakness in expressing soil quality information in single numbers to characterize the effect of soil management. Doran (2002), Sanchez et al. (2003) and Geissen et al. (2009) also realized that these indicators would be too complex to be used by land managers or policy makers. The latter authors suggested to concentrate on simple indicators which are meaningful to farmers or land managers. Sparling and Schipper (2002) identified seven key parameters that are described for agricultural land by: soil pH, total C and N, mineralizable N, P (Olsen), bulk density and macro porosity. However, considering different land use systems with different management systems Kampichler et al. (2010) defined key indicators as soil pH, soil depth, Corg. clay content and CEC. These different single indicators are subsequently integrated to form one universal indicator for soil quality (Figure 2b).

Schjonning et al. (2004) suggest a management threshold approach instead of a soil indicator approach in order to establish the effects of management on soil functions (Figure 2a). They state that the challenge of soil management should address the improvement of soil functions. Management goals involve several soil function. Each soil function is characterized by its own set of indicators. Each indicator obtains a score after monitoring and the total score of all indicators results in an index value.

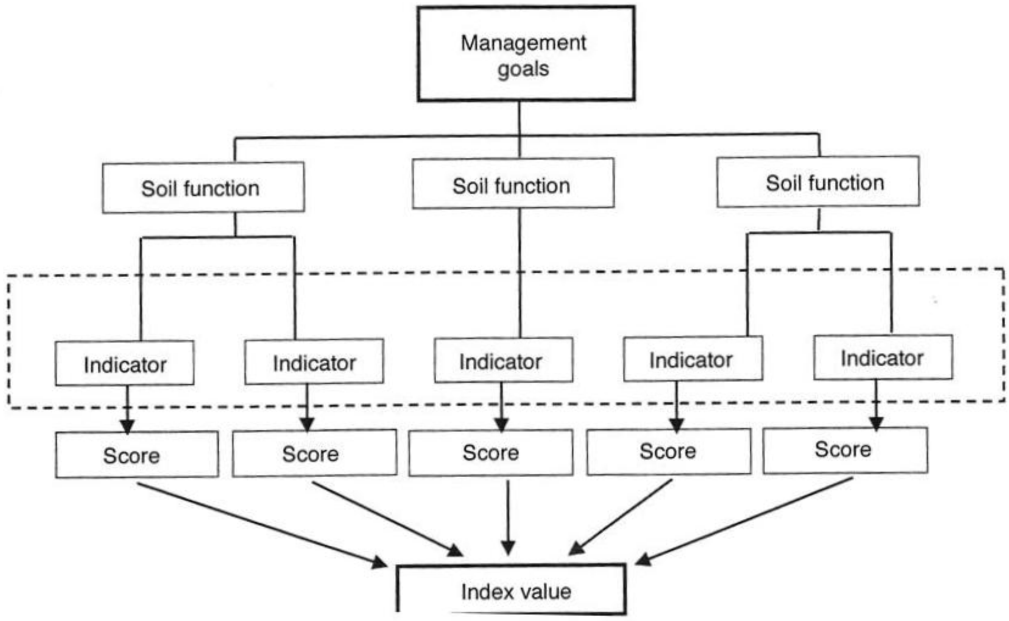

Figure 2a
A soil management assessment framework to evaluate soil quality in response to various land uses or practices (Karlen et al., 2004).

Kampichler et al. (2010; Figure 2b) developed for tropical soils a model based on soil properties to define soil quality or so call ecological conditions of the soil. This model can be adapted for European soils validating it with European data

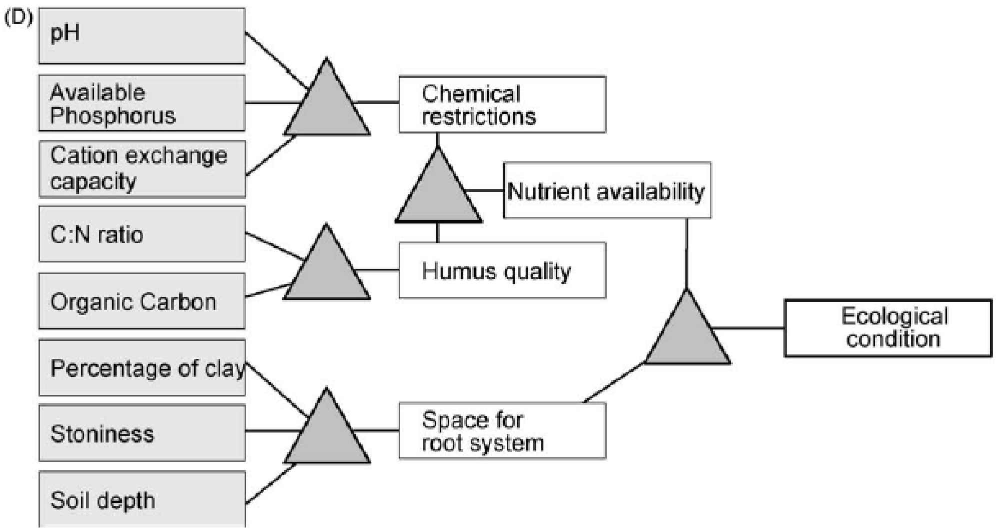

Figure 2b
Soil quality index based on soil properties (Kampichler et al., 2010).

1.3 Objectives of this study

The overall objective of this study is to describe indicators for the characterization of soil functions to assess the sustainability of soil management practices. This objective is based upon the preamble that soil functions should improve or at least remain stable as a result of such management. The method is specific for natural area management or for nature development sites.

The objectives of this study are:
To identify soil functions which are important in the natural environment or in nature development sites (Chapter 2).
To identify physical, chemical and biological soil properties which characterize each of these soil functions (Chapter 3).
To analyze the effects of soil management measures on each of these soil parameters, including the time it takes for these effects to occur (Chapter 4).
To identify soil properties that indicate the effect of nature management measures of soil functions (Chapter 5).

In a follow-up study (in 2010) we will establish the sustainability of a number of nature management plans and nature development plans using this method. Therefore, the soil parameters of each soil function need to be quantified and an index value needs to be determined.

2 Selection and description of soil functions

Ecological soil functions are important for the functioning of the soil ecosystem. They have a strong influence on the surrounding ecosystems such as water, air and vegetation. In this study we therefore focus on the following five soil functions, that determine together the overall soil quality in natural areas:

1. Habitat function
2. Filter function
3. Buffer function
4. Carbon storage function
5. Reactor function

The habitat function expresses soils as a habitat and a gene reserve for a large variety of organisms (Blum et al., 2006). The filter function of soil refers to the filtration of solid and liquid compounds in the pore space. The buffer function is defined as the adsorption and precipitation capacity of soils for all kind of organic and inorganic compounds. The reactor or transformation function reflects the microbiological and biochemical capacity of soils for transformation, through the alteration and decomposition of organic materials by mineralization and hydrolytic processes (Blum et al., 2006, 2002: Figure 3). The C storage function of soils is the capacity to sequester carbon for a long period of time. The C storage function gets increasingly more attention in view of the climate change discussion (Feller et al., 2006, Leitfeld, 2006). All five soil functions are interconnected and they need to be considered together in order to obtain a complete assessment of soil quality (Figure 4).

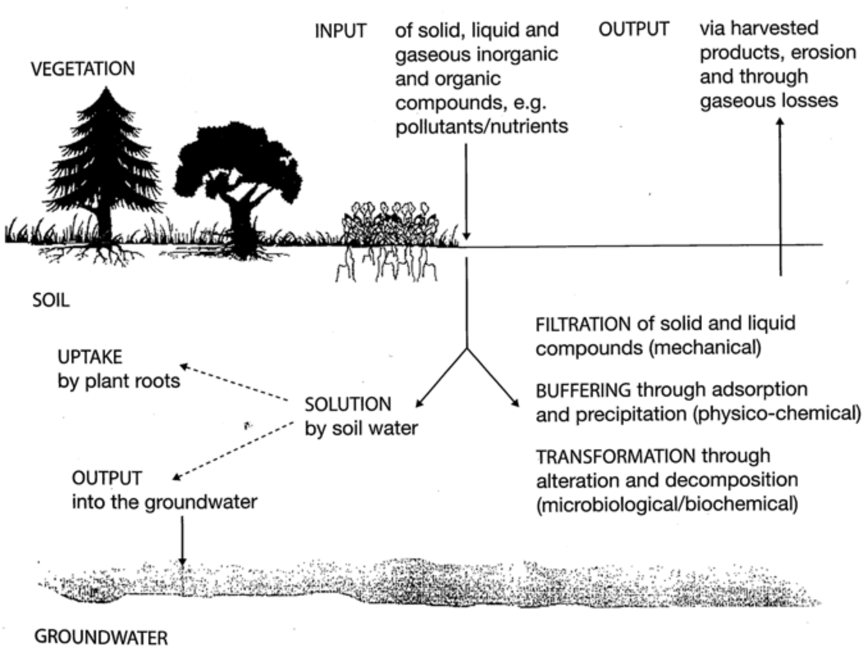

Figure 3
Filtering, buffering and transformation processes in soils (Blum, 2002).

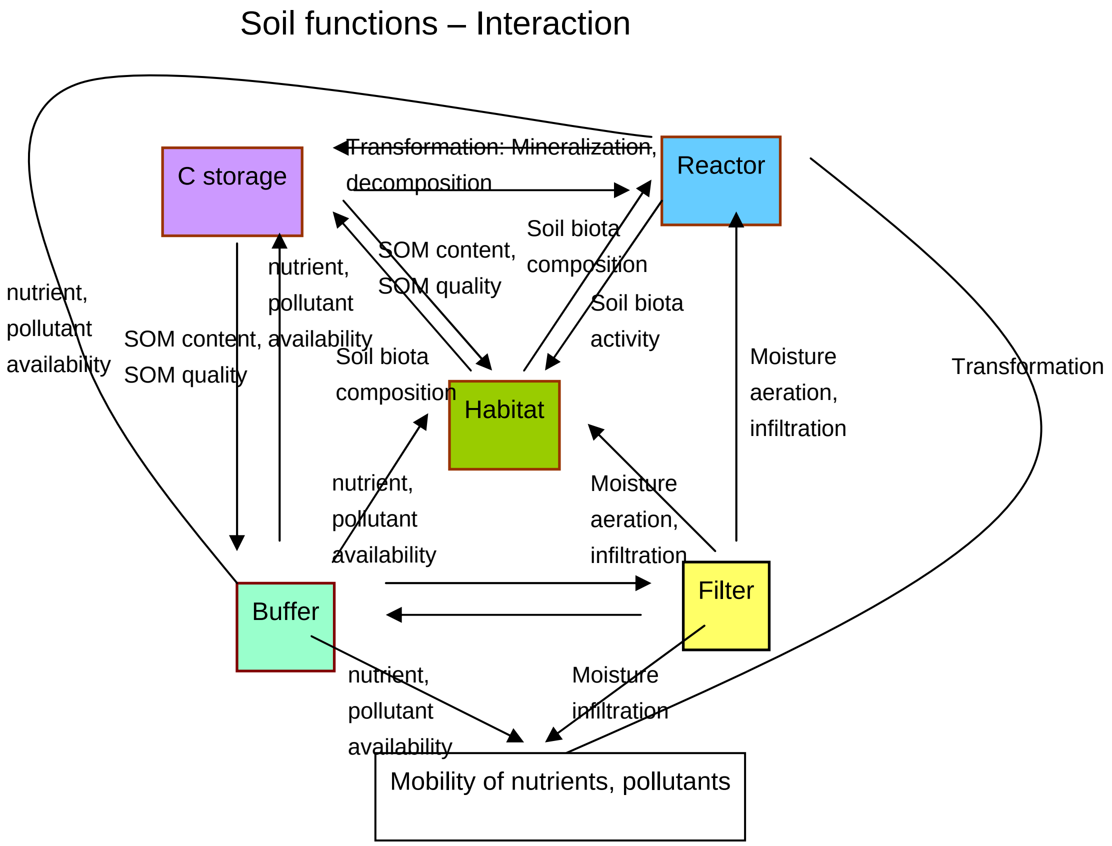

Figure 4
Relations between the ecological soil functions.

The interactions between the different soil functions are important for the functioning of the soil system (Figure 4). The mobility of nutrients and pollutants for example is determined by the five soil regulation functions. This mobility then determines the nutrient and pollutant concentration in ground water, plants and the surrounding air.

Each soil function is characterized by a number of different soil properties. In the next chapter we will describe the soil physical, chemical and biological parameters by which the five soils functions are characterized

3 Relation between soil properties and soil functions

3.1 Soil properties

Soil properties can be divided in physical, chemical and biological properties that are strongly interconnected (Scheffer and Schachtschabel, 2002; Karlen et al., 2003).

- Physical properties: texture, structure, bulk density, porosity, water holding capacity, infiltration rate, aeration (Hillel, 1982; Wolf, 1999).
- Chemical properties: soil organic matter (SOM), pH, nutrient status, content of pollutants, cation exchange capacity (CEC) (Wolf, 1999; Schoenholtz et al., 2000).
- Biological properties: microbial biomass, biological activity, abundance, biomass and diversity of soil fauna, plant root density and morphology, mycorrhizal associations, soil algae; responsible for biochemical transformations such as litter fragmentation, mineralization, synthesis, and complex formation; or biophysical transformations such as bioturbation and soil formation and aeration.

Physical/chemical soil properties can be divided into primary and secondary properties. Properties like pH, texture, clay mineral composition, soil organic matter (SOM), soil depth and nutrient content are generally referred to as **primary (abiotic) properties**. **Secondary (abiotic) properties** depend on primary properties and on biological properties. Secondary abiotic properties are soil structure, porosity, bulk density, cation exchange capacity (CEC), base saturation (BS), water holding capacity, infiltration rate, aeration and aggregate stability (Wolf, 1999, Blum et al., 2006, Kampichler et al., 2010) (Figure 3a-c). Most physical and chemical properties can be determined rather easily by mostly accepted standard methods.

Biological properties are more difficult to determine. The broad diversity of soil flora and fauna cannot be completely monitored. Therefore, there is a wide range of suggestions which soil biological properties should be used to characterize the biological soil quality (Geissen, 2000, Römbke et al., 2005). Good indicators for optimal functioning soils are a high biological activity, high diversity of earthworms and a good soil structure, respectively (Gisi et al., 1997; Geissen, 2000). These parameters are closely connected.
The EU FP6 project ENVASSO (Environmental Assessment of Soil for Monitoring) has delivered a single, integrated and operational set of EU-wide criteria and indicators to provide the basis for a harmonized comprehensive soil and land information system for monitoring. A proposal was made for a set of suitable indicators for monitoring the decline in soil biodiversity (Bispo et al., 2007). Decline in soil biodiversity was defined as the reduction of forms of life living in soils (quantity and variety) and of related functions, causing a deterioration of soil functions or ecosystem services. Whereas literature review allows the identification of about hundred potential indicators, an inventory of existing monitoring networks showed that few indicators are actually measured. Thus, three indicators were established that were thought to cover biodiversity (species level) as well as ecological functions (or services) of soil organisms (Bispo et al., 2007, Table 1):

- abundance, biomass and species diversity of earthworms (or enchytraeids) if earthworms are absent - macrofauna;
- abundance and species diversity of Collembola - mesofauna;
- microbial respiration.

In the Dutch soil monitoring system not only soil chemical and soil physical parameters are measured, also some biological parameters and processes are regularly measured. This so called Soil Biological Indicator (Bobi) contains indicators for C and N cycle, bacteria and fungi, nematodes, enchytraeids, earthworms and mites and collembola. Protozoa are not measured due too methodological difficulties. For most organisms indicators are derived, based on biomass, numbers, composition and species diversity (Schouten et al., 1997, 2002).

Kampichler and Geissen (2004), however, showed that monitoring of the biodiversity of collembola is less suitable for practical application. Therefore, we suggest that earthworms and microflora are the most important soil biota for the evaluation of management on soil functions. Geissen (2000) suggest to measure density of the three living forms of earthworms (anecic, endogeic, epigaeic), their activity (macropores) and microbial respiration. Furthermore, the decomposition rate as a characterization of the activity of all soil biota as well as the feeding activity as the characterization for the activity of the mesofauna can serve as biological soil properties (Swift et al., 1979; Van Törne, 1990).

3.2 Relation between soil properties and soil functions

Soil functions are not equal to soil properties, but are strongly related. Soil functions are affected by many soil properties and moreover, some functions interact with each other. In figures 5 and 6 the relation and interactions between soil properties and soil functions is shown.

The buffer function is mainly determined by soil chemical properties such as CEC and pH and furthermore by soil depth (Frede et al.. 2002). However, also the primary properties clay content, clay mineral composition and SOM content indirectly determine the buffer function because these properties determine the CEC (Figure 5, to the left).

The filter function is mainly influenced by soil physical properties such as soil structure and soil depth. The soil structure depends on soil pH, texture and SOM and biological activity. Soil structure determines porosity and bulk density and therefore soil aeration, infiltration and water retention (Wolf, 1999; Blum et al., 2006), (Figure 5, to the right).

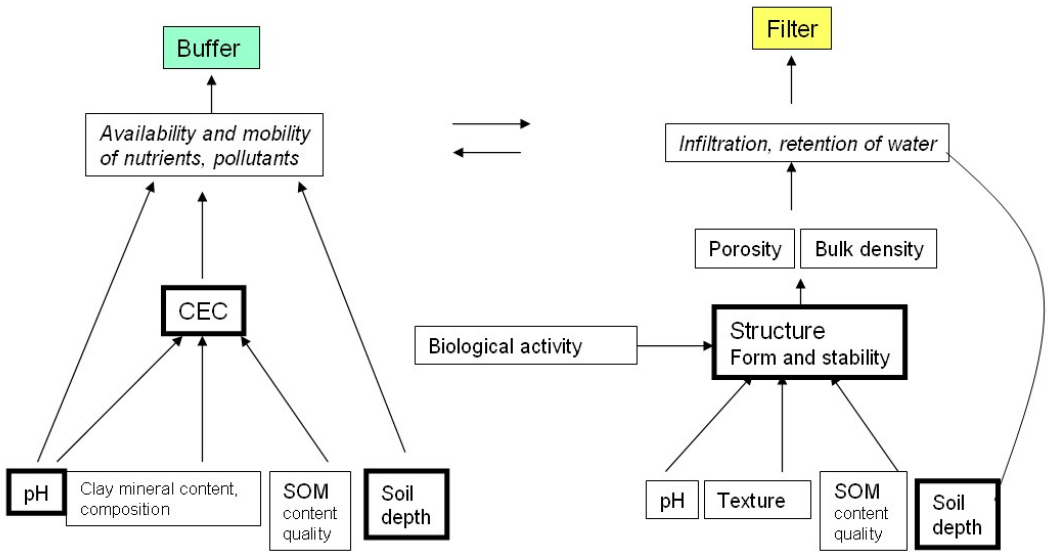

Figure 5
Influence of soil properties on soil functions: buffer (left), filter (right). Soil properties that must be determined for the characterization of the function are indicated by a bold frame.

The C-storage function almost completely depends on the biological activity in the soil and where soil biota are affected by other properties, this is reflected in the C-storage. For instance the C-storage will differ under anaerobic conditions from aerobic conditions, due to the fact that the anaerobic metabolism of soil organisms is different then. Lignin as an example, cannot be degraded anaerobically, so lignin will accumulate more under anaerobic than under aerobic conditions.

The reactor function also largely depends on biological activity of the soil although strictly chemical reactions may also occur, and these also are affected by other soil properties like pH, moisture and oxygen. Soil biota are strongly influenced by pH, SOM content and quality, base saturation (BS), soil structure and the depth of the O and A horizon (Figure 6).

So, both C-storage and reactor functions show a strong interaction with the habitat function (Gisi et al., 1997). **The habitat function** itself is strongly determined by soil structure, depth of the O and A horizon, base saturation, content of pollutants and quantity and quality of organic residue input (Gisi et al., 1997; Wolf, 1999; Blum, 2006; Feller, 2006; Leitfeld, 2006) (Figure 6).

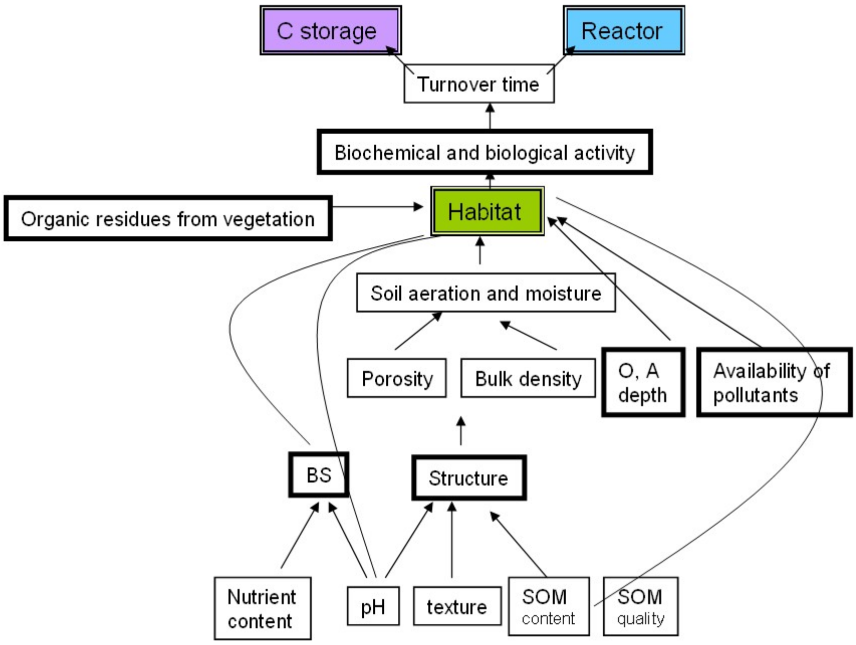

Figure 6
Influence of soil properties on soil functions: reactor, C-storage, habitat. Soil properties that must be determined for the characterization of the function are indicated by a bold frame.

Based on the descriptions of the relation between soil properties and soil functions, we propose a set of soil properties for the characterization of soil functions.

Primary abiotic properties:
- Texture (all functions)
- Soil depth (all functions)
- Depth of A and/or O horizon (C-storage, reactor, habitat) in Figure 6 secundary property
- SOM (all functions)
- pH (all functions)

- Nutrient content (C-storage, reactor, habitat) in Figure 6 secundary property
- Pollutant content (C-storage, reactor, habitat) in Figure 6 secundary property

Secondary abiotic soil properties are:
- CEC (buffer, filter, habitat)
- Base saturation (C-storage, reactor, habitat)
- Structure (all)

Biotic soil properties which influence the soil functions are:
- Microbiological activity (filter, C-storage, reactor, habitat)
- Anecic and endogeic earthworm activity (filter function)

4 Effect of soil management on soil functions and how it can be measured

Nature management mainly focuses on the improvement of conditions for natural development. In most cases the focus on soil functions in a more common perspective is hardly considered. From a sustainable soil use point of view, however, also the buffer, filter and reactor function are important, as well as the habitat function and the C-storage. In this chapter the possible effects of a selection measures (common practice) in nature management on the five soil functions are described. The practices described below are carried out in natural areas in the Netherlands as reported by Smit et al. (2007): topsoil or sod removal as mechanical measures, liming as chemical measures and rewetting to change hydrological conditions.

Since the relations between soil properties and soil functions have already been elaborated in Chapter 3, we present the effects on both properties as summarized on page 20 and functions together. The effect of top soil and sod removal, liming and rewetting on different soil properties is summarized in Table 1. In the same table also the effects on soil functions is presented. A summary and brief explanation of the effects is given below. A more detailed explanation is given in the next paragraphs.

Table 1
Effect of soil management on soil properties and soil functions. B,F,H,R and C stands for buffer, filter habitat, reactor and carbon storage functions respectively, italic indicates a decrease and bold indicates an increase of the function, otherwise the function is affected, but no direction can be given.

Measure →	Topsoil/sod removal		Liming		Rewetting	
Soil property ↓	Effect on soil properties	Effect on soil functions	Effect on soil properties	Effect on soil functions	Effect on soil properties	Effect on soil functions
Soil depth	-	*BFHR*			-[4]	*BFH*R
SOM	-	*BF*HR*C*	0/-	C	+	**BF***H*R**C**
Nmin	-	HR	+	HR	-	HR
P (availability)	-	HR	-	HR	+	HR
Pollutants (availability)	-	**HR**	-	**HR**		
Structure	-	*FH*	+/0[5]	**FH**		
Macroporosity	-	*FH*	+	**FHR**		
Biological activity	-	*FHR***C**	+	**FHR***C*	-	*FHR***C**
pH			+	**BFHR***C*	-	*BFHR***C**
CEC	-[6]	*R*	+	**BFH**		
BS			+	**BFH**		

Table 1 not only provides an overview on the effects of management on soil properties and functions, but also indicates which soil properties should be measured to further quantify the effects in the field. That analysis will be dealt with in Chapter 5.

[4] The total soil depth does not decrease, but only the unsaturated zone. This has large effects on biological activity and pH
[5] Positive effect in clay soils, little or no effect in sandy soils
[6] In sandy soils, not in clay soils

Top soil or sod removal has a negative effect on all five soil functions. The buffer and filter functions of the soil decrease immediately. The carbon storage decreases instantly due to the removal of SOM, but increases on the other hand, due to the decrease in biological activity (presuming that organic inputs are available) .

The habitat and reactor function are certainly affected by this type of management. The biodiversity (amount of species) will decrease, although the habitat will be better for some specific species. The carbon storage function may benefit from a decreasing biological activity. However, that effect is probably smaller than the decrease as a result of SOM removal.

Liming increases the buffer and filter functions and also the reactor function as a result of increased biological activity and pH. Consequently, liming decreases the carbon storage function.

Rewetting leads to an decrease of the unsaturated zone in the soils and therefore biological activity decreases. Consequently, SOM and pH are affected too. The overall effect on the buffer function is a decrease. The carbon storage function increases as a result of rewetting, mostly due to a decrease in the reactor function related to biological reduced activity.

Combinations of management actions
Combinations of different management actions may occur, for instance removal of the top soil followed by liming in dry areas, or followed by rewetting if marsh formation is aimed at. A combination of liming and rewetting seems very unlikely.

A combination of top soil removal and rewetting will lead to an initial decrease in SOM, due to SOM removal. However, eventually SOM will increase again, presuming that there will be an input of organic residues.

In case of a combination of top soil removal and liming, the negative effects of the former on the filter function can be restored by the latter. However, the positive effect of on top soil removal on the carbon storage function is counteracted by liming.

4.1 Topsoil or sod removal

Removal of the top soil is mostly done in former agricultural soils that contain large amounts of nutrients and organic matter (and sometimes pollutants). When these areas are transformed into nature development areas, the top 30 to 50 cm of the soil is removed. In this way, within a short time the abiotic conditions are altered and the parent material with low nutrient contents forms a new basis for primary succession. An additional advantage in drained areas is that after removing the topsoil the distance between surface level and the ground water level has decreased. However, by removing the top soil in most case also all soil biodiversity is removed.

Sod removal is less radical, because only the top organic layer is removed. This layer contains living and dead roots, living plants, litter, fragmented and humified plant material. Sod removal is meant to ‘reset’ succession to a pioneer stadium, to remove thick layers of organic matter in grass-encroached heath of forests, or to re-activate geomorphological processes like wind erosion (blow-outs) and the forming of new sand dunes (Smit et al., 2008). Sod removal is mostly done on poor sandy soils.

After the topsoil has been removed, the habitat for most soil biota is drastically disturbed and most soil biota is removed with the soil. Topsoil removal also has a drastic effect on the physical and chemical soil properties of the remaining soil (Figure 7).

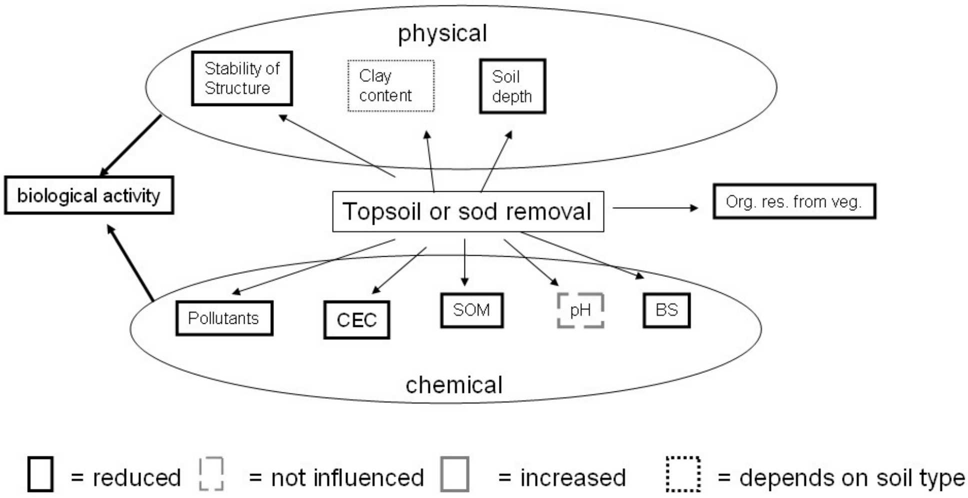

Figure 7
Effects of top soil or sod removal on soil properties.

Effects on soil chemical properties
Topsoil removal also leads to strong changes in soil chemical properties such as:

- Drastic removal of SOM and available nutrients such as Ca, Mg, N, P (Hötzel and Otte, 2003; Wairiu and Lal, 2003). Consequently, BS decreases.
- Pollutants will be removed when the topsoil is removed.
- Normally pH value of the subsoil (the new top soil after removal of top layers) is not influenced by removal of the topsoil (Woodward, 1996). A change of pH in the new habitat for plants only occurs if originally pH values in the topsoil and the lower horizons were different. This effect therefore depends on soil type. It is important to consider pH differences between the topsoil and the lower horizon to guarantee an adequate pH in the root zone (Allison and Ausden, 2004).

Furthermore, the removed material is strongly affected; it will be mixed and as a result SOM mineralization may be stimulated.

Effects on soil physical properties
Stability of soil structure may decrease because of the mechanical pressure by heavy machinery that causes compaction, which decreases soil porosity (Chauvel et al., 1991; Woodward, 1996). Heavy machinery destroys soil structure, reduces the water infiltration rate, and causes higher soil erodibility (Wairiu and Lal, 2003; Rice Creek Watershed District, 2009). Woodward (1996) observed an increase in bulk density, with a 23% increase caused by subsoil compaction alone. Total porosity consequently decreased.
However, in most Dutch nature development areas the effects of heavy machinery are acknowledged the machinery is either replaced by light equipment or the machinist works backwards, causing less damage to the new bare soil.

Both compaction and topsoil removal cause a decrease in macroporosity of the subsoil and reduce water availability (Woodward, 1996). This effect is strengths by the loss of the SOM that contains the topsoil (Woodward, 1996). Furthermore, depths of soil and organic layers decrease. The clay content may change due to vertical differences in the soil (Woodward, 1996). If the clay content in the remaining subsoil is higher then the CEC increases after topsoil removal (Woodward, 1996).

Effects on soil biota

Topsoil removal drastically decreases soil biological activity (Kardol et al., 2009) and it takes a decades until it is reestablished (Biondini et al., 1985). For reestablishment of the soil functions, first of all a recolonization has to take place to form SOM and soil structure. However, it may take decades until natural recolonization through earthworms occurs if no artificial recolonization is done (Geissen, 2000). These soils will be left as mesofauna-microflora soils for decades and therefore the restoration of all ecological functions will only take place in long-term view.

Effect on soil functions

Top soil or sod removal has a negative effect on all five soil functions. The buffer and filter functions of the soil decrease immediately. The carbon storage decreases instantly due to the removal of SOM, but increases on the other hand, due to the decrease in biological activity (presuming that organic inputs are available).

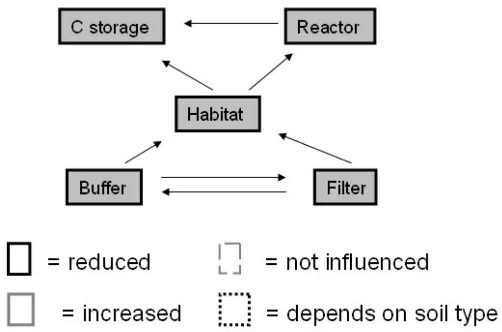

Figure 8

Effect of topsoil remove on soil functions.

4.2 Liming

In order to prevent or to stop acidification of soils and surface water, application of lime on the soil or irrigation with slight alkaline water is chosen as a measure. This might help to improve the buffer capacity of the soils and prevent further acidification.

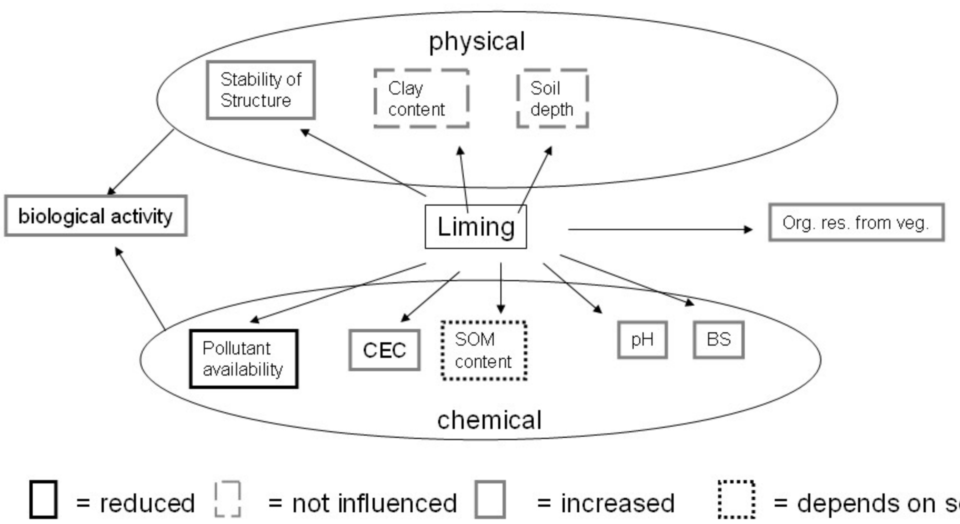

Figure 9
Effects of liming on soil properties.

Effects on chemical soil properties
Considering soil chemical properties, liming leads to a decrease in phytoavailability of Aluminum and potentially toxic heavy metals (Geissen et al., 1999) and micronutrients (Shuman, 1986; Bolan and Duraisamy, 2003). Furthermore, increased calcium content in the soil can lead to P fixation in form of apatit that reduces its phytoavailability drastically (Geissen, 2000). This leads to a decrease of toxic elements in the soil solution, however, may lead to a lack of plant available P and micronutrients.

The effects of liming can be seen after a short period if the soil initially is not very acidic and does not have a thick organic layer. However, in acidic forest soils with raw humus layers effect of liming on the chemical properties on the mineral soil can be seen after 5-10 years (Geissen et al., 1999).

Effect on physical soil properties
An important effect of liming is the increase of aggregate stability and to a better soil structure due to the fact that a higher content of Ca^{2+} leads to the formation of bridges between the aggregates (Haynes and Naidu, 1998). However, in soils with an initially good structure, liming has very little effect on soil structure (Stenberg et al., 2000). The building of biotic aggregates however cannot be expected in a short or medium time scale because natural recolonalization of this soils with anecic and endogaic earthworms does not take place in the first ten years (Schoening, 2002).

Effect on soil biota
Liming increases soil pH, CEC, base saturation and therefore the biological activity of the soils as well as the biodiversity of soil fauna (Haynes and Naidu, 1998; Geissen and Brümmer, 1999; Geissen, 2000).

Liming may lead to a temporarily flush of microbial activity and in long-term increases the biological activity (Haynes and Naidu, 1998). Its effect on SOM depends on the initial soil conditions. In acidic forest soils, liming leads to an increase of the biological activity in the O horizon and therefore, turnover rates increase (Wilhelmi and Rothe, 1990). This leads in long term to a decrease of SOM in the O horizon. Increasing activity of earthworms effects in long term an incorporation of the SOM into the A horizon of the mineral soil (Geissen and Brümmer, 1999; Geissen, 2000). However, increasing mineralization increases the danger of nitrate leaching (Gebauerl et al., 1998; Geissen et al., 2003). Furthermore, in soils with a thick organic humus layer the applied lime often leaches with a delay of several years into the mineral soil and is often neutralized in the organic layer (Geissen, 2000).

Effect on soil functions
Liming has a positive effect on the filter, reactor, buffer and habitat functions. Although changes in habitat mean an improvement to one species, it means a deterioration to other species. Overall, however, the number of species increases after liming and therefore the effect is called a positive one. The new conditions after liming cause incorporation of litter into the soil and decomposition of soil organic matter increases. Its effect on the C storage function depends on the land use form and initial state of the soil. In acidic forest soils C storage function decreases after liming because of an increased mineralization rate whereas it increases in mineral soils without organic humus layer (Haynes and Naidu, 1998; Geissen, 2000).
Liming cannot restore the primarily in acidic soils destroyed clay minerals and feldspates (Veerhoff et al., 1996). Therefore, the buffer function of these soils cannot be completely restored.

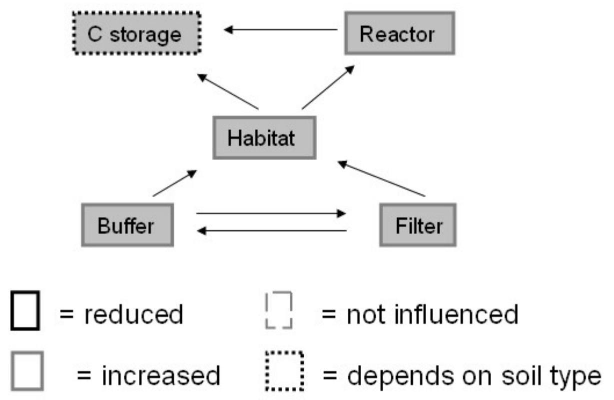

Figure 10
Effects of liming on soil functions.

4.3 Rewetting

Rewetting is carried out to restore drained peat soils. In many areas the agricultural drainage systems are removed and the ground water level raises. The most important changes after rewetting are changes in soil chemical and biological properties.

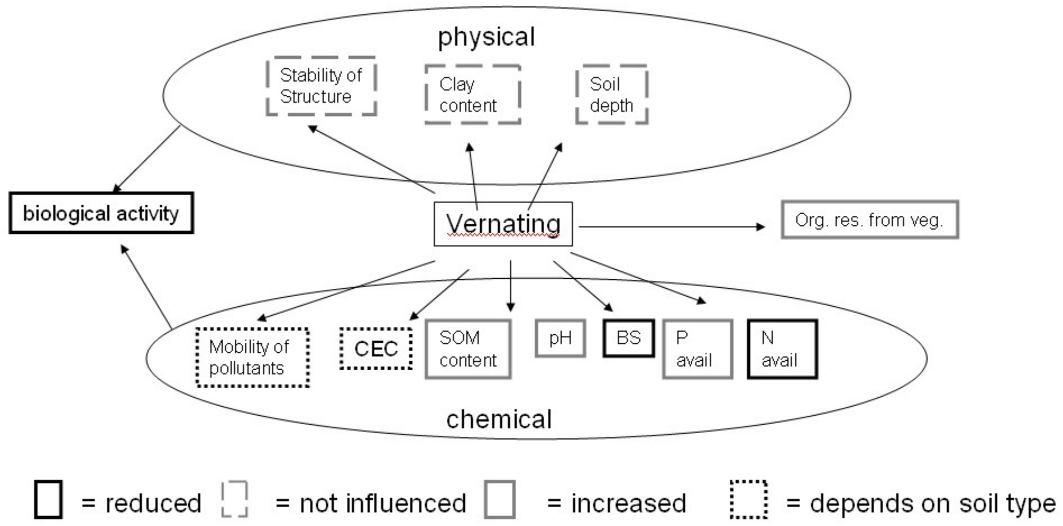

Figure 11
Effects of rewetting on soil properties.

Effects on chemical properties
Rewetting has a major effect on the availability of nutrients pointing to an interaction between nutrient and oxygen supply (Marschner, 1995; Lambers et al., 1998). Anaerobic root conditions reduce mineralization (Bodelier et al., 1998), increase denitrification (Venterink et al., 2002), gaseous N losses and therefore N availability decreases (Zeits and Velty, 2002). In contrast, phosphate availability increases due to low redox potentials (Van der Hoek and Kemmers, 1998; Van Duren and Pegtel,; 2000, Venterink et al., 2002) (Figure 9). This may lead to eutrophication since P is often the limiting factor for eutrophication. The impact of rewetting on the K supply in the soil is not yet known (Van Duren and Pegtel, 2000). The consequences of the proceeding redox processes are a

decrease of soil redox potential and an increase in soil pH. Although the effect on pH may depend on the pH of the water that is used for rewetting.

Rewetting may have a strong effect on greenhouse gas emissions. Due to increased denitrification rates high emission of N_2O in the atmosphere occur in case of changing soil moisture conditions during the year (Meyer et al., 2001). Although Augustin (2001) found a high accumulation of Corg. after rewetting, CH_4 emission increased drastically. The amount of emission depends strongly on the groundwater level (Schrautzer, 2001).

Effects on physical soil properties
The main effect of rewetting on soil physical properties is a medium and long-term increase of the organic horizon due to decreased mineralization rate after wetting.

Effects on soil biota
Rewetting has a strong effect on soil biota. The anaerobic conditions after rewetting reduce the microbial activity mainly to the activity of anaerobic soil biota. Soil animal diversity is reduced to species that tolerate anaerobic conditions over a longer period.
Microbial activity is reduced under reductive conditions since under anoxic conditions energy is less efficiently used than under oxic conditions (Zeitz and Velty, 2002). Furthermore, $Fe2^+$ is mobilized under reductive conditions and inhibits microbial activity (Brake et al., 1999). Therefore, the mineralization rate decreases and organic residues accumulate, Corg. content increases and therefore the depth of the O horizon.

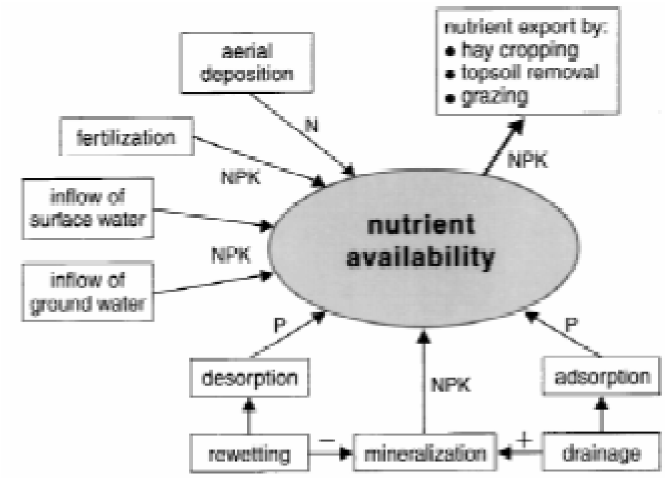

Figure 12
Factors influencing N, P, K availability for the vegetation in wet and drained peat soils (Van Duren and Pegtel, 2000).

Effect on soil functions
Rewetting results in a less favorable habitat for aerobic organisms. In addition the mobilization of Fe^{2+} inhibits the microbial activity (Brake et al., 1999). The habitat function thus changes after rewetting. As a consequence the biological activity decreases resulting in a increase in C-storage and a decrease in reactor function. The influence on the buffer and filter functions depends on the specific conditions. The shallow groundwater levels imply a less deep soil profile and therefore a reduced buffer and filter function. On the other hand, an increased amount of SOM may result in an increase in buffer and filter function.

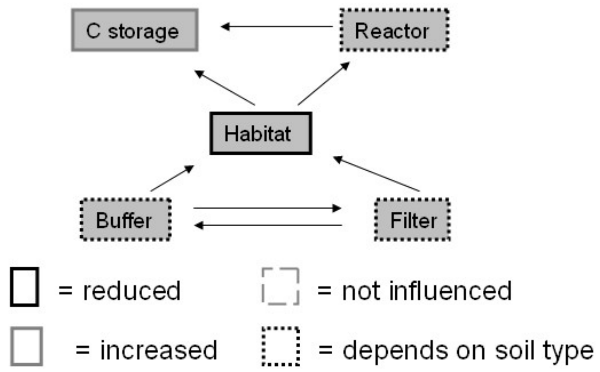

Figure 13
Effects of rewetting on soil functions.

5 Indicators for the effects of management measures on soil functions

As described in Chapter 4, the different management measures affect different soil properties, which in turn determine the changes in the soil functions. Soil functions itself can not be measured. The most important soil properties that indicate changes in soil functions can be deduced from Table 1. In that table the impact of top soil and sod removal, liming and rewetting on the key soil properties is presented. Below for each measure a set of soil properties to be measured is given.

Measuring the effect of top soil or sod removal on soil properties
The main effect of top soil removal is that all properties of the top soil are not relevant any more after the measure is taken. The new surface and top soil has new properties. In this bare soil new processes occur and it is interesting to see at what pace the soil properties start to change.

The differences between the original situation and the situation after top soil removal might be predictable by measuring soil properties at several depths. The relevant soil properties are soil depth, SOM, nutrient availability, structure, macro porosity and biological activity. As a consequence of a difference in SOM between top soil and sub soil, in the new situation also CEC, pH and BS may be affected.

The biological activity may be one of the first soil properties to change after the measure is taken, but is also very variable in space and time. Determination of changes in biological activity therefore depend on a good sampling scheme.

Measuring the effect of liming
Liming is supposed to have strong effect on soil chemical conditions as described in par. 4.2. The changes in soil chemical conditions may occur at different rates, depending on the soil type and the amounts of nutrients and pollutants in the soil. As described above, P fixation often occurs after liming as well as a decrease of the availability of micronutrients. Therefore, it is important to determine plant available P, Zn, Cu, Mn and Fe before and after the measure is taken.

The possible increase in nitrate should be taken into consideration and measuring the nitrate content in soil and groundwater (in case of a high ground water table) before and after liming is sensible.

Thickness of the organic O layers and SOM content in the A horizon may change drastically after liming and should be estimated before and after the measure. Although not mentioned before, determination of the amounts of Dissolved organic matter (DOC) may indicate changes in decomposition rates and give a more quick response to liming that the total amount of soil organic matter. Whereas changes in the organic O layer can be measured already in the first years after liming, SOM changes may occur after a longer period, depending on local conditions.

Changes in soil structure after liming occur in medium or long term range and can be determined measuring aggregate stability or in situ resistance against penetration (Geissen et al., 2009).

Biological activity (microbial respiration, decomposition rate and feeding activity) may be strongly affected and should be measured due to the methods described by Geissen (2000) and earthworm diversity and density should be monitored in the O and A horizon each spring over one decade to see the long term effect of liming. Furthermore, macropores could be counted on to soil surface.

Measuring the effect of rewetting on soil properties

The chemical effects of rewetting occur after a short term period and stay over the whole period of rewetting. It is important to measure the content of available N in the soil before and after rewetting to determine whether there is sufficient N available for plant growth. The analysis of available P in soil and the total P content in runoff water is important to determine the risk of eutrophication.
To measure the effect of rewetting on the emission of greenhouse gasses (CH_4, CO_2 and N_2O), permanent measure chambers in the filed should be installed over a long period.

Microbial respiration and feeding activity should be measured before rewetting and in the following years in spring. Earthworm density is not expected to be high in peat soils and monitoring of this group only necessary on mineral soils.

The effect on the amount of soil organic matter may take much more time. Changes might be significant after seven to ten years. In the mean time changes in microbial activity may indicate whether the amount of soil organic matter will indeed increase.

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