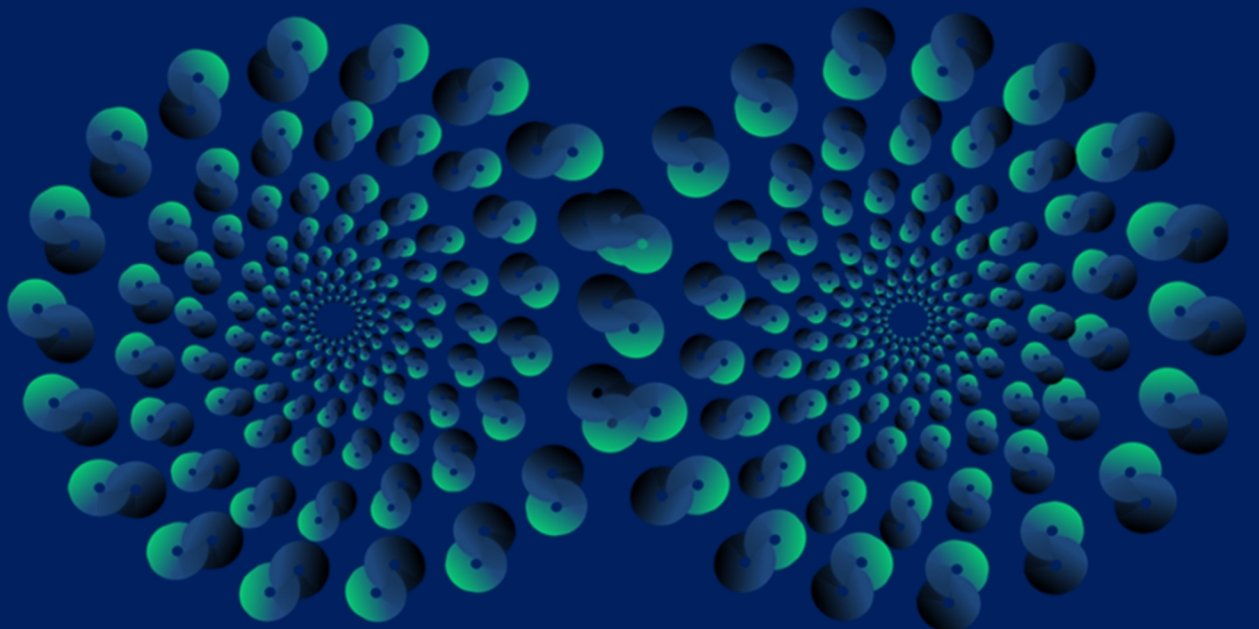# Panarchy Rules?

## Rethinking Resilience of Agroecosystems



Dirk F. van Apeldoorn

Propositions

1. Patterns and processes are de-coupled in agro-ecosystems.
   (this thesis)

2. Panarchy in agro-ecosystems can be hypothesized, but cannot be identified.
   (this thesis)

3. Empirical relationships become linear with either up- or down-scaling.

4. Scientists' unfamiliarity with the drunkard's search metaphor
   (http://en.wikipedia.org/wiki/Streetlight_effect) leads to unsupported confidence
   in global models and leaves science in the dark

5. Think global, act local is a self-refuting statement.

6. Certified organic agriculture is generally not eco-logical.

7. Eclectic rather than electric bike use should be the focus of mobility plans.

8. Dyslectics are theoretically more creative than on paper.

Propositions belonging to the thesis, entitled

'Panarchy rules? Rethinking resilience of agro-ecosystems'.

Dirk Frederik van Apeldoorn
Wageningen, 22 April 2014.

# Panarchy rules?
## Rethinking resilience of agroecosystems

Dirk F. van Apeldoorn

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# Panarchy rules?
## Rethinking resilience of agroecosystems

Dirk F. van Apeldoorn

In memory of
Marthijn Sonneveld
who will continue to inspire me

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# Chapter 1

# Introduction

## 1.1 Introduction

### 1.1.1 Motivation

Integrated studies of coupled social-ecological systems reveal a complexity which is not well understood (Liu et al., 2007). These studies show that social-ecological systems exhibit complex dynamics with thresholds, reciprocal feedback loops, time lags, resilience, heterogeneity, and surprises (Liu et al., 2007). As globalization intensifies, complexity further increases with more interactions across scales (Young et al., 2006; Anderies et al., 2013).

This complexity is fully embodied in agricultural systems. All the complexity that a social-ecological system can possibly have is present in agricultural systems (Darnhofer et al., 2010). This is supported by recent studies that demonstrate that reductionist analysis fails to capture agricultural system functioning (Giller et al., 2011). To understand the functioning of agricultural systems it should include the complex system properties of multiple scales (Sonneveld et al., 2002; Giller et al., 2006; Schulp and Veldkamp, 2008), diversity (Tittonell et al., 2005) , self-organisation (Giller et al., 2006), co-evolution (German, 2003; Sonneveld et al., 2004), path-dependency (Anderies, 2005; Overmars et al., 2007) and cross-scale interactions (Kinzig et al., 2006).

The recognition that functioning of agricultural systems is context dependent, and the failure to capture its functioning, calls for new approaches of agro-ecosystems analysis (Veldkamp, 2009). The resilience perspective offers insights into the behaviour of complex systems properties (Cumming and Collier, 2005). The resilience perspective emerged from a branch of ecology that included human actions to enable understanding ecosystem dynamics. But currently the resilience perspective is used across many disciplines (Brand and Jax, 2007). A resilience perspective allows the study of how complex social ecological systems persist over time. It encompasses the capacity to deal with change and disturbances while retaining essentially the same functions as well as the capacity for renewal, re-organisation and development (Folke, 2006; Folke et al., 2010). The resilience perspective shifts management from a command and control paradigm (Holling and Meffe, 1996) to managing the capacity to cope with, adapt to and shape change (Folke, 2006). With the rise of popularity of the concept of resilience, its meaning has been expanded (Brand and Jax, 2007). The key concepts are introduced below, definitions are given in Table 1.

*1.1.2 The resilience perspective: heuristics of change*

A new perspective needs heuristics to structure observations, I use a set of five heuristics provided by Walker et al. (2006). The heuristics are: (1) the adaptive cycle, (2) panarchy, (3) resilience, (4) adaptability, (5) transformability. Each is described in turn.

(1) Adaptive cycle

Self-organization and external drivers of a social-ecological system cause the system to change its feedbacks and function. The dynamics of such adaptations can be described in four phases of an adaptive cycle (Holling, 2001). During the growth phase (r) the system grows rapidly by abundant available resources. The increase in feedbacks takes up increasing amounts of resources, slowing the initial growth rate. At the conservation or climax phase (K), the system is functioning at its highest potential or efficiency due to delicate controlled feedbacks. The high potential, however, comes at a cost of flexibility. The increased rigidity/efficiency causes the system to be unable to respond to infrequent events/disasters which is the phase of system collapse ($\Omega$). The collapse is caused by crossing a critical threshold. With the collapse accumulated resources are released, and it gives rise to a phase of reorganization ($\alpha$). During this phase new relations and configurations occur which can lead to both new and old configurations during the growth phase (r). The new configuration might be very distinct from previous cycles.

The adaptive cycle provides system dynamics to the resilience perspective. Systems can thus not be assumed to be (close to) equilibrium but in a continuous process of development and adaptation.

(2) Panarchy

Social-ecological systems are coupled systems and as such cover many scales. Most organizational structures within social-ecological systems are not scale invariant, but rather occupy discrete domains in space or time constituting semi-autonomous levels (Holling, 2001). The levels follow the dynamics of the adaptive cycle described in the previous paragraph, but interact with other levels (see Figure 1). The dynamic link between levels can be bottom-up or top-down, and the importance of these interactions changes during the various phases of the adaptive cycle (Holling, 2001). The connection of levels to other domains and

scales in the panarchy, might cause cascading events; the collapse of one level induces similar dynamics at other levels.

Within the resilience perspective it is thus essential that the dynamics of a system at a particular scale of interest, i.e. the focal scale, can only be understood with taking into account the dynamics and cross-scale influences of the processes from the scales above and below it.
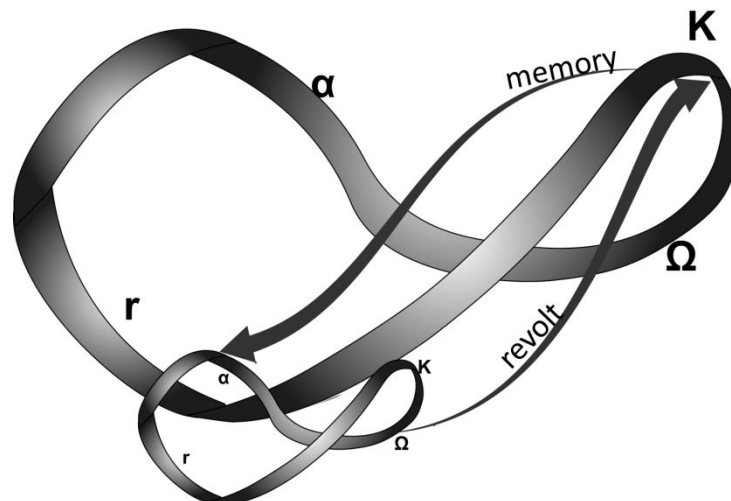


**Figure 1.** A panarchy of two linked adaptive cycles at two levels. The lower level causes a revolt at a higher level, while the higher level provides a memory to the lower level in its re-organisation phase. Based on www.resalliance.org/index.php/panarchy

(3) Resilience

Resilience is commonly defined as the capacity to deal with change and disturbances while retaining essentially the same functions and processes (Folke, 2006). Resilience in social-ecological systems is determined by the interactions of a few key variables that operate at different scales, e.g. slower and faster rates in time, or smaller or larger extents in space. The interplay of fast-slow variables defines how a system responds to disturbances (Carpenter et al., 2001). Resilient systems can either resist change by numerous internal feedbacks developed in the climax phase of the adaptive cycle or resist change by being briefly disturbed, but returning swiftly to their former functioning as is the case in the growth phase.

Resilience is often confounded with sustainability or is considered to be inherently good. Resilience of particular aspects of a system can be analysed that might arise from a particular set of sources or shocks, this is also called specified resilience. Or resilience can be studied in relation to all kinds of shocks, including completely novel ones, which is referred to as general resilience (Walker et al., 2012). Unless otherwise specified I use the term resilience in this general non-normative sense.

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(4) Adaptability

Adaptability is the capacity of the actors in a system to manage resilience. Adaptability thus introduces human capacity of intent and foresight to the dynamics of socio-ecological systems. Adaptability determines if actors can successfully avoid crossing to an undesirable system configuration or can succeed in crossing into a desirable one. At the local scale adaptability can be influenced by factors such as managerial ability, access to financial, technological and information resources, infrastructure, the institutional environment within which adaptations occur, political influence and kinship networks (Smit and Wandel, 2006).

(5) Transformability

Transformability is the capacity of the actors to create a fundamentally new system when the existing system is untenable. Highly resilient but undesirable regimes tend be created by cascading events in the panarchy (Kinzig et al., 2006) and changing most of multi-scale relationships in the panarchy is the difference between transformability and adaptability. Walker et al. (2012) speculate that attributes required for transformability will emphasize novelty, diversity, and organization in human capital.

*1.1.3 In summary*

The resilience perspective implies that social-ecological systems are evolving, adapting and out of equilibrium. Evolution, adaptation and out-of-equilibrium conditions pose challenges for system analysis (Cumming et al., 2005). When studying agro-ecosystems¸ a useful metaphor to keep in mind to remind us of dynamics is our self-perception. Although we perceive ourselves as stable on a day-to-day basis, it is clear that our body, abilities and relations to the outside world change when we develop from toddler to advanced adult. Likewise when analysing agro-ecosystems we have to assume that it components, characteristics and environment change with time.

## 1.2 Methodology

Although I set out to use the resilience perspective to analyse agro-ecosystem functioning, during my research I needed to elaborate on two concepts which were not fully covered by the resilience perspective: scale and asymmetry. I introduce them here as part of the methodology since they follow from my application of the resilience perspective.

*1.2.1 Scale*

The heuristic of Panarchy implies multi-scale dynamics. However, concepts associated with scale are used in many contradictory ways in different disciplines (Vervoort et al., 2012). Scale is a central theme in my thesis and therefor I sketch below my understanding of the difference between scale and level.

Since agro-ecosystems are coupled integrated systems of people and nature, feedbacks within these systems are multi-dimensional. Not only temporal and spatial dimensions interact but other dimensions such as jurisdictional, institutional, management, networks and knowledge (Cash et al., 2006). To structure and study these dimensions a scale is applied (Vervoort et al., 2012). Following (Gibson et al., 2000; Cash et al., 2006; Vervoort et al., 2012) a scale is here defined as the reference systems used to structure dimensions, such as the Julian calendar, the metric system and administrative units. Scales can be further subdivided by their resolution, such as days, months, years for the Julian calendar, centimetres, metres, kilometres for the metric system or district, state, country for administrative units. The choice of resolution is not arbitrary since it defines what is measured. For example (Mandelbrot, 1967) showed that the measured length of the coast of Britain increases without limit as the resolution decreases towards zero. The extent of a scale is the limit or boundary of the observation. For example one year, a hectare or a district.

Thus a scale is constructed to make observation of the real world. In this real world phenomena tend to cluster to discrete positions on a scale. This position is called a level (Gibson et al., 2000; Cash et al., 2006; Vervoort et al., 2012). A level is thought to be the result of self-organisation, for example the adaptive cycle, while a scale is a construct to observe these levels. In systems that are influenced by humans, scale and level often coincide , since the scale used, determines the observations and therefor their management. Examples of levels within agro-ecosystems are leaf, crop, cow, field, season, family, farm, community, farmers-cooperation and rural landscapes.

*1.2.2 Asymmetry*

The adaptive cycle is also considered the engine of diversity (Holling, 2001). However the role of diversity in systems performance is not well captured by the adaptive cycle. I there for use the concept of asymmetry (Cumming et al., 2008).

Agro-ecosystems are spatially organised systems and are highly heterogeneous (Tittonell et al., 2005), with a large diversity of system components. For example, soil fertility is not homogeneous for all fields within a farm. These components are generally not interchangeable but are the effect of systematic differentiation. For example fertility gradients with a decreasing fertility of fields with increasing distance from the homestead. Such gradients can be explained by the restricted availability of resources for smallholder farmers and their preferential allocation of resources to the fields near the homestead (Giller et al., 2006). These differences in soil fertility caused by past management have strong influence on the current efficiency of resource use. This systematic differentiation leads to repeating patterns across sub-Sahara Africa and can be used to enhance system performance.

Following Cumming et al. (2008) I define this non-random heterogeneity as asymmetry. Asymmetry can arise through differences in: 1) rates, frequency or magnitudes in different locations (e.g. differentiated manure application to the fields), 2) processes that are constrained by environmental variation (e.g. sandy soils being less fertile than clay soils), 3) process of equivalent rates and magnitudes that occur asynchronously in space (e.g. the time since the fields have been cultivated).

Asymmetry can be part of the system functions (e.g. yields are greater with a gradient than without), or can emerge through interaction of the components (e.g. fields further away requiring more labour) or can be a responses to an external process (e.g. lack of fertilizers on the market) or any combination of these as the example of the soil fertility gradients makes clear. As such asymmetry provides insights in the relationship between pattern and process.

**Table 1.** Concepts and defintions as used in this thesis.

| Concept | Definition and reference |
| --- | --- |
| Adaptive cycle | Resilience perspective heuristic that describes four phase of change (growth, conservation, collapse, reorganisation) that are characteristic for many complex systems (Holling, 2001) |
| Agro-ecosystem | A social-ecological system, in which humans manage and use communities of plants, animals, soils and their interactions in order to make a living (Gomiero et al., 2006; Darnhofer et al., 2010) |

| | |
|---|---|
| Asymmetry | Non-random systematic variation. Asymmetry links pattern to a generating process (Cumming et al., 2008) |
| Co-evolution | A dynamic interaction between two or more interdependent systems, which account mutually for each other's development (Rammel et al., 2007). |
| Level | A discrete position on a scale, which position resulted from self-organisation (Gibson et al., 2000; Cash et al., 2006; Vervoort et al., 2012). Therefore also referred to as a level of self-organisation. |
| Panarchy | Resilience perspective heuristic of hierarchically arranged adaptive cycles, that represents cross-scale interactions (Holling, 2001) |
| Regime | A set of dominant feedbacks which lead the system to self-organize into a distinct structure and function (Kinzig et al., 2006) |
| Resilience | Resilience perspective heuristic that describes the capacity to deal with change and disturbances while retaining essentially the same functions and processes (Folke, 2006) |
| Resilience perspective | A set of five heuristics that structure observations of social-ecological systems provided by Walker et al. (2006). The heuristics are: adaptive cycle (1), panarchy (2), resilience (3), adaptability (4), transformability (5). |
| Scale | Reference systems used to structure dimensions of complex systems. A scale is constructed to make observations of the real world (Gibson et al., 2000; Cash et al., 2006; Vervoort et al., 2012) |
| Self-organization | Reinforcing local processes from which patterns emerge at a higher level (Levin, 2005). |
| Social-ecological system | Coupled interdependent system of humans and their environment (Folke, 2006) |
| Threshold | The combination of variables that direct the system to an alternative regime (Cumming, 2011) |

*1.2.3 From concept to case studies*

The resilience perspective evolved out of observation, using models as a tool for understanding (Folke, 2006) and has scarcely been used for theory-driven investigation of empirical social-ecological systems (Cumming, 2011). Currently no standard approach for theory-driven research on social-ecological systems is available and the diversity and complexity of agro-ecosystems offer a large variety of possible research avenues. I chose to study landscape-management interactions, while acknowledging that many other dimensions of agro-ecosystems are important to understand their functioning (for example networks (Hermans et al., 2013; Nelson et al., 2013)

Panarchy suggests the importance of taking into account the cross-scale influences of the processes from the scales above and below the focal scale. As my focal scale, I chose the scale above the individual farm but a sufficiently small scale, such that an individual can make a difference (sensu Cabell and Oelofse (2012)). This places farm management in a landscape, where (past) management differences still have an effect. The reasons for selecting this scale of analysis were two-fold: next to a disciplinary bias, soils and landscape become important when you work at the soil geography and landscape group! Yet my choice of scale has a more fundamental reason as well. Many applications of the resilience perspective separately analyse the ecosystems and the social system whereafter they are integrated. I find this approach problematic since it treats social and ecological systems as separate entities that can be taken apart to understand their emergent behaviour.

I see the decision of farmers to disturb an (ecological) process as both based on their beliefs, values and goals as on their perception of the ecological system condition. Management therefore is really at the interface of the social and the ecological system. The landscape-management focus captures the essence of social-ecological systems namely the dynamic interaction of human decision making on the management of natural resources.

*1.2.3.1 Case studies*

In this thesis two landscapes are investigated. One landscape in the Netherlands and one in Zimbabwe.

Agriculture in the Netherlands is characterized by high stocking densities, high inputs of chemical fertilizer and concentrates while facing multiple challenges on

environment and landscape (Vellinga et al., 2011). Dairy farming is the most important livestock sector in the Netherlands, and it is highly productive with regard to both animal and land productivity (Vellinga et al., 2011). Due to the intensity of production the dairy sector is at risk to lose its 'license to produce' from society (Veldkamp et al., 2009). The Dutch landscape of the Northern Frisian woodlands is an example of an experiment of farmers aiming for self-regulation in environmental and landscape management. The experiment has received considerable scientific attention for the farmers' attempt to reconcile farming and landscape (see among others Wiskerke et al. (2003); Groot et al. (2006); Sonneveld et al. (2012)). The Northern Frisian woodlands is a traditional rural landscape in the north of the Netherlands and has an area of about 60,000 ha. Dairy farming is the dominant land use in this area. The landscape is characterized by relatively small fields with a high density of hedgerows on sandy soils, alternated by relatively open areas on lower peat and clay soils. A unique mosaic of parcels is formed by hedges and belts of alder trees surrounding the plots of land.

The Zimbabwean case study is the Murewa smallholder farming area in Zimbabwe which is located about 80 km east of Harare. Smallholders In Zimbabwe face multiple challenges of land, labour, cash and organic resources (Giller et al., 2011) in a disfunctional institutional environment. The majority of the food in Zimbabwe is produced by smallholder farmers while located on the poorest soils most vulnerable to droughts (Andersson, 2007). Most smallholder farmers practice a mixed crop-livestock system with maize (*Zea mays* L.) as the dominant staple crop. Cattle are the main livestock which freely graze in communal rangelands during the day and are tethered in kraals close to homesteads at night. Close interaction between crop and cattle production occurs through crop residues that are used to feed cattle and the reciprocal use of manure to fertilize crops. Preferential allocation of manure, compost, mineral fertilizers and labour on fields near the homesteads give rise to fertility gradients. As a result soil fertility declines with increasing distance from the homestead. The village is well studied in relation to soil fertility and these gradients (Rufino et al., 2011; Zingore et al., 2011).

Both case studies are human dominated in the sense that a large part of the original ecosystem has been replaced, however still close interaction is found between ecological dynamics of the landscape and human management.

*1.2.3.2 Soil organic matter as a key variable*

To study landscape-management interactions I selected soil organic matter (SOM). SOM has been identified as an essential natural resource in many land-based agro-ecosystems because of its impact on physical, chemical and biological soil properties, SOM is considered to be the most important indicator of soil quality and agronomic sustainability (Reeves, 1997). SOM consists of decomposing materials originating from mainly plant tissue. The carbon content of SOM may be influenced by vegetation cover, organic matter composition, depth in profile, amount of organic matter, clay in the soil, and degree of decomposition, but is generally around 50% (Pribyl, 2010). Patterns of SOM can be linked to processes at global (Post et al., 1982; McLauchlan, 2006), European(Schulp et al., 2008), Dutch (Hanegraaf et al., 2009) , landscape (Schulp and Veldkamp, 2008) and farm (Tittonell et al., 2005) scale. Next to spatial variable processes, SOM is affected by management actions that alter accumulation and decomposition rates and the length of that time that SOM may accumulate in the soil (Post and Kwon, 2000). The spatial and temporal variance of SOM and the management effects of SOM on agro-ecosystems function, make SOM a good candidate variable that captures the long-term memory of management and landscape interactions.

## 1.3 Methods

The focus on management-landscape interactions allows me to build upon previous work of the Plant Production Systems and Soil Geography and Landscape groups. Plant Production Systems has a strong history of farming system analysis using both systems models and participatory approaches to explore management options. While Soil Geography and Landscape has strong history of spatial-temporal land use modelling and analysis at higher scales. The models provide hypothetical possibilities in which to embed the observed, in order to understand why we observe what we do, and don't observe what we don't (Levin, 2005). On the other hand current observations have been influenced by long-term processes that are unlikely to have been observed. And consequently current observation cannot be explained solely based on the current conditions. By using inverse modelling techniques (Tittonell et al., 2007) models can provide possible explanations of what we observe. This thesis is also pursuit of proper methods to incorporate a dynamic view in agro-ecosystem analysis. For example a dynamic model is well suited to explore long-term effects of fixed management in a fixed context. However the heuristics of adaptive cycle, panarchy and adaptive capacity state that processes, context and management cannot be assumed to be

static. These dynamics cause a large diversity of systems in different states of their adaptive cycle. Classifying systems on their current conditions misses the dynamic context. Therefore the asymmetry found in agro-ecosystems is embraced to represent these dynamics. Again this demands for unconventional methods in system description, rather than employing diversity-reducing methods of system description (classification, regression), other statistical methods are used to explore the diversity in relation to system functioning.

## 1.4 Problem definition

Agriculture is faced with new challenges while at the same time conceptualisations of agricultural systems are shifting. The resilience perspective offers a new conceptualisation of system dynamics which might shed light on the functioning of agricultural systems. An improved understanding of agricultural system functioning can contribute to overcome these challenges.

The general objective of this thesis is to employ a resilience perspective to agro-ecosystems to increase our understanding of agro-ecosystem functioning. In the separate chapters I try out several approaches and methods to test if the resilience perspective is useful for analysing agro-ecosystems.

In Chapter 2 'Panarchy rules', the objective was to identify multiple stable states of dairy farms in the Northern Frisian Woodlands. Literature as well conceptual models suggested the existence of a state with high nutrient use efficiency and one with low nutrient use efficiency. I analyse the dynamics in the Northern Frisian Woodlands by the five heuristics of the resilience perspective and a dynamic farm model.

In the subsequent Chapter 3, 'landscape asymmetry', my aim was to link the high nutrient use efficiency at farm level to locations in the landscape. I identify asymmetries and their effect on soil organic matter. Subsequently these asymmetries and SOM are set in a multi-scale framework that connects dynamics at patch farm and region scale with the ecological, economic and socio/cultural domain.

In Chapter 4 'co-evolution' I set out to localize regimes of production intensifying farms and farms that aim to reconcile farming and landscape. The previous chapter showed that a strategy of farm intensification and the re-balancing strategy can be characterised by regimes of positive feedbacks at field, farm and regional

scale. I identify relations between landscape patterns and production intensity, collect field scale data and analyse their relation with non-parametric statistics.

In Chapter 5 'scale-mismatch', I first investigate the landscape pattern or asymmetry at village scale, which I subsequently attempt to link to agro-ecosystem functioning. The initial hypothesis for this chapter was that lack of fertilizers would lead to less biomass returned to the fields, which would lead to steeper gradients. I design a sampling scheme, map soil organic carbon at the village scale and relate this farm management and landscape characteristics.

In the final chapter 'to Panarchy rules?' I highlight the increased understanding of agro-ecosystem functioning gained by employing the resilience perspective. Paradoxically the empirical results of my thesis challenge the fundaments of the resilience perspective. I therefore suggest an additional heuristic in order to focus the lens of the resilience perspective for agro-ecosystem analysis.

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# Chapter 2

# Panarchy Rules: Rethinking Resilience of Agro-Ecosystems

**Abstract**

Resilience has been growing in importance as a perspective for governing social-ecological systems. The aim of this paper is first of all to analyze a well-studied human dominated agro-ecosystem using five existing key heuristics of the resilience perspective and secondly to discuss the consequences of using this resilience perspective for the future management of similar human dominated agro-ecosystems.

The human dominated agro-ecosystem is located in the Dutch Northern Frisian Woodlands where cooperatives of dairy farmers have been attempting to organize a transition towards more viable and environmental friendly agro-systems. A mobilizing element in the cooperatives was the ability of some dairy farmers to obtain high herbage and milk yield production with limited nitrogen fertilizer input. A set of reinforcing measures was hypothesized to re-balance nitrogen flows and to set a new equilibrium. A dynamic farm model was used to evaluate the long-term effects of reinforcing measures on soil organic matter content, which was considered the key indicator of an alternative system state.

Simulations show that no alternative stable state for soil organic matter exists within a plausible range of fertilizer applications. The observed differences in soil organic matter content and nutrient use efficiency probably represent a time lag of long-term non-equilibrium system development. The resilience perspective proved to be especially insightful in addressing interacting long-term developments expressed in the panarchy. Panarchy created a heterogeneity of resources in the landscape providing local landscape-embedded opportunities for high N-efficiencies. Stopping the practice of grassland renewal will allow this ecological landscape embedded system to mature. In contrast, modern conventional dairy farms short-cut the adaptive cycle by frequent grassland renewals, resulting in high resilience and adaptability. This comes at the cost of long-term accumulated ecological capital of soil organic matter and transformability, thus reinforcing the incremental adaptation trap. Analysis of such a human dominated agro-ecosystem reveals that rather than alternative states, an alternative set of relationships within a multi-scale setting applies, indicating the importance for embedding panarchy in the analysis of sustainable development goals in agro-ecosystems.

## 2.1 Introduction

Classic agronomical research has been largely driven by a commodity-based, plot- or field-scale approach with an emphasis on the potential for short-term maximization of crop and livestock production (Giller et al. 2006). Recent studies demonstrate that multiple spatial and temporal scales need to be addressed in order to understand current patterns in agricultural system functioning (Sonneveld et al. 2002, Giller et al. 2006, Schulp and Veldkamp 2008). In addition, the role of rural areas is changing and ecosystem services other than primary production are increasingly valued as well (Carpenter et al. 2009). This changing role of rural areas has led to explorations of new modes of rural governance (Renting and van der Ploeg 2001, Wiskerke et al. 2003). At the same time, agriculture faces the challenge of an increasing global demand for food, while maintaining the capacity of the biosphere to provide goods and services on the long term (Foley et al. 2005, IAASTD 2008).

To face this challenge, new sustainable development perspectives are needed (Veldkamp et al. 2009). The resilience perspective has become increasingly popular, because it appeals to the notion of sustainable and dynamic development (Carpenter et al. 2001, Kremen and Ostfeld 2005). Resilience has been growing in importance as a perspective for understanding, managing, and governing complex linked systems of people and nature (Anderies et al. 2006a, Folke 2006). From a measure of how fast a system returns to an equilibrium state after a disturbance, resilience has evolved to a perspective that is used by various scientific disciplines to analyze ecological as well as social-ecological systems (Anderies et al. 2006b, Brand and Jax 2007). The resilience perspective specifically focuses on the interplay between periods of gradual change and periods of rapid change, and how such dynamics interact across temporal and spatial scales (Folke 2006).

Agroecosystems, in which humans manage and use communities of plants, animals, their biophysical environment, and their interactions (Gomiero et al. 2006), can be considered as social-ecological systems. In most modern agroecosystems, the native ecosystem has been replaced and has been dominated by humans over long periods of time. Although they are human-dominated, agroecosystems still rely on ecological processes.

The resilience perspective has originally been applied to social-ecological systems where the native ecosystem is still in place. The aim of this study is to apply the resilience perspective to a human dominated agroecosystem. The aim is realized

by addressing two objectives: (1) Analyze a well-studied agroecosystem using five key heuristics of the resilience perspective, and (2) discuss the consequences of using this resilience perspective for the future management of similar human dominated agroecosystems.

## 2.2 Materials and methods

To organize our analysis on resilience of agroecosystems we use a set of five heuristics provided by Walker et al. (2006), and that are generally accepted as important elements of resilience. The heuristics are: the adaptive cycle, panarchy, resilience, adaptability, and transformability. Below we introduce the heuristics and their application to agroecosystems.

### 2.2.1 Agroecosystems and the resilience heuristics

1. Adaptive cycle

The adaptive cycle describes four commonly occurring phases of growth, conservation, collapse, and reorganization in social-ecological systems. For agroecosystems, dynamics of the adaptive cycle might not always hold. Allison and Hobbs (2004) for example, found a pathological state of lock-in. Exceptions to the adaptive cycle seem particularly to occur under the influence of large, external disturbances and a lack of critical forms of capital (Walker et al. 2006).

2. Panarchy

A panarchy is a heuristic of linked, hierarchically arranged adaptive cycles. The linkages between the adaptive cycles in the panarchy might cause cascading events: the collapse of one level inducing the exceeding of other thresholds. Kinzig et al. (2006) describes several examples of agroecosystems where changes at field level might cause regional change. Such cascading events often lead to very resilient, although often less desirable, alternative states. Moreover, there is strong evidence that agricultural modification can produce a variety of ecological regime shifts that operate across a range of spatial and temporal scales and domains (Gordon et al. 2008).

3. Resilience

Because of increased popularity of the resilience concept (Brand and Jax 2007), resilience is often confused with sustainability or is considered inherently good. We use resilience as a non-normative heuristic. Resilience describes if and how a

disturbed system returns to its former functioning. The high resilience of the pathological state of lock-in (Allison and Hobbs 2004) and the cascading events of Kinzig et al. (2006) are examples of high resilience, where degradation within the agroecosystem creates a persistent system, which is difficult to disturb.

4. Adaptability

Adaptability is the capacity of humans to manage resilience. Modern agroecosystems have a mixed reputation on adaptability. On the one hand, they are able to stabilize production via access to external resources, e.g., artificial fertilizers, concentrates etc., thus showing a high adaptability to external fluctuations. The access to external resources comes at a cost of dependency on forces that farmers are unable to control, and that must be taken as constraints upon the system. At the regional level, however, the strategy followed continues to have impact on the slow ecological variables, reducing the potential or capital through time (Anderies et al. 2006a). Thus, an undesirable system configuration is created, leading to a reduced adaptive capacity (Milestad and Darnhofer 2003).

5. Transformability

Transformability is the capacity of the actors within the system to create a fundamentally new system when the existing configuration is untenable. Determinants of transformability include incentives to change, cross-scale awareness, experimentation, reserves and convertible assets (Walker et al. 2006). Highly resilient, undesirable regimes tend be created by cascading events in the panarchy (Kinzig et al. 2006). Modern agroecosystems can generally be seen as low transformable, with eroded natural resources, a low diversity in crops, large scale subsidies, vested interests of the conglomerated agri-foodchain reducing innovation, diversity, and human organization.

*2.2.2 Description of study area*

The Northern Frisian Woodlands is an area of about 60,000 ha located in the north of the Netherlands and is dominated by dairy farming. In the 1990s, the exceedance of environmental quality standards for atmosphere and groundwater resulted in national regulations that forced farmers into new modes of organization. Because some of the imposed regulations conflicted with local conditions, regional environmental farmer cooperatives were established with the aim to move towards viable and environmental friendly agro-systems that fit in their landscape (Renting and van der Ploeg 2001). With the rural-environmental

cooperatives, new modes of science, learning, governance and rural development were explored by communities of practice, in which scientists work together with various stakeholders and policy makers of different scales in a joint learning mode (Renting and van der Ploeg 2001, Roep et al. 2003, Stuiver et al. 2003, Van der Ploeg 2003, Wiskerke et al. 2003, Eshuis and Stuiver 2005, Bouma et al. 2008).

A mobilizing element in the cooperatives was the ability of some farmers to obtain high herbage and milk yield production with limited nitrogen fertilizer input (Reijs et al. 2004). A regional nutrient management project was initiated to perform on-farm analysis of nitrogen balances, and to assist farmers in the transition to more sustainable farming with reduced nutrient inputs (Groot et al. 2006). Reijs et al. (2004) reported that farmers in the Northern Frisian Woodlands had found a new equilibrium by re-balancing nitrogen flows resulting in a well-balanced system (Groot et al. 2006). This suggests that, from a resilience perspective, possibly an alternative stable state was discovered. The alternative state might not be a true alternative stable state (Scheffer et al. 2001), but at least represents a regime shift in the sense of being a drastic change in the properties of a system, resulting from smaller perturbations or smooth changes in independent controlling variables (cf. Scheffer and Carpenter (2003), Kinzig et al. (2006), Walker and Meyers (2004)).

*2.2.3 Modeling resilience of agroecosystems*

For identifying alternative stable states, system models are particularly useful. They organize the key elements of a case into a structure that can be used to identify the slowly changing variables, stabilizing and destabilizing forces, and important thresholds that determine the resilience of a system (Bennett et al. 2005). In the Northern Frisian Woodlands, farmers and scientists had together identified a set of measures that would mutually reinforce each other and would self-balance the farm (Reijs et al. 2004). Specifically, they experimented with the following measures:

- Reduction of artificial fertilizers and concentrates,
- A lower crude protein and higher fiber content in the silage,
- A higher fraction of organic matter and organic nitrogen in the manure,
- Limited grassland renewal and maize production.

The measures were considered to reinforce each other. A reduction of artificial fertilizers would lead to lower crude protein content in feed, complemented by cutting the grass later in the season. This diet would in turn increase the C:N ratio, and decrease the inorganic N content of the manure, in turn leading to higher soil organic matter content, finally leading to reduced need of fertilizers. Although

some farmers experimenting with the reinforcing measures also changed other aspects of their farming practice, for example applying microbiological active additives to the manure, and manure application practices, the main aim of the reinforcing measures was to reduce external fertilizer need (Reijs et al. 2004). Grassland renewal and maize production need plowing of the field, resulting in lower soil organic matter contents (Hanegraaf et al. 2009). When plowed and converted to arable land, 50% of the organic matter is lost within 6 years (Whitmore et al. 1992). Therefore, soil organic matter content can be conserved by limiting these practices.

*2.2.4 Key variables*

Nitrogen and soil organic matter were used as key variables for modeling the resilience of intensive dairy farming. Nitrogen is considered a key variable for intensive dairy farming (Whitehead 1995). Moreover, inputs and outputs are commonly monitored in Dutch dairy systems for which generally applicable process-based models exist (Van den Pol-van Dasselaar and Lantinga 1995, Kohn et al. 1997, Groot et al. 2003, Schröder et al. 2003). Soil organic matter is a slow variable and because of its impact on other physical, chemical, and biological soil properties, it is often chosen as the most important indicator for soil quality and agronomic sustainability (Reeves 1997). Additionally, the observed differences in N balances were considered to be mainly caused by differences in water balance and soil organic matter (Groot et al. 2007).

*2.2.5 Model description of an intensive dairy farm in the Netherlands*

In the studied intensive dairy farming practice, only part of the total dry matter production is sold or consumed by cattle (Whitehead 1995). A large part remains on the farm as roots, stubble, manure, etc. the remains are part of a nutrient cycle on the farm. In Figure 1 the flows of the nitrogen cycle and their magnitude on conventional farms (lower number) and farms that are experimenting with the reinforcing measures (upper number) are given.
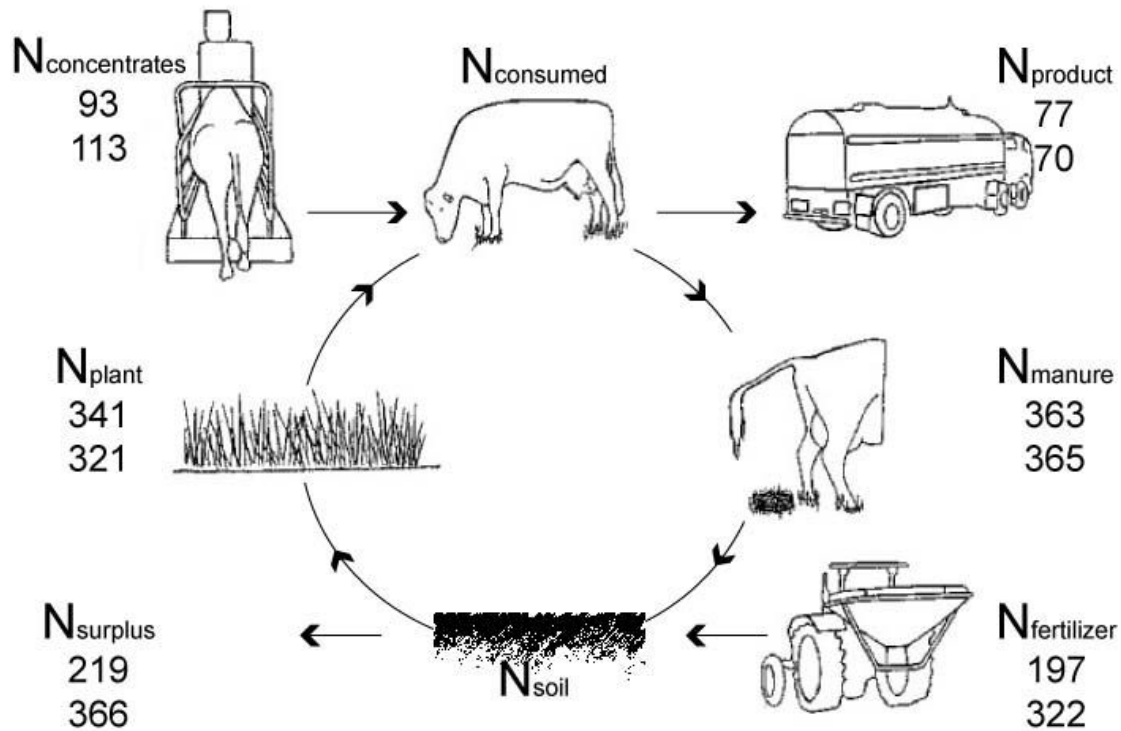
**Figure 1.** The N cycle at a dairy farms, the numbers are N flows (kg/ha). The upper number is averages of farmers applying the reinforcing measures, the lower number are averages of conventional farmers in the area. Data are based on group averages in 1997 (Groot et al. 2006) and 17.8% and 16.1% efficiency of the cow.

Next to export and import of manures, crops, animals, and animal products, the N-cycle receives inputs from atmospheric deposition, biological fixation, fertilizers, and concentrates, and loses nitrogen to the atmosphere, the groundwater, or surface waters. Whereas most resilience models use hypothetical nonlinear functions to describe multiple stable states and system behavior, we based our model on observed relationships that have been published in Whitehead (1995), Groot et al. (2003), and Reijs et al. (2007). Since we are interested in the interaction of management and ecological processes as observed in the Northern Frisian Woodlands. We generalized relationships and did not model a particular farm or make prescriptions on management practice. The general relationships could be verified by the data available from the nutrient management project at the Northern Frisian Woodlands.

*2.2.6 Feedbacks of nitrogen and soil organic matter of intensive dairy farming*

The cycling of nitrogen is divided between organic and inorganic nitrogen. The carbon to nitrogen (C:N) ratio regulates the conversion from the organic nitrogen form to the inorganic nitrogen form (Janssen 1996). In return, the nitrogen and carbon fixed in organic matter is mainly a function of available inorganic nitrogen

taken up by the grass. The division between the nitrogen bound to organic matter and inorganic nitrogen determines the speed of recycling. Inorganic nitrogen is a fast component of the cycle and is very volatile, and can be taken up by plants.

We indicated the internal feedbacks of nitrogen and interactions with soil organic matter of intensive dairy farming in the nitrogen cycle at farm level (Figure 2).
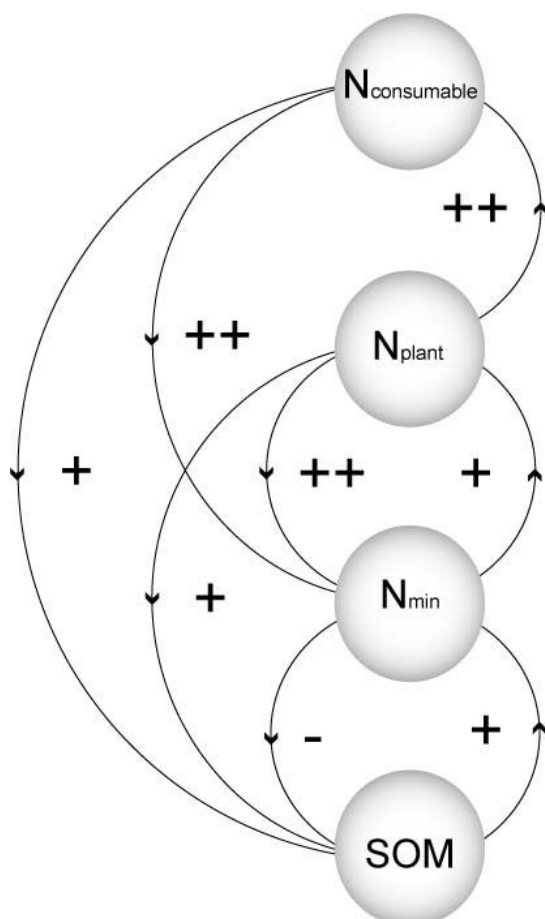


**Figure 2.** Feedbacks within the nitrogen cycle at farm level. Non-linear increases in flows are depecited as ++. For description of feedbacks see text.

Grass has a high capacity of soil mineral nitrogen (Nmin) uptake, but risks for environmental losses increase with higher amounts of mineral nitrogen in the soil (Sonneveld et al. 2002). Part of the nitrogen captured in the plant (Nplant) is harvested or grazed and consumed by livestock (Nconsumable). Increasing mineral nitrogen in the soil has two effects: 1) the root/shoot ratio of the biomass becomes lower (Van den Pol-van Dasselaar and Lantinga 1995) and 2) the nitrogen concentration in the plant increases (Whitehead 1995). The higher the uptake of nitrogen by the biomass, the larger the proportion of nitrogen is harvested and removed from the field (depicted as ++ in Figure 2). Nitrogen consumed by cattle is distributed between urine, feces, milk, and meat. The higher the concentration of nitrogen (crude protein) in the diet of cattle, the higher the

proportion of nitrogen that ends up in the urine (Whitehead 1995) (depicted as ++ in Figure 2). Part of the nitrogen from feces and urine is lost during housing and storage. The remaining nitrogen in feces and urine is returned to the field as manure. The nitrogen in the urine directly returns as inorganic nitrogen in the soil. The organically bound nitrogen in the feces and soil organic matter (SOM) contributes to the inorganic N pool via mineralization. The remaining unharvested biomass immobilizes inorganic nitrogen when the C:N ratio of the unharvested biomass is higher than that of the decomposing soil microbes (Janssen 1996). With larger amounts of mineral nitrogen available, the C:N ratio of the unharvested biomass decreases (Whitehead et al. 1990). When the unharvested biomass decomposes, it contributes back to the mineral nitrogen pool. The remaining organic compounds of the feces and the unharvested biomass (mostly roots) contribute to the buildup of the soil organic matter pool. The buildup of soil organic matter is mainly regulated by the input of carbon (Hassink 1994), thus for soil organic matter to increase, more carbon has to be returned to the soil.

The soil inorganic N pool (Nmin) and the nitrogen uptake by the plant (Nplant) cycle within a year, whereas soil organic matter can have turnover rates of decades or even centuries (Janzen 2005, Schulp and Veldkamp 2008). There are thus two cycles that control the nitrogen in the system. One cycle is from inorganic nitrogen from fertilizer or urine (Nmin) to the grass (Nplant), then to the livestock and back to inorganic nitrogen via urine and mineralization of feces and unharvested biomass. This is a fast cycle, which is used for environmental regulations and nutrient balances. The other cycle is via soil organic matter (SOM) in the soil. This cycle is slower because the turnover rate of soil organic matter is at least one order of magnitude higher.

Details of the model formulation are given in the Appendix 1. To simplify matters, we assumed that the herd size and accompanying milk production follows biomass production. Storage or selling of feed and manure were not included in the model. The model was used to test if alternative stable states could be identified by reducing nitrogen input.

## 2.3 Results and discussion

In this section we first analyze the effect of different fertilizer applications and accompanying farm management using the five heuristics and model simulations.

Thereafter, we discuss the consequences of using the resilience perspective on this human dominated agroecosystem.

In Figure 3, the required time is calculated to reach equilibrium conditions for a range of fertilizer applications and soil organic matter contents. The time needed was plotted on the Z-axis, generating a stability landscape (see Scheffer and Carpenter (2003). At the bottom of Figure 3, the solid line shows that over time for all simulated fertilizer applications a comparable soil organic matter content is reached.
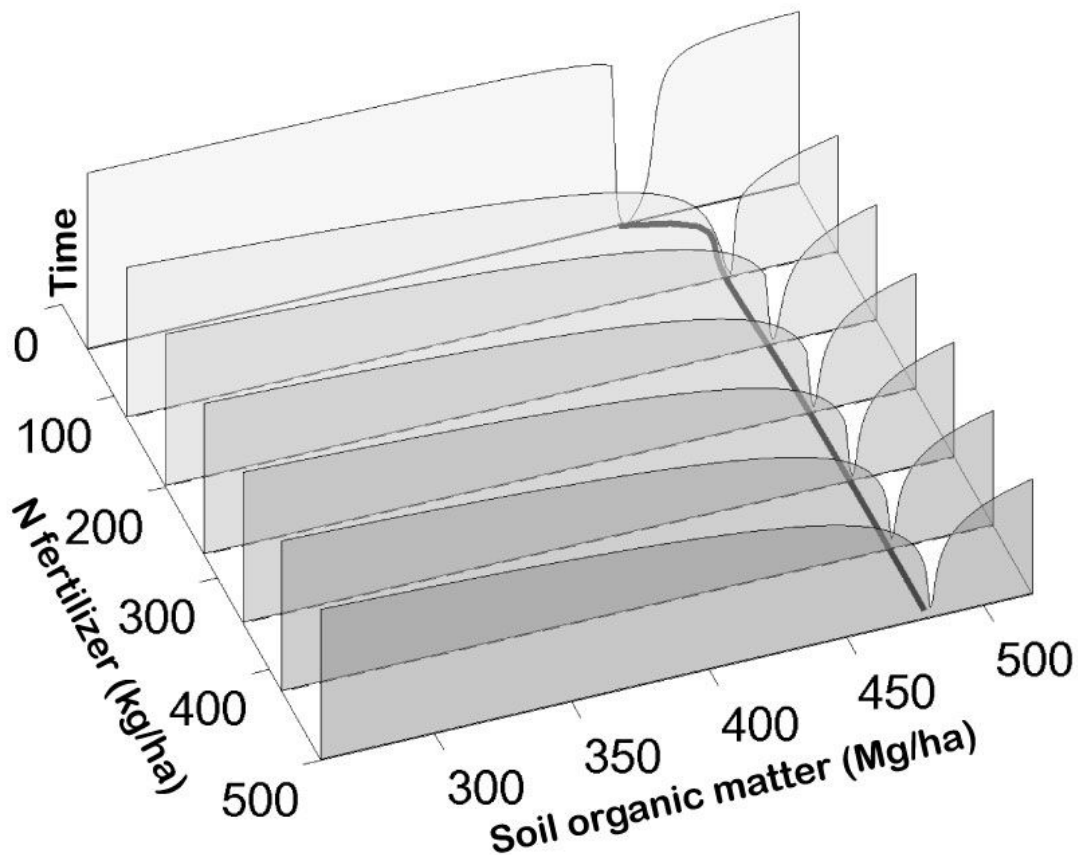


**Figure 3.** Stability landscape of the interaction between fertilizer input and soil organic matter. For a broad range of soil organic matter values the time of reaching equilibrium conditions with a certain N-fertilizer application is calculated. This period of time needed to reach equilibrium is represent by height of the landscape. Initial condition is a field after maize cultivation and based on Sonneveld et al. (2002).

The simulations show that no true stable alternative state for soil organic matter exists within a range of 50-500 kg N/ha applications. The relatively flat landscape with the steep gully suggests a low response of soil organic matter to the management variable of artificial fertilizer; the system is resistant to change in fertilizer application. The steep slope at the edge of the gully is not caused by changes in management, but is the effect of a long-term process. Only when the

soil organic matter is almost at its equilibrium value does the return time drop. With such a low response of the management variable no catastrophic shifts or thresholds can be detected at this level.

High levels of inorganic nitrogen do not influence the accumulation of soil organic matter. With increasing concentrations of mineral nitrogen, more mineral nitrogen is lost. Thus, given enough time, every reasonable amount of nitrogen fertilizer application would result in the same soil organic matter content. Consequently, differences in soil organic matter cannot be explained by alternative states caused by fertilizer application. Alternatively, the observed differences in soil organic matter content and nutrient use efficiency probably represent systems that are out of equilibrium. This has implications when analyzed using the five heuristics of the resilience perspective.

*2.3.3 Discussion of the heuristics*

1. Adaptive cycle

Farms that are experimenting with the reinforcing measures aim to optimize nutrient recycling in the system with less dependency on external resources, notably artificial fertilizer. The high productivity of the managed grasslands is reached through a high efficiency of recycling nitrogen in soils that have high organic matter content. This state is comparable with the conservation phase of the adaptive cycle.

Conventional modern farm management is mainly limited by prices of the inputs and constraints of management regulations rather than their recycling of nitrogen. Current policies induce a strategy that aims at optimizing the fast conversion of mineral Nfertilizer to Nconsumable in order to get high outputs (Schröder et al. 2003). This can be classified as a command and control strategy (Holling and Meffe 1996) that builds on the fast response of grassland productivity to external inputs and continuous high levels of grass production. The main goal of this strategy is fast response instead of resistance to change. The design on the fast response of external inputs has a contra-ecological consequence: the development of internal recycling, the growth phase, is halted.

Steering on output of the field and disregarding internal dynamics leads to frequent grassland renewals. With grassland renewal, the sod is destroyed, the soil is tilled, and the field is reseeded with high productive grass varieties. After renewal, the grassland starts accumulating organic matter again (Vellinga et al.

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2004). However, after a few years the renewed grassland declines in production again. This decline is, however, only temporary, as the buildup of soil organic matter (the growth phase) is not matched with the mineralization capacity of soil biota (Hoogerkamp 1984), leading to a perceived deterioration of the grassland.

In combination with a sward deterioration caused by urine scorching, treading, winter mortality, and late mowing or grazing, frequent grassland renewal, including soil tillage, becomes an attractive option (Van Loo 1993).

Grassland renewal keeps soil organic matter and its N-supply at low levels. The development of the soil's internal recycling is associated with the increase of potential in the adaptive cycle. Rather than developing toward a quasi-equilibrium, the system is regularly disturbed, preventing it from developing the internal recycling. Within the adaptive cycle, the conventional strategy puts the agroecosystem in a short-cut loop from rapid growth phase to the reorganization phase (α; Figure 4).
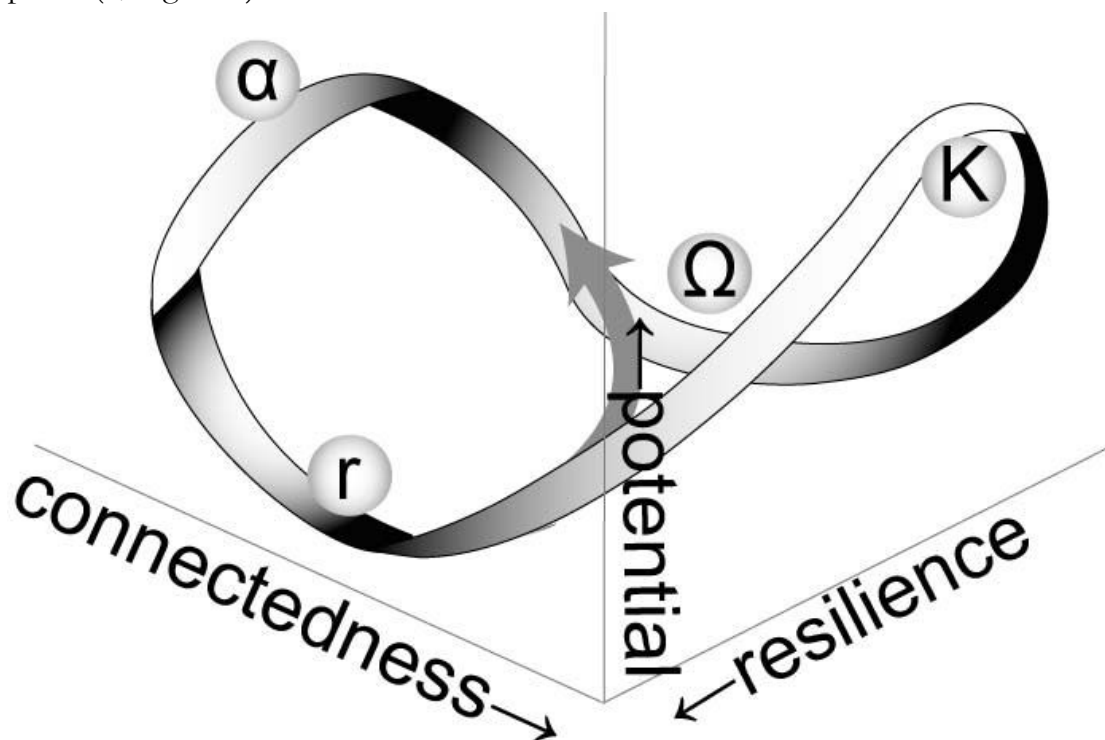


**Figure 4.** Conventional farming short-circuit the adaptive cycle. The dynamics are characterised by fast feedbacks. frequent disturbances prevent the system from developing recycling mechanisms in ecosystems associated with a high potential. The high inputs during the reorganization (α) -phase enable a high potential and adaptability.

The reorganization phase in the adaptive cycle with conventional farms is characterized by a low connectedness, high potential, and high resilience (see Figure 4). The low connectedness causes the system to be leaky (Holling and

Gunderson 2002). This results in large amounts of nitrogen being lost through leaching and gaseous emissions, causing environmental problems.

In ecosystems, the dynamics of the reorganization phase are characterized by physical structures and their residual vegetation (Holling 2001). The reorganization phase has a high uncertainty, meaning that the final outcome (K phase) is uncertain. With the renewal of grasslands, external inputs of seeds and herbicide make sure that preferred species, namely high productive grass varieties, dominate during the reorganization phase. The large input of artificial fertilizer compensates for nutrient losses that normally occur in this phase, to offset a loss of potential.

## 2. Panarchy

Soil organic matter is a variable that connects multiscale ecological dynamics and farm management. For farms experimenting with the reinforcing measures, three main timescales influence the organic matter content of their soils. The longest is landscape evolution on a geological timescale of millennia, when glacial till and cover sands were deposited and land topography developed. Till deposits affect soil organic matter content through impeded soil drainage, which influences mineralization of organic matter. The next timescale comprises the centuries of reclamation. The top soil is created by human management. Remains of peat and heath were mixed or added to the soil to increase the agricultural value of the topsoil. Superimposed on the long-term processes is current management, such as plowing and manuring, affecting soil organic matter content on the scale of decades. The three time scales together create a heterogeneous soilscape (Veldkamp et al. 2001).

The aim of reaching high soil organic matter contents of fields can only be achieved by not disturbing the field with tillage and by accounting for the effects that the drivers of these timescales have. This requires a more ecological and long-term perspective on management actions.

High soil organic matter content at the field level is the cumulative result of historical management actions. As such, history is reflected in the small-scale landscape, which provides an identity (Antrop 2005) to the Northern Frisian Woodlands. In contrast, conventional grassland management calls for large scale homogenized fields, causing a loss of accumulated capital of soil organic matter and possibly regional identity.

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Conventional management with its high reliance on artificial fertilizers and large machinery does not depend on locality and land use history. The frequent disturbance of plowing disconnects fields from their spatial position in the landscape and resets the accumulation of soil organic matter.

The access to artificial fertilizers and concentrates is essential for the conventional strategy. The high dependence on external resources and cheap energy inherently makes the strategy vulnerable for higher scale shocks such as energy scarcity (Anderies et al. 2007). Furthermore, the conventional strategy is closely tied to agricultural science and environmental regulations at regional, national and European scale (Van der Ploeg et al. 2007), which are based on assumptions of full control and steady-state conditions. This strategy, where inputs and outputs at farm level are well-monitored and easy to control, complies with the existing environmental policies that use static nutrient balances. Conventional management is thus much more controlled by its socio-technical regime than by its ecological context. In other words, the fields are much more connected to organizational levels of the farm and higher, rather than the landscape level.

Clearly both management strategies are embedded in forces that extend from the plot to the global scale. However, rather than alternative states, an alternative set of relationships within a multiscale setting applies to these systems. Conventional management seems to be much more part of institutional panarchy whereas the reinforcing measures are more ecologically embedded.

## 3. Resilience

Independently from fertilizer input, soil organic matter will increase. Thus, differences in soil organic matter content represent different positions on the trajectory of soil organic matter accumulation. During this trajectory, the response of the soil to disturbances changes gradually; the trajectory from low soil organic matter to high soil organic matter content is long and strongly nonlinear. When a farmer intends to move from conventional management to the reinforcing management measures, the stocks of inorganic nitrogen and soil organic matter change over time (Figure 5). First, a steep decline of mineral nitrogen in the soil occurs, because input of inorganic nitrogen is greatly reduced. After conversion, the nitrogen provided by soil organic matter will increase slowly (Whitehead 1995).
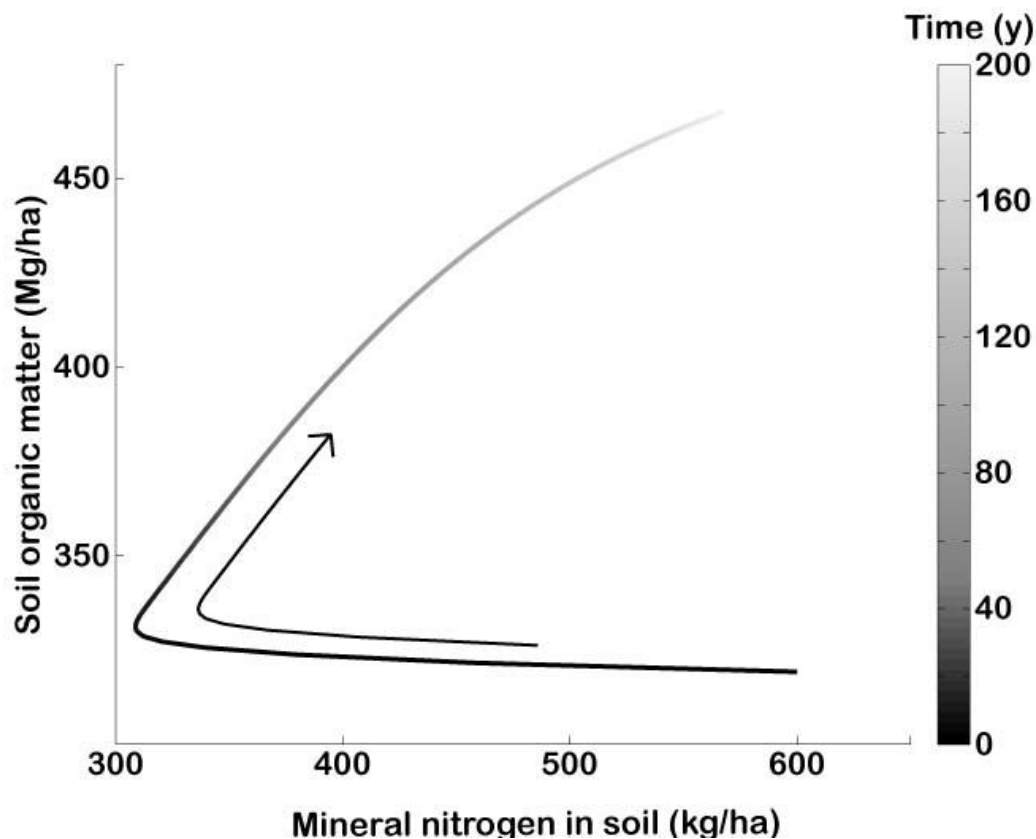
**Figure 5.** Modeled trajectory of change (line) in the phase space of mineral nitrogen $N_{min}$ and soil organic matter. Initial condition is a field after years of maize cultivation, based on Sonneveld et al. (2002) and afterwards receives 125 kg fertilizer N/ha. Mineral nitrogen determines the yield of the field and in 200 years the farmer will have almost the same yield with half of the external fertilizer input. The trajectory is strongly non linear, the fast variable of mineral nitrogen decreases steeply and recovery of this variable is slow with the increase of soil organic matter.

Near-equilibrium conditions associated with the reinforcing measures are resistant to frequently occurring disturbances. For example, biomass production on fields managed according to the reinforcing measures are less affected by variation in precipitation and temperature (Groot et al. 2007). The high soil organic matter content and well-developed rooting system of the fields provide a buffer to these changes. Moreover, changes in regulations or in price of external inputs will have less effect on the systems, because they use less of these external inputs.

In contrast, conventional grassland management with its frequent disturbances represents a system that is easily disrupted, for example, more highly affected by weather variation, but can also be easily adjusted because its controls (inputs) lie outside the field's borders. The lack of recycling creates a nearly linear system with a fast response. These properties make it more adaptable and easy to manage.

The transition toward more nutrient efficiency thus requires a trade-off: to decrease nitrogen losses and dependency on external finite and market-dependent

resources, the system has to move from the reorganization and growth to the climax phase. The increase in internal regulation will make the system more efficient and resistant, but, according to the adaptive cycle, also less resilient.

### 4. Adaptability

As argued above, the accumulation of soil organic matter is slow and hardly affected by operational management. At field level, the adaptability of the reinforcing measures is thus low. This low field-level adaptability however, can be compensated for at farm and regional level. The reinforcing measures combine well with other functions of the landscape (Wiskerke et al. 2003). For example, extra income is obtained by activities such as maintaining characteristic landscape elements of hedge rows, the conservation of meadow birds, or tourism. At the institutional level, the environmental cooperatives have been very successful in obtaining support from local, regional and national institutes (Roep et al. 2003).

Conventional farming has a high adaptability at field level, by the high control the farmer can exert with application of external inputs such as artificial fertilizers, concentrates, seeds, and pesticides. The high adaptability is further enhanced by the dominant position of the conventional strategy within Dutch institutions, providing further support when shocks occur (Van der Ploeg et al. 2007).

### 5. Transformability

The region as a whole has shown a high transformability in the socio-institutional domain by creating the environmental cooperatives. From a governance perspective, a new system with new multi-level relationships was developed (Wiskerke et al. 2003), Transformations to other system configurations are not to be expected nor aimed at, as current activities and social support are all based on maintaining a form of land-based agriculture connected to the landscape.

The prolonged success of the transformation is unsure because it depends on the slow variable of soil organic matter accumulation. Conventional farming practices of maize cultivation and grassland renewal are still widely practiced (Sonneveld et al. 2002). When plowed, the organic matter content will decrease drastically. Subsequently, the fields must be managed according to the needs of fields with low organic matter values that are responsive to fertilizer change.

The high adaptability and fast recovery of conventional farming are causing a trap of incremental adaptation (Anderies et al. 2006a). By incrementally adapting, short-term returns become a trade-off for other system configurations. Each small

adaptation reinforces the dominant social and economic structures, further reinforcing the incremental adaptation process by economic forces and vested interests. The inertia thus generated by the land use history and biophysical processes might become so large that it precludes transformability of the system.

*2.3.4 Discussion of the Resilience perspective*

Given the discussion above, we consider that the resilience perspective adds understanding to the system. In Table 1 we summarize the findings of the previous section.

**Table 1.** Summarized findings of our analysis of conventional managed systems and the reinforcing measures

| Heuristic | Conventional management | Reinforcing measures |
|---|---|---|
| Adaptive Cycle | from growth to reorganisation | from growth to conservation |
| Panarchy | institutional panarchy | ecological panarchy |
| Resilience | fast return | resistant |
| Adaptability | high due to institutional connection | low at field level/ high at farm level due to multi-functional use |
| Transformability | low, incremental adaptation trap | low, is still developing from past transformation |

A practical result of analyzing this case study with the resilience perspective is that it provides a possible explanation of the observed unrelated inputs and outputs of the farms in the region. The lack of correlation between inputs of nitrogen fertilizer and output of herbage appears to be a timelag. In Figure 6, we plotted the simulated input-output relation of artificial fertilizer and consumable nitrogen at different timespans after plowing a maize field and converting it to grassland. The input-output relationship was calculated after simulating one year, five years, and 200 years over a range of 0-1200 kg/ha of N-fertilizer applications. The figure shows that the consumable N production (kg ha$^{-1}$ yr$^{-1}$) increases with time if not plowed, given a fixed fertilizer input (kg ha$^{-1}$ yr$^{-1}$).
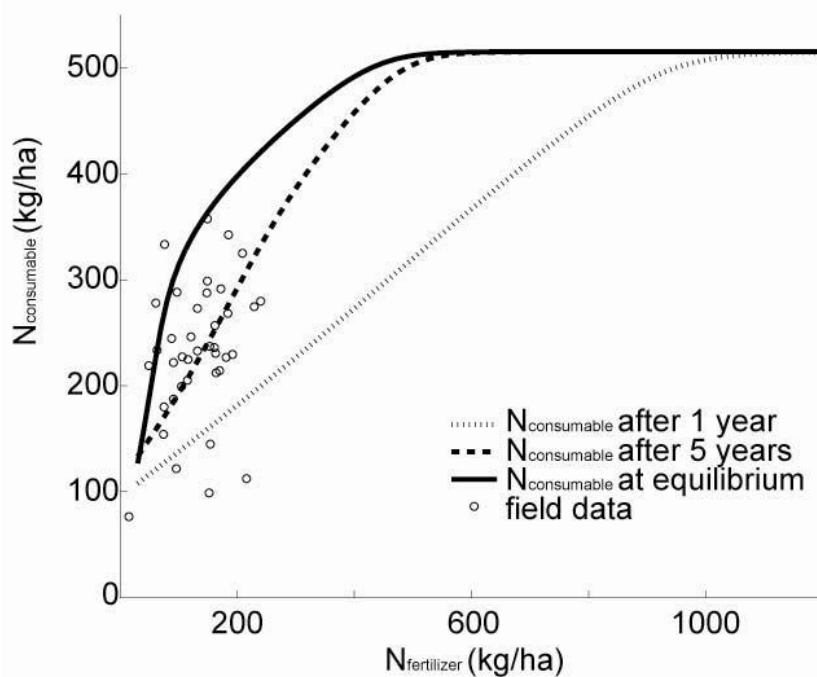


**Figure 6.** The change of input-output relation of the consumable part of the plant to external nitrogen input. For a field after years of maize cultivation, the dotted line is the response of the consumable part to fertilizer after 1 year. The dashed line after 5 years and the solid line when the system has reached equilibrium. The circles are the input-output relation of farms in 2006.

With increasing inputs, the relative contribution of soil N supply decreases. In other words, the dominance of internal dynamics decreases. This might explain why the difference in nutrient use efficiency was not observed earlier, because fertilizer applications of more than 400 kg/ha were not uncommon, thus masking the difference. The area between the first year line and the equilibrium line is the modeled space of possible input-output relations. In Figure 6, we also plotted the observed (2006) input-output relations of farms in the region. First, this shows that regionally, the uncorrelated inputs and outputs are still visible after almost a decade of the nutrient management project. It furthermore demonstrates that

most actual data points are within the modeled space of input-output relations. It also illustrates the limitations of the model approach. The almost vertical increase of nitrogen in consumable biomass in equilibrium systems is not observed in practice. In the model, all sources of external nitrogen are considered to be fertilizer, whereas fields also receive external nitrogen via nitrogen deposition and nitrogen fixation by leguminous plants (up to 70 (kg ha -1 yr-1)) in comparable farming system (Sonneveld et al. 2008)). This input, together with the nitrogen supplied by mineralization of soil organic matter, is then labeled as soil nutrient supply, shifting the Y-axis and observed fertilizer applications to the right. Furthermore, we assumed that the whole farm was managed as one field with a consistent strategy, whereas different strategies evolved (Groot et al. 2006) and not all fields were managed similarly. The location of points below the first year line can be explained by the fact that these are farm-scale figures, and not all fields are grasslands for some farms. A field used for maize cultivation, for example, receives manure that would otherwise have been applied to grassland. The grasslands of these farms in turn receive more fertilizer.

Importantly, Figure 6 shows that input-output relations are time-dependent. The recognition that grasslands are not in equilibrium and are internally developing toward a system with other characteristics needs to be taken into account in further research. In Figure 6, time and space relations are combined. This hides the possibility that nutrient efficient systems are developed on favorable locations. Three qualitatively different temporal processes of the panarchy, i.e., landscape evolution, reclamation history, and current land management, together created a heterogeneous landscape with a potentially high soil organic matter content and associated high nutrient use efficiency. The theoretical trajectory of change (Figure 5) has probably never been followed completely. The panarchy that created the heterogeneity of resources in the landscape provides local landscape-embedded opportunities for high N-efficiencies.

## 2.4 Rethinking resilience of agroecosystems

Although we used a temporal model at field-farm level, and only skimmed over spatial and social dynamics, several elements of this study are relevant for further resilience-based studies of human dominated agroecosystems. For modern, conventionally managed agricultural systems, the heuristic of the adaptive cycle is less applicable. These systems do not follow the adaptive cycle but rather a shortcircuit version: from reorganization to exploitation to reorganization (Figure 4). High output is reached at the cost of high losses, as in short circuits. In Holling

and Gunderson (2002) this trajectory is hinted at for both arid grassland systems and more productive systems. Systems in this trajectory are continuously adapting to external variability and, according to Holling and Gunderson (2002), they are remarkably resilient. Although globally modern agroecosystems are seen as the epitome of nonresilience with their monocultures and energy-intensive farming practices (Holling and Meffe 1996), they are highly resilient at farm-field level. The short -term focus and institutional setting of modern agroecosystems leads to properties of high resilience and high potential that cannot be observed in natural ecosystems.

The continuous disturbance by farm management prevents the system from developing a structure of internal recycling. The high inputs during the reorganization phase enable a high capacity and adaptability of the agroecosystem. The high adaptability of the intensively managed systems has resulted in a system that is unlikely to transform fundamentally. Most disturbances can be dealt with within the existing system configuration. Societies might desire agricultural transformations (Veldkamp et al. 2009), but are hindered by the high adaptability and resilience of conventional strategies. This trap of incremental adaptation (Anderies et al. 2006a) might be common in intensively managed agroecosystems as found by others (Allison and Hobbs 2004, Anderies et al. 2006a). The trap is deepened by destroying its transformability and long-term accumulated ecological capital, in our case soil organic matter, leading to an increasing dependency on external inputs.

*4.1 Panarchy and governance*

The development of environmental cooperatives in the Northern Frisian Woodlands resulted in an increase of socioeconomic capital. Self-governance and the interest in developing a multifunctional agroecosystem are illustrative of this capital. The increase of soil organic matter as a result of the reinforcing measures contributes to the development of ecological capital. Therefore, from a sustainability perspective, the region has developed to a more sustainable landscape scale system that is less resilient at the field level. The success of the environmental cooperatives to establish a new type of regional governance however, is dependent on the intrinsically slow dynamics at field level of soil organic matter accumulation. Institutional dynamics require fast and measurable results, which do not match with the slow ecological dynamics at field level. This cross-scale dynamic system property is often difficult to address in our governance

approaches (Cash et al. 2006). The concept of panarchy might prove insightful for tackling this kind of interactions at different time-scales.

## 2.5 Conclusions

A dynamic farm model was used to evaluate the long-term effects of the reinforcing measures in the Northern Frisian Woodlands. Simulations show that no alternative stable state exists for soil organic matter, considered to be a key indicator of sustainability, within a plausible range of fertilizer applications. The slow variable of soil organic matter accumulation is hardly affected by operational management. The observed differences in soil organic matter content and nutrient use efficiency probably represent a time lag of long-term nonequilibrium system development. Rather than alternative stable states, observed differences in N-efficiency represent a timelag effect. Stopping grassland renewal will allow ecological processes to mature and the slow buildup of soil organic matter capital. The panarchy created heterogeneity of resources in the landscape providing local landscape embedded opportunities for high N-efficiencies. Panarchy proved to be especially insightful for studying long-term developments, which are generally overlooked by traditional agronomic studies.

In contrast, modern conventional dairy farms with short -term focus and their institutional setting leads to properties of high resilience and high potential that cannot be observed in natural ecosystems. These systems shortcut the adaptive cycle by frequent grassland renewals, resulting in high resilience and adaptability. This comes at the cost of long-term accumulated ecological capital of soil organic matter and transformability, thus reinforcing the incremental adaptation trap. The continuous disturbance by farm management prevents the system from developing structures of internal recycling. These systems however, tend to be locked up in the incremental adaptation trap, hindering society's desire for agricultural transformations. Analysis of such a human dominated agroecosystem reveals that rather than alternative states, an alternative set of relationships within a multiscale setting applies, indicating the importance for embedding panarchy in the analysis of sustainable development goals in agroecosystems.

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# Chapter 3

# Landscape asymmetry
# of soil organic matter as a source
# of agro-ecosystem resilience

## Abstract

In agricultural landscapes, drivers at different spatial and temporal scales result in a non-random spatio-temporal variability of landscape characteristics. Patterns of soil organic matter (SOM) are for example controlled by both pedological and climatic factors as well as historic and current land use. The observed patterns linked to their generating processes can be referred to as the landscape asymmetry of SOM.

In this paper we identify and evaluate landscape asymmetry of SOM in an agricultural landscape in the Netherlands. Subsequently we infer implications of applying the concept of landscape asymmetry for understanding agro-ecosystem resilience.

We modeled SOM dynamics of grassland soils to identify dominant long-term drivers and combined and analyzed land use history and landscape characteristics to explain the spatial variability of SOM contents. Sensitivity analyses show that the dominant parameter for attainable SOM content is the mineralization rate of SOM. Results furthermore indicate, that SOM content is related to *temporal variability* in land use and to *spatial variability* of groundwater hydrology and soil texture. The landscape asymmetry of SOM provides windows of opportunities for farmers who wish to reduce fertilizer input. However, connecting landscape asymmetry to other scales reveals potential cascades of events that might undermine agro-ecosystem resilience.

## 3.1 Introduction

Human-environment interactions are intrinsically complex (Liu et al., 2007). Agro-ecosystems are no exception as in these systems, humans manage and use communities of plants, animals, soils and their interactions in order to make a living.

In order to understand this complex behavior, the resilience perspective is increasingly used as an integrative approach (Folke, 2006). Resilience of social-ecological systems, including agro-ecosystems, can be defined as the underlying capacity of the system to maintain a desirable state of ecosystem services in the face of human use under a fluctuating environment (Brand and Jax, 2007). The point at which one relatively stable state gives way to another is called a threshold. Thresholds that are crucial in agro-ecosystems are influenced by a number of controlling slow processes (Carpenter et al., 2001). One of these slow controlling processes is the accumulation and decrease of soil organic matter (SOM). SOM generally responds very slowly to changes in factors that control its accumulation (Freibauer et al., 2004). Agricultural fields, therefore, rarely reach equilibrium conditions of SOM, since management often changes before equilibrium is reached (Schröder et al., 2003).

SOM has been identified as an essential natural resource in many land-based agro-ecosystems. It is often said to be the most important indicator of soil quality and agronomic sustainability, because of its impact on other physical, chemical and biological soil properties (Reeves, 1997).

In agricultural landscapes, drivers at different spatial and temporal scales result in a non-random spatio-temporal variability of SOM. This non-random spatial-temporal variability can also be referred to as the landscape asymmetry of SOM, following the definition of landscape asymmetry of Cumming et al. (2008). Landscape asymmetry differs from descriptions of landscape heterogeneity and temporal variation, since it aims at linking the observed patterns to processes.

Spatial patterns of SOM content have been documented at global (Post et al., 1982; McLauchlan, 2006), European (Schulp et al., 2008), Dutch (Hanegraaf et al., 2009), landscape (Schulp and Veldkamp, 2008) and farm (Tittonell et al., 2005) scale. Likewise, Post and Kwon (2000) have reported temporal variability in SOM, expressed by the large amount of variation in accumulation and decomposition rates and the length of time that carbon may accumulate in the soil. Dominant

drivers of SOM vary with spatial scale. At global scale, spatial patterns of SOM are related to the effect of climate on inputs (primary productivity) and outputs (decomposition) (Post et al., 1982; McLauchlan, 2006). At landscape scale, topography and hydrology further differentiate the pattern, while at plot scale vegetation type interacts with soil biota and physical properties do add more variation to the pattern. Potentially overriding all these drivers at different scales, is land use and soil management (Post and Kwon, 2000; Schulp and Veldkamp, 2008).

Soil management can either amplify the spatial heterogeneity by concentrating management (e.g. manure inputs) on particular fields (Tittonell et al., 2005), or nullify the spatial heterogeneity through tillage (Vellinga et al., 2004).

In order to obtain adequate yields, minimize environmental losses, preserve ecosystems and potentially contribute to carbon sequestration, a better understanding of the SOM dynamics and the relationship with the behavior of agro-ecosystems is required (Janzen, 2005).

The aim of this paper is to identify and evaluate the landscape asymmetry of SOM at farm and regional level in an agricultural landscape in the Netherlands. This is done using a combination of modeling and analysis of spatial patterns of SOM. Specific objectives in this study are therefore to: (1) model temporal SOM dynamics of grassland soils used for intensive dairy farming systems to identify the dominant long-term drivers and (2) combine and analyze data on SOM, land use history and landscape characteristics to explain the spatial variability of SOM contents at field level. We will apply the existing multi-scale framework from (Kinzig et al., 2006) to infer implications of applying the concept of landscape asymmetry for understanding agro-ecosystem resilience.

## 3.2 Materials and Methods

### 3.2.1 Study area

The study area is the Northern Frisian Woodlands, a glacial till landscape located in the north of the Netherlands. The area of 140 km² has an undulating topography with elevations ranging from 5 m above mean sea level in the south to 1 m below mean sea level in the north (Sonneveld et al., 2002). The parent material in the area predominantly consists of late Weichselien cover sands deposited on Saalian till deposits. In many places, the glacial till is found within 1.20 m below the surface and promotes the occurrence of relatively shallow

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groundwater tables because of its low permeability. As a consequence of varying depth of the glacial till and variation in the thickness of the overlying sandy deposits, the average highest groundwater level in sandy soils varies from 25 cm below the surface to more than 80 cm below the surface (Sonneveld and Bouma, 2003). The overlying eolian cover sand deposits are composed of fine sands with varying clay+silt (< 50 μm) contents (%) that range from less than 17.5% to more than 35%. During the Holocene, much of the lower lying areas became covered with peat, which has later been removed for fuel. Remnants of these peat layers have been mixed with the underlying sandy sediments to reclaim the soils for agricultural use. Thus, an anthropogenic topsoil of 30 to 50 cm is found in many places, locally also as a result of manuring with heather sods and household waste. The sandy soils are classified as Gleyic Podzols (Reijs et al., 2007). There are no indications that within the study area the climate varies to the extent that SOM contents are affected. Although mixed farming was widely practiced in the area (Van der Ploeg, 2003) nowadays land use in the area dominantly consists of grassland for dairy farming (> 80%). The area is characterized by a small-scale landscape, formed by hedges and belts of alder trees surrounding the plots of land, resulting in a unique mosaic of parcels (Wiskerke et al., 2003).

*3.2.2 Modeling long term dynamics of soil organic matter*

To investigate long-term interactions between grassland management and SOM build-up, i.e. the temporal variability, we adapted a simple existing mechanistic model using MATLAB (R14). The functional expressions that integrate the interactions between soil, feed, manure and animal components were largely based on the model developed by Groot et al. (2003), Groot et al. (2007) and Reijs et al. (2007). A Monte-Carlo procedure was then used to investigate the parameter space that results in the observed range of SOM values. See appendix for the actual formulation and parameter ranges. The model is described in the following sections and in Figure 1.
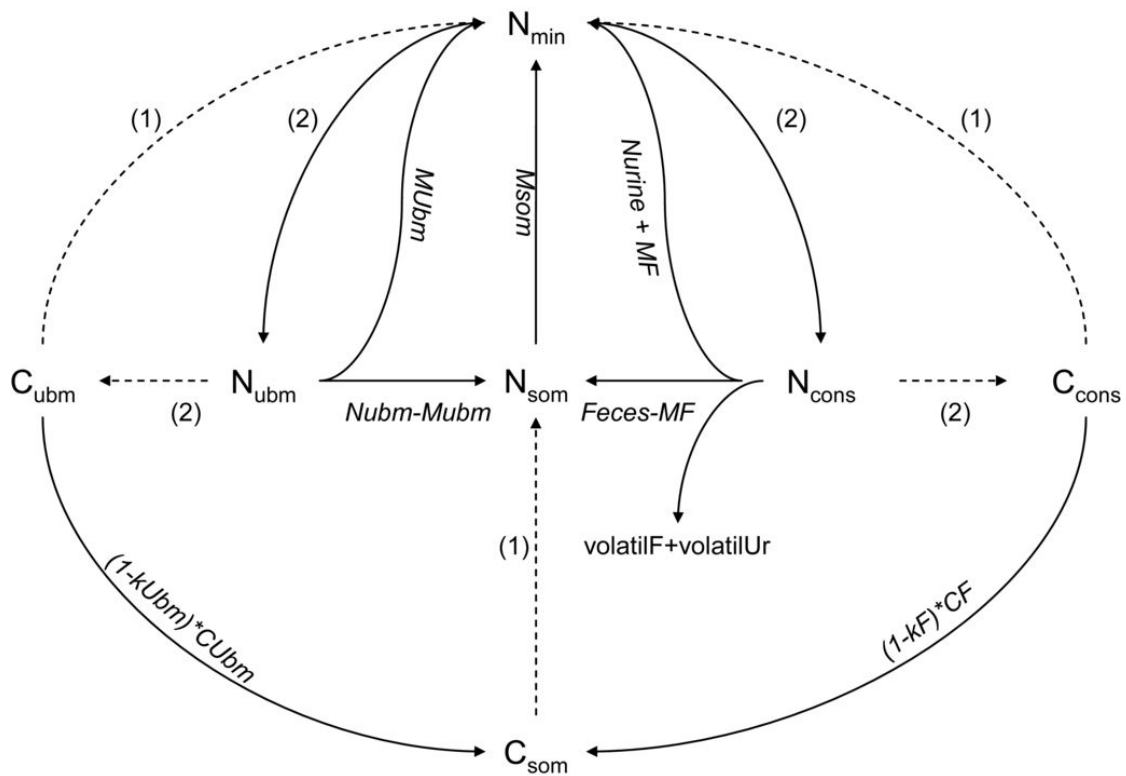
**Figure 1.** Chart of N and C flows (solid lines) and interactions (dashed lines). Numbers between brackets refer to equations in the text, for abbreviations of parameters and flows see also text.

*3.2.2.1 Soil*

Soil nitrogen (N) is mainly stored in SOM (Whitehead, 1995). For nitrogen to become available for plant uptake, SOM has to decompose. The rate of decomposition and the release of mineral nitrogen depend among others on the chemical composition of the organic material, temperature, aeration, soil microbes, soil moisture, clay content and nutrients (Jenkinson, 1988). In the model the interaction between these factors was simplified following Bloemhof and Berendse (1995). SOM decomposition is described by the composition of the organic material by their carbon to nitrogen ratio (C/N), the effect of soil microbes by their own quotient of nitrogen to carbon (qsm) and the microbial growth efficiency (eff). The other effects are lumped in an annual decomposition rate (k, year$^{-1}$). The total amount of nitrogen becoming available from mineralization of SOM (Msom, in kg ha$^{-1}$ year$^{-1}$) is calculated by multiplying the decomposition with the amount of carbon (C, in kg ha$^{-1}$) present in the organic matter:

$$Msom = C * k/(1\text{-}eff) * (N/C - eff * qsm) \tag{1}$$

Mineralization thus linearly increases with more carbon, but decreases to its ratio N/C when only C is increased. Note that Msom becomes negative when C/N of

the organic matter is lower than the C/N of the soil microbes (1/qsm) multiplied by their efficiency, resulting in net immobilization. We assume the carbon content of SOM to be constant (Pribyl, 2010), thus any statement on processes affecting soil organic carbon (SOC) can be converted to SOM and statements on SOC are therefore equally valid for SOM. Moreover we model the SOC stock to one meter depth, and thus model outcomes cannot directly be compared with the top 5 cm SOM content of the soil.

### 3.2.2.2 Plant

Nitrogen uptake by the grass depends among others on nitrogen availability, temperature, soil pH, and growth stage (Whitehead, 1995). The relation between growth stage and nutrients was simplified following Goudriaan and Monteith (1990) and Groot et al. (2003), assuming nutrient uptake to be an expo-linear function of nutrient availability. At low availability of mineral nitrogen (Nmin, in kg ha$^{-1}$ year $^{-1}$) the uptake (kg $^{-1}$ year$^{-1}$) follows a linear nutrient use efficiency (nue, in kg kg$^{-1}$ ha$^1$ year$^{-1}$), with increasing availability the efficiency of uptake declines (decl, in kg$^{-1}$) until it reaches the maximum capacity for uptake (max, in kg ha$^{-1}$ year$^1$).

$$uptake = max - nue/decl * \ln(1 + \exp(-decl * (Nmin - max/nue))) \qquad \textbf{(2)}$$

The availability of nitrogen changes the division of assimilates between the consumable part and total plant. We assumed that the harvestable part starts to grow only after a minimum amount of nitrogen is available and for remainder follows an expo-linear function independent from the total uptake. The assimilation of biomass (total and consumable) is related to the nitrogen uptake by the expo-linear function as well. The C/N ratio of plant tissue thus changes with nitrogen availability (Whitehead, 1995).

### 3.2.2.3 Cattle

The consumed grass is converted by the animal in produce and manure. The efficiency of this conversion is among others dependent on the breed, physiological state of the animal and the quality of the feed (Kebreab et al., 2004). Following Whitehead (1995), a linear relationship for the fraction of N excreted in the urine with the N content of the feed was assumed. Ranging from less than 50 % excreted N in urine to more than 80% when the diet is rich in protein. Thus with decreasing C/N ratios, relative more nitrogen ends up in the urine of the animal.

*3.2.2.4 Manure*

The excreted manure is returned to the field. We assumed that a fixed fraction of the feces (0-40%) and the urine (15-75%) is volatized and is lost from the cycle. Urine contributes directly to the available soil nitrogen pool as does the mineralization of the feces. The remainder of feces contributes to the $N_{SOM}$. Mineralization of the feces was calculated in the same manner as mineralization of SOM (Equation 1).

*3.2.2.5 State variables*

Mineral nitrogen ($N_{min}$, in kg ha$^{-1}$ year$^{-1}$), nitrogen in SOM ($N_{SOM}$, in kg ha$^{-1}$ year$^{-1}$) and carbon in SOM ($C_{som}$, in kg ha$^{-1}$ year$^{-1}$) are modeled with an annual time step using three difference equations.

The available $N_{min}$ –pool is renewed every year by the input from fertilizer and urine and the mineralization (M) of feces (F), unharvested biomass (Ubm) and SOM (equation 3)

$$N_{min}(t+1) = \textit{Fertilizer input} + Nurine + MF + MUbm + Msom \tag{3}$$

$N_{SOM}$ is calculated by subtracting the mineralization from SOM (see equation 1) and adding the nitrogen stored in unharvested biomass and feces (equation 4).

$$N_{SOM}(t+1) = N_{SOM}(t) - MSOM + F - MF + Ubm - Mubm \tag{4}$$

$C_{SOM}$ is calculated by subtracting the decomposed carbon with the mineralization and adding the carbon in the feces and unharvested biomass.

$$C_{SOM}(t+1) = C_{SOM}(t) - kSOM * C_{SOM}(t) + (1-kUbm)*C_{Ubm} + (1-kF)*C_F \tag{5}$$

*3.2.2.6 Monte Carlo approach*

Nutrient dynamics depend on a multitude of factors that interact in many ways. Although uncertainties of processes exist, we assumed that the model as formulated here adequately captures nitrogen-carbon interactions in the long term (Reijs et al., 2007). Because SOC dynamics vary in time, space and management, exact values of parameters are hard to determine. Therefore, we opted for a Monte Carlo approach to perform a sensitivity analysis. With a Monte Carlo approach random combinations of parameter settings are tested. We used Latin hypercube sampling to ensure a uniform distribution of random numbers for the full parameter space. With our model, we tested if a combination of 28 parameters

resulted in a specified range of SOC after 200 years. Parameter combinations that pass this test are assumed to be a possible representation of quantification of processes in model. As a simple method to assess the importance of parameters in governing the long-term SOC stock, the correlation between SOC stock and parameters were calculated.

As an acceptable range of SOC stock after 200 years we have chosen a minimum value of 8% SOM content in the top 5 cm of the soil. For Dutch grassland soils, with this value and above nitrogen supply from SOM is considered constant (Hassink, 1996). And as a maximum acceptable value we chose approximately 15 % SOM contents, which is the upper value for sandy soils (De Bakker and Schelling, 1966).

The SOM content of the top 5 cm however cannot directly be used in the model. First, we modeled SOC and consequently SOM needs to be converted to SOC (Pribyl, 2010). Moreover SOM affects bulk density of the soil and roots and biological homogenization leads to carbon rich soils deeper than 5 cm. We estimated that the range of 8-15% SOM content of the top 5 cm soil amount to a total SOC stock to a depth of 1 m range between 200 000 and 310 000 kg ha$^{-1}$. We modeled the development of the total SOC stock for two hundred years of a field that has been used for maize and is reseeded with grass. As initial condition for the model we used a field previously cropped to maize with a SOC stock of 155 000 kg ha$^{-1}$and a total organic nitrogen stock of 13 300 kg ha$^{-1}$for a 1 meter profile (Sonneveld and Bouma, 2003).

*3.2.3 Spatial data*

For our analysis to identify effects of landscape, historical land use and SOM, different spatial datasets were used. This included a detailed (1:25 000) soil survey, performed in 1991 (Makken, 1991), historical land use maps (see table 1) and previously analyzed SOM contents of agricultural fields from routine soil analyses (see Figure 2).
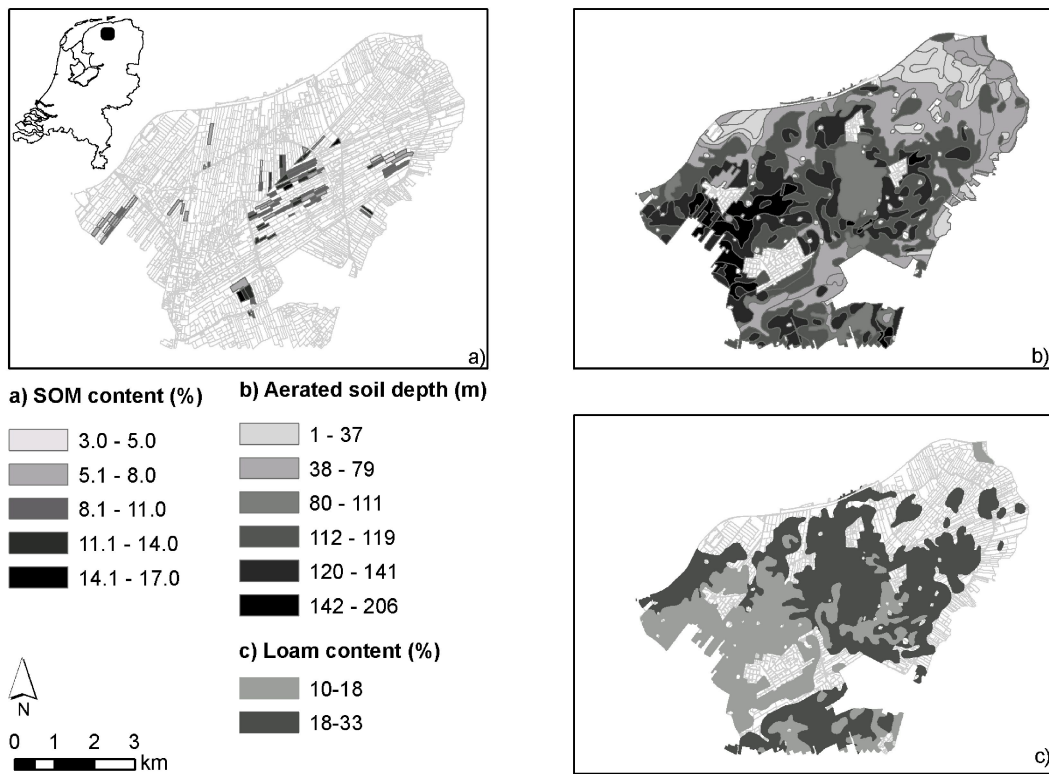
**Figure 2.** Location of the study area in the Netherlands (53:16°N; 6:05°E).
a) Location of the sampled fields in the study area and their soil organic matter content.
b) Groundwater hydrology regime represented by the annual aerated soil depth (m).
c) Loam content (%).

**Table 1.** Overview of sources of spatial data and its use in this study

| source | scale | use |
|---|---|---|
| Topographical map, 1897, Leeuwarden | 1:50 000 | grassland age classification |
| Topographical map, surveyed in 1854 partly revised 1904,Leeuwarden | 1:50 000 | grassland age classification |
| Topographical map 1929, surveyed in 1926, Drogeham, Nr, 94 | 1:25 000 | grassland age classification |
| Topographical map 1953, surveyed in 1925-1929, partly revised in 1942, Leeuwarden, Nr 6 Oost | 1:50 000 | grassland age classification |
| Topographical map 1962, surveyd in 1959, Leeuwarden, Nr 6 Oost | 1:50 000 | grassland age classification |
| Topographical map 2001, aerial photography 2000, Surhuisterveen, 6 G | 1:25 000 | grassland age classification |
| Soil and groundwater map (Makken, 1991) | 1:25 000 | soil and groundwatertable classification |

Firstly, from the detailed soil survey (1:25 000) soil characteristics of texture and ground water table classes were derived. This survey covered only a part of the Northern Frisian Woodlands and we restrict our analysis to this area. This soil survey covered an area of 91 km² with 39 different soil mapping units. This dataset gives a more accurate representation of soil properties and groundwater level compared with a previous 1:50 000 soil survey of 1981.

Since groundwater fluctuates between summer and winter we combined the groundwater table classes of the detailed soil map (Makken, 1991) and the groundwater table frequency distribution curves (Van der Sluijs and de Gruijter,

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1985). These curves describe the fluctuations of water tables over a year for each groundwater table class. This combination yields the non-saturated soil depth available for the mineralization of SOM over one year (annual aerated soil depth). Integration of the polynomials describing the frequency distribution of water tables yields:

$$D_{100} = -367.5 + 54.5 * MeanHighestWater + 50.5 * MeanLowestWater \qquad \textbf{(6)}$$

Where $D_{100}$ is depth of the soil (m) not saturated by groundwater integrated over the whole year (frequency= 100%), and *MeanHighestWater* and *MeanlowestWater* are derived from the groundwater classes.

Secondly, for each of the 99 fields an analysis of the grassland age, i.e. the continuous time under grassland was calculated by tracing their map classification on six topographical maps ranging from 1897 to 2001 (see Table 1 for details).

Lastly, 99 soil fertility analyses from 1998 to 2003 were retrieved from 13 dairy farms. Soil analyses were performed by agricultural laboratories, routinely measuring mixed samples of the top 0-5 cm of individual fields. SOM was measured using Near Infra Red Spectrometry and total N was measured using an Autonalyser. All fields are geo-referenced and data on soil, groundwater, and land use history were coupled to the SOM data in ArcGIS. Fields were classified to their most dominant soil- and groundwater class. For this study, only fields that were used as grassland at the time of sampling were included. The analyses result from farmers' demands for soil analysis and they may require a soil analysis more often in fields of lower soil fertility, which implies that the samples might be biased (Hanegraaf et al., 2009).

### 3.3 Results and Discussion

*3.3.1 Long term dynamics of soil organic matter*

In total, 250 000 parameter combinations were tested in the model simulations using the Monte Carlo approach. About 4% of these parameter combinations resulted in a SOC stock between the set limits of 200 000 and 350 000 kg ha$^{-1}$ after 200 years (Figure 3).
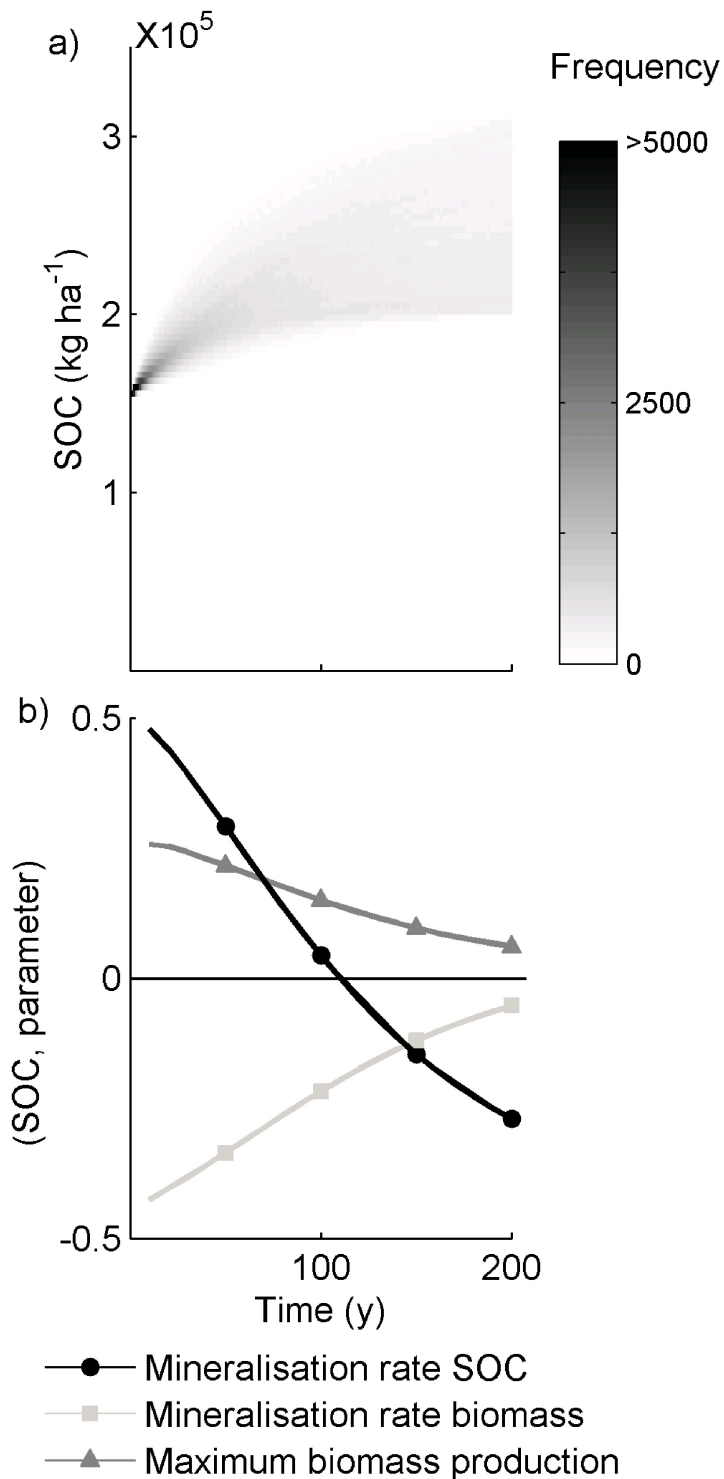
**Figure 3** a) density plot of SOC accumulation curves as simulated in the Monte Carlo simulation b) Correlation of simulated soil organic carbon (SOC) stock and three strongest correlated model parameters over time. A strong correlation between a parameter and SOC are an indication for the importance of the parameter to the SOC stock at a particular moment.

With this sensitivity analysis the relation between management, time and SOC can be assessed. The analysis identified dominant parameters regarding SOC accumulation in dairy farms, namely: the genetic maximum biomass production of

the grass variety; mineralization rate of unharvested biomass; and the mineralization rate of SOC (Figure 3). In the short term, the total biomass production together with its slow mineralization contributes to SOC build-up. After 200 years, only the mineralization rate of SOC has a clear correlation (-0.4) with the SOC content of the soil. After this period, all other parameters had correlation values near 0. Chi-square test for uniformity of the selected parameter ranges was also done, but its results fall outside the scope of this study.

The correlation of parameters with SOC over time show, when initially the field has been plowed and SOC content is small, SOC content can indeed be enlarged by high inputs of organic matter, both through biomass and manure. Especially when the input of organic matter has a low mineralization rate, the SOM content can be enlarged. In the long run, the contribution of the annual input is minimal in comparison with increasing stock of SOM content. Thus, according the model simulations, strategies aiming at increasing the amount of SOM of grassland soils via manure are relative ineffective in the long term because the SOC decomposition rate is more important.

This seems to contradict the formation of the anthropogenic topsoil. However in this analysis only "closed" agro-ecosystems are considered, thus only manure produced from biomass of the fields is returned to the fields. It does not include addition of organic matter origination from other locations, such as city waste or the addition of heather sods which are resistant to decomposition (Springob and Kirchmann, 2010).

Thus according to the model simulations, the dominant factor for the attainable SOC content (and thus also SOM) under grassland fields is mineralization rate of SOC.

*3.3.2 SOM and land use history*
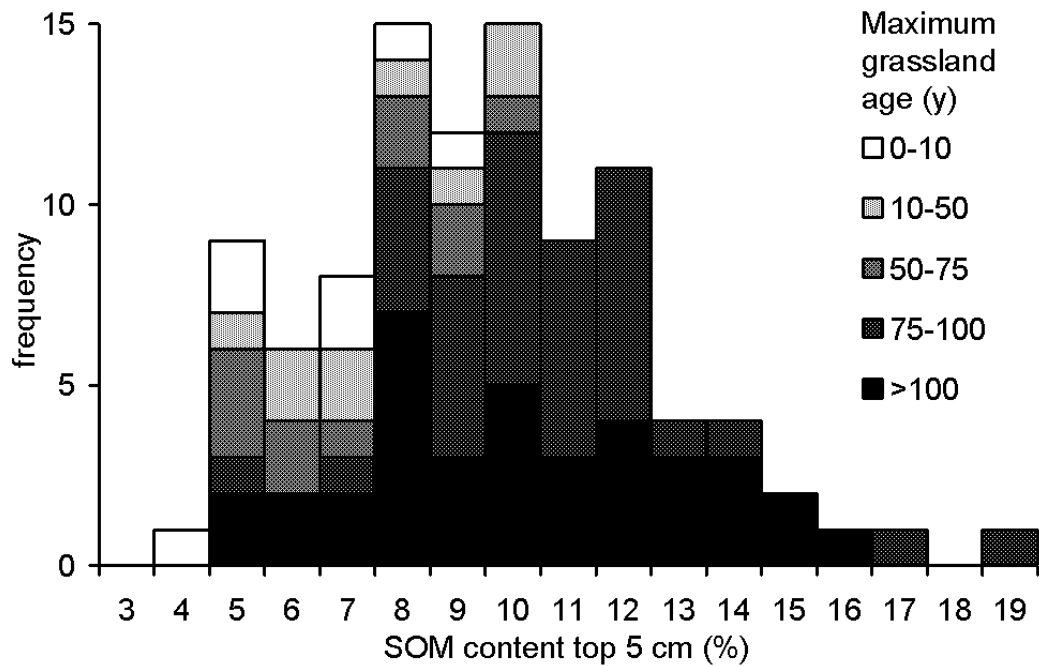
**Figure 4.** Frequency distribution of 99 soil samples of SOM content on sandy soils. The shade classes represent the continuous time a field has been classified as grassland.

Figure 4 shows the frequency distribution of 99 SOM samples of sandy soils with grassland cover in the Northern Frisian Woodlands. The total distribution is not normally distributed (Shapiro-wilk test, $p<0.05$) and has a skewness of 0.57. The dataset has an average SOM content of 9.3 % (Std. 2.9) with a minimum of 3.9 % and a maximum of 18.7 %. The Kruskall Wallis test suggests that at least one grassland age class median is significantly different ($p<0.05$) from the others. Mann-Whitney comparisons between the classes shows that classes younger than 75 years are significantly different ($p<0.05$) from classes older than 75 years. Current SOM content is related to the *temporal variability* in land use: the older fields of more than 75 years of age have median values of >11% SOM contents whereas the younger grasslands have lower median values (<8%). The bell-shaped distribution for an accumulative process of SOM build-up either means that fields with disturbances are more frequent than fields that reach equilibrium (> 100 years) or equilibrium conditions differ in space (see below). Disturbances of SOM reflect most likely a change in management, since it is the fastest and smallest scale driver. Moreover various studies have shown the strong effect of land use history on SOM (e.g.. Pulleman et al. (2000), Springob et al. (2001), Sonneveld et al. (2002), McLauchlan (2006), Schulp and Veldkamp (2008)). Conversion of grassland to arable land involves considerable loss of SOM; within six years 50 % of SOM can be lost when cultivated (Whitmore et al., 1992). Reaching equilibrium conditions of SOM content when arable land is converted to grassland, however, takes more than a century (Freibauer et al., 2004). The two extreme values of

17.0% and 18.7% are most probably not a reflection of equilibrium conditions. The two fields are situated in an area that was original peat and the remnants of the peat were mixed with the topsoil. The occurrence of young fields with high SOM contents might further be caused by recent changes in land use which have not been captured in the land use maps. The occurrence of old fields in the lower half of the SOM distribution can be caused by the result of the snapshot character of topographical maps. It is possible that these fields have been tilled between map recordings.

### 3.3.3 Factors affecting SOM content

The Monte Carlo analysis showed the importance of the mineralization rate of SOM for the attainable SOM content. In the model, the SOM mineralization rate represents the net effect of temperature, aeration, soil moisture and clay content on SOM decomposition. In this section, we show how *spatial variability* of groundwater hydrology and soil texture are related to SOM contents and its mineralization rate.

The total annual aerated soil depth provides an indication for the depth to which aerobic decomposition is possible and for soil moisture content (Figure 5).
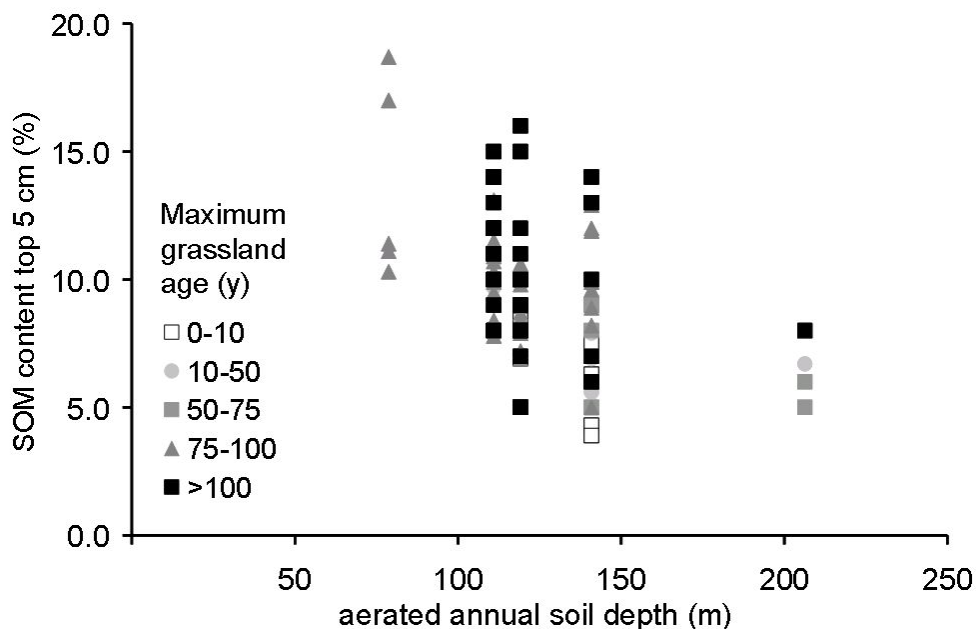


**Figure 5.** Effect of groundwater hydrology on SOM content with different grassland age. The symbol classes represent the continuous time a field has been classified as grassland. Total annual aerated soil depth is calculated based on Van der Sluijs and Gruijter (1985). Note the trend in both the maximum an minimum values.

The SOM content has a significant ($p < 0.01$) negative correlation (spearman rank) of -0.51 with annual aerated soil depth. The decrease in SOM content with

increasing total aerated annual depth, is also observed earlier by Sonneveld and Van Den Akker (2011). It appears that high groundwater levels and accompanying anaerobic conditions during winter and spring, have a stronger effect on the mineralization rate of SOM in this area. This contrasts with the study of Hassink (1994), who found increasing SOM with groundwater depth which he attributed to drying out of the top soil in summer. In our study SOM continued to decrease with increasing total annual aerated soil depth, and the four drier classes only differ in highest mean groundwater level (see Equation 6) during winter. The five fields with the most shallow total annual aerated soil depth of 79 meter are all previous peat areas that were reclaimed between 1904 and 1926. The fields older than 75 years are generally found on the wetter soils. This might be explained by the poor workability of fields with high ground water level. In spring these fields are still wet, renovation of grassland or tillage for arable production would most likely damage soil structure and lower yields. These fields are however highly suitable for permanent grassland.
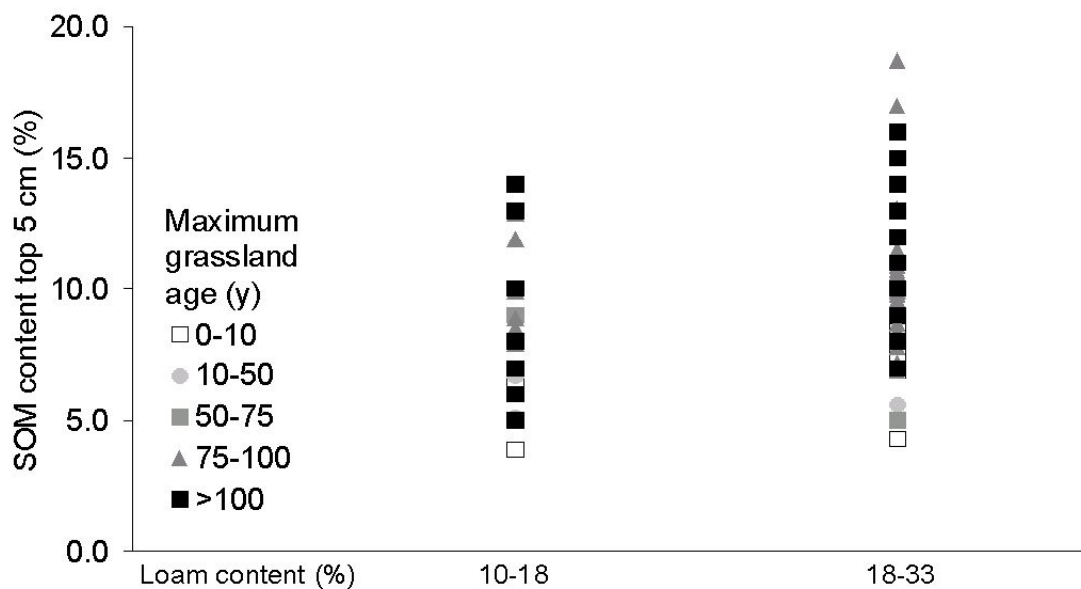


**Figure 6.** Relation of loam content on SOM content with different grassland age. Classification based on Makken (1991). The symbol classes represent the continuous time a field has been classified as grassland.

The SOM content between the two loam classes (Figure 6) are significantly different from each other (Mann-Whitney comparison, p<0.01). The SOM content increases with the loam content of the soil. The effect of texture on mineralization is well studied see for example Hassink (1994) for mineralization of grassland soils. Texture differences between the soils we studied however are very

small and all fields are classified as loamy fine sands. Most fields in the region have an anthropogenic topsoil. The topsoil was formed through continuous addition of organic material (city waste, manure or heather sods) over long periods of time. This system was abandoned in the beginning of the twentieth century (Sonneveld et al., 2002), but the relation between organic matter and texture is still clear. Hassink (1994) also found a positive relation between silt+clay and organic matter content. Clay-particles (<2 μm) physically protect organic matter particles against decomposition. The sandy soils we studied however, hardly contain clay. We can think of two possible explanations of increasing SOM content with loam content: 1) loam content is a reflection of landscape position. For example, the two soils with most shallow annual aerated soil depth (Figure 5) also have the largest loam content and texture size, or 2) The loam was imported during the creation of the anthropogenic topsoil and an increase of loam reflects longer/higher inputs of organic matter from other areas (Dercon et al., 2005). For example in the second half of the 19th century many terps, artificially raised dwellings made of household waste and sods, were excavated and used at the sandy soils as fertilizer (Barends et al., 2010).

Large differences of SOM content can also be observed within the same soil texture, groundwater hydrology and age class. This might be largely due to the nature and scale of the maps used. As already noted, the snapshot character of historical maps is a source of uncertainty in the estimation of maximum age. Furthermore, local heterogeneity between neighboring fields caused by either anthropogenic influences or subtle landscape characteristics are not represented on the soil maps used. Both the scale of the soil map and the support of the map do not permit this kind of detailed analysis. However, field observations indicate that the same factors of land use history, texture and groundwater hydrology also provide plausible explanations of SOM content at field scale.

### 3.4 Landscape asymmetry

*3.4.1 Landscape asymmetry and opportunities for farm management*

Landscape asymmetry of SOM is reflected in non-random patterns of SOM in the landscape. In the Northern Frisian Woodlands, SOM can be linked to landscape features of hydrology and soil texture (Figures 5 and 6). The landscape provides windows of opportunity (Bouma, 2004) in the landscape for farmers experimenting with alternative practices (Verhoeven et al., 2003). Their idea was to decrease fertilizer input, which would lead to a higher root/shoot ratio (Whitehead et al., 1990; Van den Pol-van Dasselaar and Lantinga, 1995) and feed

lower crude protein and higher crude fiber content which would lead to an increase of the carbon to nitrogen ratio (C/N) of manure, this would in turn lead to an increase of the SOM content (Van Bruchem et al., 1999). These activities have also been described as the re-balancing strategy. The success of this strategy seemed to be for a large part dependent on the groundwater and SOM content (Groot et al., 2007). The model simulations suggest that the higher SOM contents in their fields cannot be fully attributed to their operational management but rather to the field's position within the landscape. Local high SOM contents generated by the landscape asymmetry compensates by its N-mineralization for the reduced fertilizer input at the farms (Groot et al., 2006). Recognizing landscape asymmetry allows for the further development of improving the sustainability of agro-ecosystems.

*3.4.2 Landscape asymmetry as a source of agro-ecosystem resilience*

The agro-ecosystem resilience of the Northern Frisian Woodlands, in the sense of its underlying capacity to maintain its state of ecosystem services, is connected to the landscape asymmetry. Kinzig et al. (2006) proposed a framework to connect local dynamics to the agro-ecosystem's capacity to maintain its services. The framework identifies the domains of ecological, economic and socio-cultural dynamics, in combination with the field, farm and landscape scale (see Figure 7). Essential in their framework is that these domain-scale components interact and might cause a cascade of events. The new emerging system configuration is likely less desirable (Kinzig et al., 2006).

In the framework every domain-scale component has a dual state governed by a threshold, for example high or low SOM. Although these states might not be true alternative stable states, the differences between a field with a high or low SOM are quite large. The threshold for SOM might be the field's ability to provide enough nitrogen via mineralisation to make the re-balancing strategy viable for the farmer.

Transitions between these states can be regulated by processes at its own scale (like SOM accumulation) or induced by other scales (farm management).
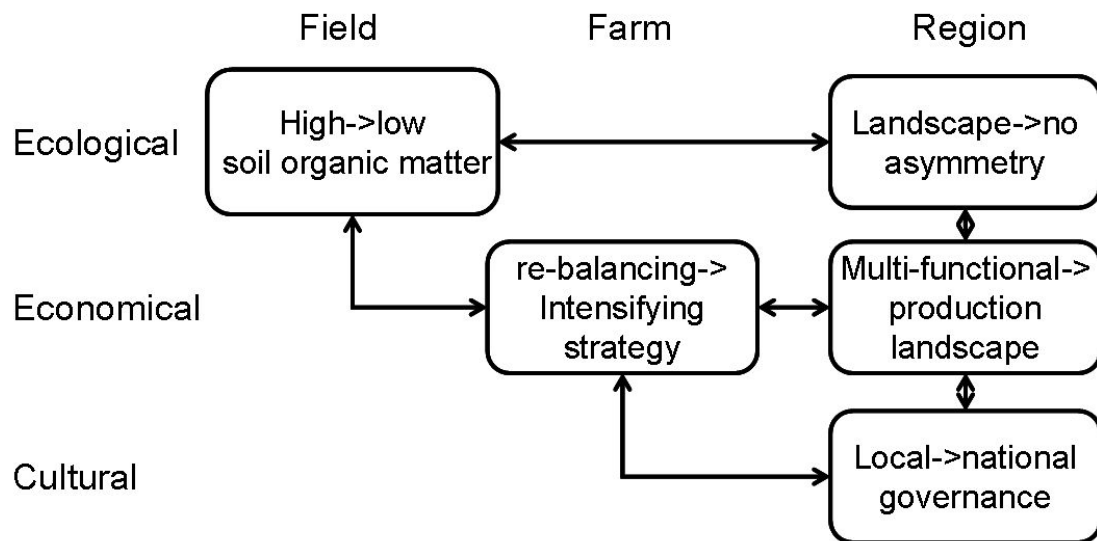
**Figure 7.** A multi-domain and –scale framework for studying cascading interactions (based on Kinzig et al. (2006)). The boxes represent components with a potential threshold. For instance when SOM is high, a nutrient efficient re-balancing strategy can be followed, enabling a multi-functional landscape embedded in the landscape asymmetry. The arrows between boxes show interactions between thresholds (see text).

In our adoption of the framework (Figure 7), we can identify an important cascading effect: the drivers of landscape asymmetry regulate the accumulation of SOM and when SOM content of the fields is sufficiently high, the farmer can reduce external inputs (re-balancing strategy) while maintaining productivity. The resulting preservation of the small-scale landscape allows for the development of associated ecosystems services, such as tourism and regional branding. Maintaining this particular agricultural landscape is dependent on the dedication of the farmers, and calls for environmental policies that recognize the importance of location as part of the landscape asymmetry. This contrasts with the current restrictive rules to protect nature and landscape by the national government. Therefore, farmers have established environmental co-operatives as a means to create more room for self-regulation to develop these locally effective measures to realize environmental objectives (Wiskerke et al., 2003).

The underlying capacity of the region to maintain its functioning as a small scale attractive landscape, however, is eroding. Popularity of grassland renovation and the cultivation of silage maize will drastically decrease SOM of the fields (Figure 3, Hanegraaf et al. (2009)). As a result, fields with low SOM will need additional inputs to maintain productivity. When a critical number of fields are converted, an intensification strategy based on high external inputs and rationalized fields

become a favorable management strategy for the whole farm. In turn, when a critical number of farmers will follow this intensification strategy, the small scale landscape may disintegrate. Because of rationalization of the area, landscape asymmetry of soil organic matter contents will be erased. Location of the field and farm ceases to be a distinctive characteristic and can accordingly be managed by regulations set by the national government. The resilience of the region is thus undermined by every field that is plowed.

Although landscape elements such as hedgerows are protected and its maintenance subsidized, the landscapes identity is still at risk. When the coherence between the small composing elements and the broader spatial context (i.e. the landscape asymmetry) is lost, identity and the overall value will be at risk (Antrop, 2005). So far, the region has been able to maintain its identity as expressed in its status as a national landscape. A critical buffering factor might be the social network present in the Northern Frisian Woodlands. Traditionally, the region has had a strong social control on how to farm (Van der Ploeg, 2003). There was a culture of independency of markets. Agricultural modernization only slowly gained a foothold in the region. It was only in the 1990s that land consolidation took place whereas in other sandy areas this was already done before 1950. The consolidation was also in contrast with previous consolidation projects, as it was only an exchange of land and no rationalization, which would have had devastating effects on landscape features and SOM. The farmers in the Northern Frisian Woodlands were also the first to argue for compensation for their role in landscape protection (Renting and van der Ploeg, 2001). The landscape is part of their identity and the social network has been extremely strong in generating support for their cause of self-governance and landscape protection (Renting and van der Ploeg, 2001; Wiskerke et al., 2003; Termeer, 2009). Although this buffer in the socio-cultural domain seems strong and well developed, failure to recognize the landscape asymmetry might lead to an unintended cascade of low-soil organic matter fields of intensive farms in a monotonic landscape.

## 3.5 Conclusions

The Monte Carlo analysis identified the mineralization rate of SOC as the dominant parameter for attainable SOC content on the long term. Analysis of land-use history of fields reveals that current SOM content is related to the *temporal variability* in land use. Older grasslands tend to have higher SOM content. Further more detailed soil data reveals that current SOM content is related to the *spatial variability* of groundwater hydrology and soil texture. SOM content tend to

increase with loam content and more shallow groundwater tables. Landscape asymmetry of SOM is reflected in these drivers of SOM content in the landscape. The landscape as such provides windows of opportunity for farmers. Recognizing landscape asymmetry allows for the further development of more sustainable farming practices.

The agro-ecosystem resilience of the Northern Frisian Woodlands is connected to the landscape asymmetry. In adopting a multi-scale framework we can identify an important cascading effect: Landscape asymmetry regulates SOM contents, SOM contents regulate the opportunity farmers have to reduce external inputs. The resulting preservation of the small-scale landscape allows for the development of a multi-functional landscape. Maintaining this particular agricultural landscape calls for environmental policies that recognize the importance of location as part of the landscape asymmetry. In contrast loss of landscape asymmetry might cause a collapse of current agro-ecosystem resilience.

## Acknowledgements

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## Appendix: dynamic simulation of nitrogen and carbon stocks in a grassland-based dairy farming system.

Model formulation

For full model description see Groot et al. (2003) and Reijs et al. (2007)

**Plantgrowth**
```
Nplant=max(0.0001,maxNplant-nueNplant/declNplant*ln(1+exp(-declNplant*(Nmin(t)-maxNplant/nueNplant))))
rangeNcons=maxNcons+NconsB;
Ncons=max(0.00001,rangeNcons-nueNcons/declNcons*ln(1+exp(-declNcons*(Nmin(t)-rangeNcons/nueNcons)))-NconsB)
DMplant=max(0.001,maxDMplant-nueDMplant/declDMplant*ln(1+exp(-declDMplant*(Nplant-maxDMplant/nueDMplant))))
DMcons=max(0.01,maxDMcons-nueDMcons/declDMcons*ln(1+exp(-declDMcons*(Ncons-maxDMcons/nueDMcons))))
DMubm=DMplant-DMcons
Nubm=Nplant-Ncons
Ccons=DMcons*cc
Cubm=DMubm*cc
Cplant=DMplant*cc
```
**Animal conversion**
```
MilkEff=-MilkA*Ncons/DMcons+MilkB
phiUr=UrA*Ncons/DMcons+UrB
phiF=1-phiUr
exretedN=Ncons-Ncons*MilkEff;
```
**Mineralisation**
```
qF=(volatilF*exretedN*phiF)/(Ccons*(1-dH))
qubm=Nubm/(Cubm)
MUr=volatilUr*exretedN*phiUr
MF=kF/(1-smEff)*Ccons*(1-dH)*(qF-smEff*qsm)
Mubm=kubm/(1-smEff)*Cubm*(qubm-smEff*qsm)
Msom=ksom/(1-smEff)*Csom(t)*(Nsom(t)/Csom(t)-smEff*qsm)
```
**Soil**
```
Nmin(t+1)= inp+MUr+MF+Mubm+Msom
Csom(t+1)= Csom(t)+(1-kF)*Ccons*(1-dH)+(1-kubm)*Cubm-ksom*Csom(t)
Nsom(t+1)= Nsom(t)+(Ncons*phiF)-MF+Nubm-Mubm-Msom
```

## Abbreviations

```
N=nitrogen
C=carbon
max=maximum
nue=Nitrogen use Efficiency
decl=decline of nitrogen use Efficiency
cons=consumed
DM=Dry Matter
Ubm=unharvested biomass
cc=carbon content
Eff=efficiency
A=gradient
B=intercept
phi=fraction that ends up in substance
Ur=urine
F=faeces
q=N/C fraction
k=mineralisation rate
M=mineralisation
sm=soilmicrobes
som=soil organic matter
dH=digestibility consumed biomass
W=fractional rate of Nmin withdrawal
```

| parameter | min | max | Unit | source: |
|---|---|---|---|---|
| declDMcons | 0.001 | 0.05 | $kg^{-1}$ | based on Conijn (2005) |
| declDMplant | 0.001 | 0.03 | $kg^{-1}$ | based on Conijn (2005) |
| declNcons | 0.001 | 0.03 | $kg^{-1}$ | based on Conijn (2005) |
| declNplant | 0.001 | 0.03 | $kg^{-1}$ | based on Conijn (2005) |
| maxDMcons | 8000 | 18000 | $kg\ ha^{-1}\ year^{-1}$ | based on Conijn (2005) |
| maxDMplant | 20000 | 35000 | $kg\ ha^{-1}\ year^{-1}$ | based on Conijn (2005) |
| maxNcons | 200 | 900 | $kg\ ha^{-1}\ year^{-1}$ | based on Conijn (2005) |
| maxNplant | 300 | 1000 | $kg\ ha^{-1}\ year^{-1}$ | based on Conijn (2005) |
| NconsB | 0 | 100 | $kg\ ha^{-1}\ year^{-1}$ | based on Conijn (2005) |
| nueDMcons | 30 | 60 | $kg\ kg^{-1}\ ha^{-1}\ year^{-1}$ | based on Conijn (2005) |
| nueDMplant | 40 | 100 | $kg\ kg^{-1}\ ha^{-1}\ year^{-1}$ | based on Conijn (2005) |
| nueNcons | 0.45 | 0.75 | $kg\ kg^{-1}\ ha^{-1}\ year^{-1}$ | based on Conijn (2005) |
| nueNplant | 0.7 | 1.3 | $kg\ kg^{-1}\ ha^{-1}\ year^{-1}$ | based on Conijn (2005) |
| cc | 0.35 | 0.45 | $kg\ kg^{-1}$ | based on (Groot et al., 2003) |
| dH | 0.5 | 0.85 | $kg\ kg^{-1}$ | based on (Groot et al., 2003) |
| kubm | 0.2 | 0.8 | $year^{-1}$ | based on (Groot et al., 2003) |
| qsm | 0.08 | 0.15 | - | based on (Groot et al., 2003) |
| smEff | 0.2 | 0.4 | $kg\ kg^{-1}$ | based on (Groot et al., 2003) |
| ksom | 0.005 | 0.03 | $year^{-1}$ | based on (Groot et al., 2003) |
| Csom (0) | 155000 | 155000 | $kg\ ha^{-1}\ year^{-1}$ | (Sonneveld and Bouma, 2003) |
| Nmin (0) | 500 | 500 | $kg\ ha^{-1}\ year^{-1}$ | estimate |
| Nsom (0) | 13300 | 13300 | $kg\ ha^{-1}\ year^{-1}$ | (Sonneveld and Bouma, 2003) |
| kF | 0.2 | 0.8 | $year^{-1}$ | based on Whitehead (1995) |
| MilkA | 6 | 8 | $kg\ kg^{-1}$ | based on Whitehead (1995) |
| MilkB | 0.4 | 0.5 | $kg\ kg^{-1}$ | based on Whitehead (1995) |
| UrA | 12.5 | 15 | $kg\ kg^{-1}$ | based on Whitehead (1995) |
| UrB | 0.22 | 0.26 | $kg\ kg^{-1}$ | based on Whitehead (1995) |
| volatilF | 0.6 | 1 | - | (Whitehead, 1995) |
| volatilUr | 0.25 | 0.85 | - | (Whitehead, 1995) |

# Chapter 4

# Co-evolution of landscape patterns and agricultural intensification: An example of dairy farming in a traditional Dutch landscape

## Abstract

The intensification of agricultural production strongly affects the characteristics of traditional rural landscapes. Yet, the complexity of these landscapes also puts constraints on intensification. This interrelationship lead to the hypothesis that the degree of intensification and locality are interdependent. Feedbacks between landscape and intensification often go unnoticed, while such a coupling would argue for spatial explicit studies with a co-evolutionary perspective. In this study, we localized and quantified interactions between landscape patterns and agricultural intensification for dairy farming systems in a traditional Dutch rural landscape. First, a conceptual diagram was made that maps causal interactions between landscape patterns and production intensity. This conceptual diagram was converted to spatial explicit descriptors of landscape patterns, such as hedge density, field size, clay content, ground water hydrology and spatial explicit descriptors of management such as hedgerow change, field aggregation, field grazing days and fertilizer application. Next, these landscape patterns and management descriptors were linked to the current production intensity of farms such as total farm milk yield, milk yield per cow and milk yield per hectare. These descriptors were tested for interrelations by applying two-sample Kolmogorov-Smirnov tests. We found that a higher milk production was significantly linked to larger fields, fewer hedgerows, fewer grazing days, higher use of N-fertilizer and a decrease of nutrient cycling. Furthermore, production intensity was found to differ with the landscape pattern of clay content and groundwater hydrology. On top of this landscape template, man-made patterns of field sizes and hedgerows from before 1930 are still visible in the current differences of milk production intensity. Current farm management was found to have relations with the hedgerows, field size, clay content and groundwater hydrology. These relations hint at a co-evolution of landscape pattern and agricultural intensification. Interestingly, the largest differences between descriptors of landscape pattern and intensity were found for similar values of clay content, groundwater hydrology and fertilizer use. We speculate that these similar values indicate the existence of tipping points for diverging trajectories of intensification. Identification of such tipping points have implications for policies that deal with the future dynamics of rural landscapes.

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## 4.1 Introduction

Government, public and farmers in Western Europe increasingly prefer rural landscapes that provide more than food alone. Despite an increase of supportive policies to stimulate multifunctional land use, however, intensification of production continues to dominate (European Commission, 2011). This follows the general trend going back to the second half of the 20th century, when the Common Agricultural Policy (CAP) strongly supported increases in production. This policy stimulated farmers to invest in mechanization, external inputs, animal housing and in the number and productivity of dairy cows, leading to an unprecedented increase of agricultural productivity (European Commission, 2011). In the Netherlands, for example, the average farm size increased from 6 ha in 1950 to 26 ha in 2010 (CBS, 2012a), while annual milk production increased from 27 t milk/farm to 362 t milk/farm. In the neighboring countries (Belgium, Germany and Denmark), average farm size and number of dairy cows per holding tripled to 45 ha and 39 cows per farm between 1975 and 2005 (European Commission, 2000; Eurostat, 2009). These rapid changes in farming systems in post-WWII decades had a severe impact on other services landscapes provided. For example, in Flanders, more than half of the hedgerows disappeared between 1900 and 2000 (Deckers et al., 2005), while nitrogen (N) concentrations in shallow groundwater in Western Europe increased tenfold in the period 1955-1995 (Van Drecht et al., 2003). Together, these changes dramatically affected the ecology of the landscape (Billeter et al., 2008; Stoate et al., 2009). In the new CAP reform for 2013, stimulation of "green" agricultural practices of maintaining permanent pasture, hedgerows and landscape elements is foreseen. Additionally, the Rural Development program of the EU will promote, among others, the restoration, preservation and improvement of ecosystems. However, abolition of milk quota will further increase milk production, which is expected to come from fewer but larger farms with more productive cows that graze less outside (Vellinga et al., 2011).

Intensive agriculture is considered as one of the main threats for the continuation of traditional landscapes (Antrop, 2005). Traditional landscapes are characterised by their distinct and recognisable pattern which reflects long-term interactions between the composing elements (Antrop, 1997). These interactions between soil, climate, topography and land use lead to complex patterns of non-random heterogeneity. At the same time, landscape pattern was found to be a driving factor of agricultural development (Thenail, 2002). For example, structurally complex landscapes were found to have a lower land-use intensity, lower fertilizer use, less land consolidation and lower farm specialization in

comparison with simple landscapes (Thenail, 2002; Roschewitz et al., 2005). The complex relation between landscape pattern and agricultural intensification is further increased by lack of central management. A landscape consists of numerous pieces of land with a multitude of owners each managing their land according to their own interests (Antrop, 2005). We therefore consider an agricultural landscape as an agro-ecosystem of which the scale is larger than the individual farmer and farm, but is sufficiently small, such that an individual voice can make a difference (sensu Cabel and Oelofse, (2012)). Furthermore, we consider agro-ecosystems as social-ecological systems (Darnhofer et al., 2010; Tomich et al., 2011; van Apeldoorn et al., 2011b) characterized as strongly coupled, complex and evolving integrated systems of people and nature.

Based on the above we hypothesize that agricultural management and landscape patterns interact, leading to a interdependency of the degree of intensification and locality. These interrelationships of landscape and agricultural intensification often go unnoticed, while such a coupling would argue for spatial explicit studies with a co-evolutionary perspective in order to design effective policies for multi-functional landscapes. The aim of this paper was therefore to localize and quantify interactions between landscape pattern and agricultural intensification. This was done for a traditional Dutch landscape dominated by dairy farming, for which spatial explicit landscape pattern and management data are available. Firstly, causal interactions between landscape patterns and agricultural intensification were visualized and described in a conceptual diagram. Secondly, a dataset was assembled, integrating spatial explicit descriptors of milk intensity, land use history, management records and landscape elements. From a co-evolutionary perspective it is impossible to assume equilibrium conditions. Therefore, non-parametric statistics were used to localize and quantify interactions. Finally, possible implications will be explored.

## 4.2 Materials and Methods

### 4.2.1 Study area

The system under study is the landscape of the Northern Frisian Woodlands. This is a traditional rural landscape in the north of the Netherlands and has an area of about 60,000 ha. The landscape is characterized by relatively small fields with a high density of hedgerows on sandy soils, alternated by relatively open areas on lower peat and clay soils. A unique mosaic of parcels is formed by hedges and belts of alder trees surrounding the plots of land. The area is well studied in relation to the attempts of farmers to reconcile

farming and landscape (see among others (Wiskerke et al., 2003; Groot et al., 2007b; Sonneveld et al., 2012)).

*4.2.2 Interactions of landscape pattern and intensification of milk production*
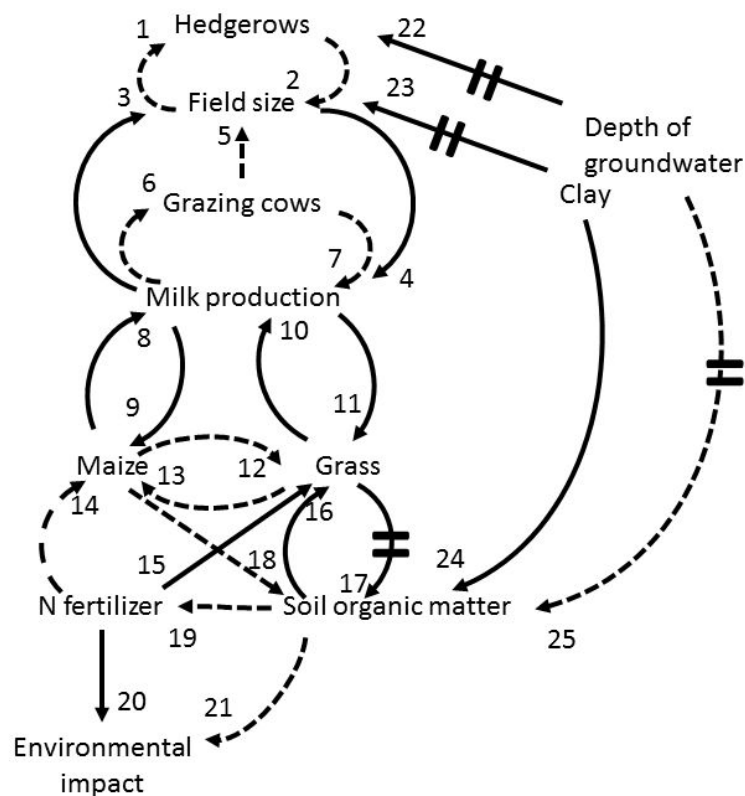


**Figure 2.** Conceptual diagram of the hypothesized interactions between landscape pattern and intensification of agricultural production. Dashed lines represent negative feedbacks and hatches slow feedbacks. The interactions are described throughout the text using the indicated numbers.

Figure 1 presents a conceptual diagram of the hypothesized interactions between landscape pattern and intensification of production. Intensification of production is represented here as the increase of milk production. The conceptual diagram represent temporal interactions, of which the outcome lead to spatial differences in milk intensity and landscape pattern. The landscape pattern is represented as the patterns of clay content and depth to the groundwater table, but also field size, hedgerows, soil organic matter content, and the occurrence of maize fields. Many of these patterns are interrelated through (historical) management and Figure 1 represents our hypothesized relations between agricultural intensification and landscape pattern.

In the Northern Frisian Woodlands, historical allotment and land use were determined by the landscape properties of groundwater hydrology and ease of tillage (affected by the soil clay content). The higher, relatively well-drained parts were used for mixed farming until the 1950s. In these farming systems, hedgerows were established to serve as a means for fencing, wind breaks, and the provision of wood (22; Figure 1). In contrast, the lower clayey areas were used for grazing and hay production with larger parceling (23). The landscape properties influence current land use: clay protects soil organic matter (SOM) from decomposition (24) (Hassink, 1994), while soil hydrology determines the potential of maximum soil organic matter content (25) (van Apeldoorn et al., 2011a). SOM content has a positive effect on physical, chemical and biological soil properties, contributing to higher grassland quality (16) (Groot et al., 2007a), reduced environmental impact (21) and reduced need for fertilization (19). SOM slowly increases under continuous grassland (Vellinga et al., 2004; van Apeldoorn et al., 2011b), while maize cultivation has almost irreversible negative effects on SOM content (18) (Vellinga et al., 2004; Hanegraaf et al., 2009).

At field level, intensification leads to the increases of field size (3) and removal of hedgerows (1) (Petit et al., 2003) to enlarge the productive area (4). Hedges are a barrier to aggregation of fields since these are expensive to remove (Groot et al., 2007b) and/or nowadays protected landscape elements (2). The increase in herd size and dietary demands because of intensification lead to a decrease in grazing (6-7) (Vellinga et al., 2011). When fields are not grazed anymore, fences can be removed leading to larger fields (5). Highly productive cows need more dry matter, which can be delivered by either increased acreage of maize or grass (8-11), with maize and grass competing for the same area (12-13), or increased dry matter yields per unit area. A reduction of N-fertilization leads to loss of dry matter of grass (15) which can be compensated by the high dry matter production of maize (14) (Vellinga et al., 2011). An increase of N-fertilization increases the environmental impact (20) (Schröder and Neeteson, 2008).

### 4.2.3 Spatio-temporal data

To test the conceptual diagram outlined in Figure 1, descriptors were sought for the variables that we identified. These descriptors needed to be spatial explicit and available at the field level, ideally over a long time period to be able to detect changes in landscape patterns. In a GIS-environment (ArcGIS 10.0), a soil and groundwater hydrology map (1:50,000), topographical maps (1:10,000), historical maps (1:25,000) and 1107 spatial explicit records of field management in 2006 of 58 farms were brought together. Of these

58 farms the production characteristics of 2006 were known as well. In appendix A, details of data sources, data scales and derivations of the descriptors are given.

Digitized and geo-referenced historical topographical maps from around 1930 were compared with current presence of hedgerow and alder belts. The number of removed hedges around or in a field was given a negative value, whereas newly established hedges were given a positive value. To account for differences in hedgerow length, the change of a hedge from the 'long side' of a field was counted for two 'short sides'. The same historical maps were used to assess field aggregation by counting the number of fields that were part of the current fields' boundaries. Grazing days per field where derived from the management records. Grassland age was defined as the maximum time a field has been classified continuously as grassland. Historical classification (grass, arable land or other) was obtained from geo-referenced scanned images of topographical maps from 1950 to 1990. The classification was obtained from these maps by assigning to each field, the land use class of the most frequent pixel value within this field. Each map was separately classified in this way to account for printing differences between maps. For the maps of around 1930, this method was unable to differentiate between arable fields and grassland and every field was manually classified on the basis of visual appearance. The historical vector datasets from 1995 and onwards were queried for their land use classification and the source date of this classification. Finally, grassland age was calculated as the maximum time a field was classified as grassland going back from 2004. N-fertilizer application per field was derived from the spatial explicit management records. Distance to farm was calculated from the field centroid inside a field to the farm location that was derived from the farm survey. The average clay content ($kg/m^2$) in the soil profile (1.2 m) was calculated from representative soil profile descriptions that were associated to the mapping units of the soil map (De Vries, (1999). Groundwater hydrology was included by calculating the accumulated aerated annual soil depth (AAASD) following van Apeldoorn et al. (2011a). Where multiple groundwater hydrology classes or soil profiles were present in one field, the spatial average was calculated for that field. Milk yields per farm, per cow and per hectare were derived from the 2006 farm survey. Since no long-term data of milk yield intensity were available, we assumed that the external driver to intensify was identical for all farms in the region. The response to this external driver was different for each farm, we assume that differences in intensity in 2006 are the result of farm characteristics. The N surplus was measured as the difference between farm N-inputs and farm N-outputs.

Table 1 shows the descriptors, their units and their relations with the feedbacks in Figure 1. This dataset of descriptors provides a spatial explicit description of management (history) and landscape at field level combined with descriptors for intensity at farm level.

**Table 2.** Descriptors with their units and their relation with the feedbacks in Figure 1.

| | | Descriptor | Relation with feedback number in Figure 1 |
|---|---|---|---|
| Field level | management | Hedge density (m/ha) | 1,2,22 |
| | | Hedge change | 1,2,22 |
| | | Field size (ha) | 1-5,23 |
| | | Field aggregation | 1-5,23 |
| | | Grazing days (d) | 5-7 |
| | | Grassland age (y) | 12,13,17-19,21,24 |
| | | N-fertilizer (kg/ha) | 14,15,19,20 |
| | landscape | Distance to farm (m) | 8-11 |
| | | Clay content (kg/m²) | 23,24 |
| | | Accumulated aerated annual soil depth (m) | 22,25 |
| Farm level | management | Milk (t/y) | 3,4, 6-11 |
| | | Milk (t/cow) | 3,4, 6-11 |
| | | Milk (t/ha) | 3,4, 6-11 |
| | | N-surplus (kg/ha) | 3,4, 6-11 |

*4.2.4 Statistical analysis*

Using standard parametric or linear statics to identify relationships between intensification and landscape pattern has a number of conceptual problems. Landscape change is notoriously chaotic (Antrop, 2005). In combination with the almost instantaneous changes like tillage or hedgerow removal, and changing drivers of policy, milk price, research, farm succession, makes that agro-ecosystems cannot be assumed to be in (or even close to) equilibrium. When statistically analyzing evolving agro-ecosystems, assumptions on (normal) distributions, independency and linearity are therefore likely to be violated. Because of this, we used non-parametric methods to explore relationships between agricultural intensification and landscape pattern. First, the Kendall's tau rank correlation coefficient was used to measure the association between each combination of ten descriptors derived from the entire dataset of 1107 fields. To further identify non-

linear differences in relations, the population of fields was divided in two groups for each descriptor, by a median split. In this manner, the upper and lower half of the field populations can be compared with a two-sample Kolmogorov-Smirnov test (KStest2 in Matlab 2011a). For each half, an empirical cumulative distribution function was generated. The KS-test compares the two functions and calculates the KS-statistic, which is based on the largest absolute distance between the functions. Under the null hypothesis that the two samples are drawn from the same distribution, the KS-statistic equals 0 when there is no difference between the two samples, i.e. the two samples were taken from a homogeneous population, and it is equals 1 when the samples have no overlap. Besides a measure on how different the two distributions are, the test also provides information on the value of the descriptor where the largest difference can be found. As such, the test can localize non-linear changes in the relationships of intensity and landscape pattern.

Not all descriptors can be tested for significance with the two Sample Kolmogorov-Smirnov test. Farm level descriptors of milk intensity and N-surplus cannot be disaggregated to field level. Non-continuous or ordinal data violate the assumption made by the two sample Kolmogorov-Smirnov test, so the ordinal data of field aggregation and hedgerow change and the non-continuous data of grassland age were only used for splitting the population.

## 4.3 Results

Tables 2 and 3 present summary statistics for the landscape and management descriptors at field and farm level (see table 1). Hedge density was on average 138 m/ha, which indicates that more than two short sides of any field are bordered by hedgerows, with a common ratio of 2:1 for long and short sides of a field. Hedge change was on average negative, indicating a net loss of hedges. Fields are generally small, about 2 ha, and the number of fields has decreased by one third since 1930. Fields have on average been grazed for 32 days per year, which is about one seventh of the grazing season. Fields have been grassland for 83 years. On average, these fields have received 121 kg N/ha in 2006, which is 10 kg N/ha less than the Dutch average. The average clay content is comparable to that of a sandy loam soil and the average accumulated aerated annual soil depth (AAASD) is comparable to a mean lowest water table of 1.2 m and a mean highest ground water table of 0.4 m (ground water table IV (Van der Sluijs and de Gruijter, 1985)).

**Table 3.** Summary statistics of landscape and management descriptors at field level.

| | Hedge density (m/ha) | Hedge change | Field size (ha) | Field aggre-gation | Grazing days (d) | Grass-land age (y) | N-fertilizer (kg/ha) | Distance to farm (m) | Clay content (kg/m²) | AAASD (m) |
|---|---|---|---|---|---|---|---|---|---|---|
| Mean | 138 | -0.61 | 2.01 | 1.53 | 32.0 | 83 | 121 | 774 | 175 | 80.3 |
| Standard deviation | 162 | 1.38 | 1.10 | 0.85 | 42.9 | 32 | 80 | 883 | 163 | 32.1 |
| Min | 0 | -6.00 | 0.03 | 0.00 | 0.0 | 0 | 0 | 43 | 0 | 21.6 |
| Max | 1035 | 6.00 | 7.70 | 7.00 | 228.0 | 100 | 408 | 8113 | 628 | 128.1 |

Average milk production per dairy farm in 2006 was 599 tons, which is 50 t more than the average Dutch milk production in that year. On average, with 10.7 t per cow, the cows were more productive than the Dutch national average of 7.9 t per cow, while producing 7.3 t milk per hectare, which is less than the Dutch national average of 12.8 t milk per hectare. N-surplus was 26 kg/ha lower than the Dutch average of 171 kg N per hectare for the year 2006.

**Table 4.** Summary statistics of of intensification and environmental impact descriptors at farm level. The Dutch Mean values are based on the Farm Accountancy Data Network for the year 2006 (LEI, 2012).

| | Milk (t/y) | Milk (t/cow) | Milk (t/ha) | N-surplus (kg/ha) |
|---|---|---|---|---|
| Mean | 599 | 10.7 | 7.3 | 145 |
| Standard deviation | 267 | 2.4 | 1.1 | 46 |
| Min | 190 | 5.9 | 4.5 | 31 |
| Max | 1401 | 15.5 | 9.6 | 264 |
| Dutch 2006 mean | 549 | 7.9 | 12.8 | 171 |

The Kendall's tau correlation matrix yielded 26 associations with $p<0.05$ (Table 4). In agreement with Figure 1, a negative association between field size and hedgerows was found (1, 2). The larger fields also tend to be made up by multiple fields (3). Changes of field size were related to the removal of hedges (1). No association was found between field size and grazing days (5). The relation of grassland age via SOM on N-fertilizer application was likewise not found (17, 19). Clay content had no association with field size (23) nor with grassland age (24). Grassland age had a negative association with AAASD (25), while no association was found with clay content (24). AAASD had a positive association with current hedge density (22). Apart from these associations that supported our hypothesized relationships in Figure 1, other significant associations were found as well. A high hedge density was correlated with high grazing intensities, low grassland age and low fertilizer use. Large fields were correlated with old grasslands and high fertilizer application. A high number of grazing days were correlated with old grasslands. The bio-

physical pattern of AAASD was negatively correlated with field size and distance to farm and fertilizer use, while clay content had negative association with hedge density.

**Table 5.** Kendall's tau correlation matrix of relations between the descriptors, significant relations are highlighted corresponding their significance

| | Hedge change | Field size (ha) | Field aggre-gation | Grazing days (d) | Grass-land age (y) | N-fertilizer (kg/ha) | Distance to farm (m) | Clay content (kg/m2) | AAASD (m) |
|---|---|---|---|---|---|---|---|---|---|
| Hedge density (m/ha) | -.234 | -.244 | -.027 | .066 | -.171 | -.091 | .027 | -.157 | .515 |
| Hedge change | | .088 | -.159 | .006 | .223 | -.044 | -.037 | .047 | -.323 |
| Field size (ha) | | | .364 | .038 | .078 | .068 | .009 | .030 | -.201 |
| Field aggregation | | | | .046 | -.049 | .058 | -.028 | -.062 | -.028 |
| Grazing days (d) | | | | | .097 | -.004 | -.094 | -.096 | .020 |
| Grassland age (y) | | | | | | -.003 | -.071 | .045 | -.147 |
| N-fertilizer (kg/ha) | | | | | | | -.182 | -.019 | -.070 |
| Distance to farm (m) | | | | | | | | .003 | -.050 |
| Clay content (kg/m2) | | | | | | | | | -.001 |

| p<0.05 | p<0.01 | p<0.001 |
|---|---|---|

In Figure 2, an example of two cumulative distribution functions is given for N-fertilizer application when the population was split in half by the median amount of produced milk per cow (10.7 t/ha). At 140 kg applied N per ha, the difference between the two frequency distributions is largest. Figure 2 shows that 76% of the farms with a milk production per cow of less than 10.7 t milk applied less than 140 kg N fertilizer per hectare, whereas only 39% of the farms with an average milk production per cow of more than 10.7 t applied less than 140 kg N/ha.
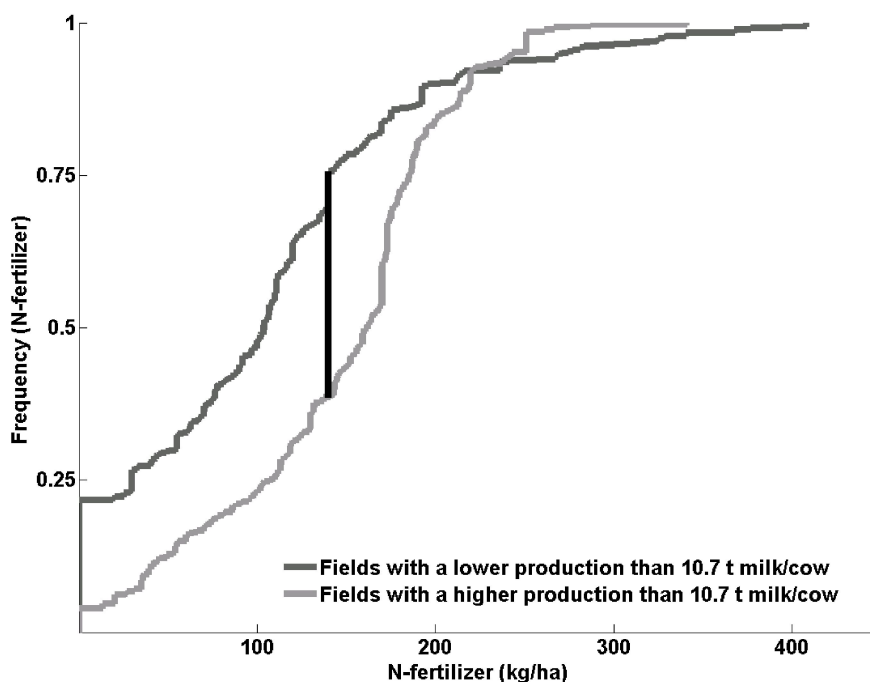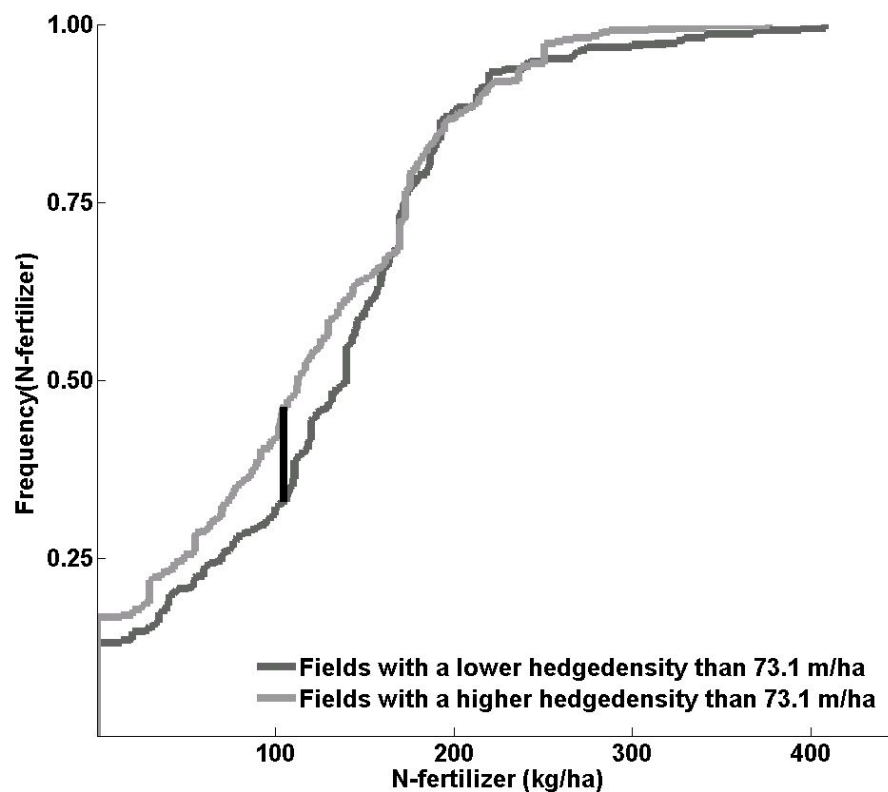
**Figure 3.** Cumulative distribution functions of N-fertilizer application. The population is split at the median of 10744 kg milk/cow, the largest frequency difference is 0.37 (0.76 − 0.39) at 140 kg N/ha (depicted by the solid black vertical line)

Likewise, all continuous descriptors at field level were split-up and compared to each other (Table 5). The largest difference of 140 kg N/ha of Figure 2 was found at the intersection of the Milk (t/cow) row (the splitting variable) and N-Fertilizer (kg/ha) column (the continuous descriptor). The value of the descriptor where the largest difference was found, provides a position or location in comparison with the whole population (e.g. Table 2 or national statistics), while the *p*-value quantifies the difference. Seven continuous descriptors, split up by the median of the ten field descriptors, lead to 63 comparisons at field level. The four farm level descriptors resulted in 28 comparisons. A *p*-value less than 0.05 was found for 57 comparisons at field level and 24 at farm level. A p-value smaller than 0.05 represents a maximum frequency difference of more than 0.08. The practical relevance of the significant differences is an absolute difference between the two groups of more than 44 fields or 2 farms.

**Table 6.** Values of descriptors, where the maximum largest frequency difference of the two distributions split by population median was found. The population was split by the row variable. Significant relations are highlighted corresponding to their p-value. Columns are grouped by management and landscape descriptors. Rows are grouped by field and farm level.

| | | Median | Management | | | | Landscape | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Hedge density (m/ha) | Field size (ha) | Grazing days (d) | N-fertilizer (kg/ha) | Distance to farm (m) | Clay content (kg/m2) | AAASD (m) |
| Field | Hedge density (m/ha) | 73.1 | - | 2.17 | 1 | 105 | 659 | 167 | 77 |
| | Hedge change | 0 | 47.6 | 2.17 | n.s. | 167 | 694 | 167 | 92 |
| | Field size (ha) | 1.80 | 158.1 | - | 10 | n.s. | n.s. | 65 | 78 |
| | Field aggregation | 1 | 332.3 | 2.03 | n.s. | 99 | n.s. | n.s. | n.s. |
| | Grazing days (d) | 18 | 129.1 | 2.32 | - | 139 | 523 | 127 | 111 |
| | Grassland age (y) | 100 | 62.3 | 1.51 | 6 | 161 | n.s. | 167 | 97 |
| | N-fertilizer (kg/ha) | 124 | 157.1 | 1.13 | 39 | - | 587 | 167 | 99 |
| | Distance to farm (m) | 468 | 0.6 | n.s. | 1 | 107 | - | 92 | n.s. |
| | Clay content (kg/m2) | 126 | 121.6 | n.s. | 13 | 161 | n.s. | - | 113 |
| | AAASD (m) | 97 | 89.4 | 1.74 | 32 | 135 | n.s. | 61 | - |
| Farm | Milk (t/y) | 589 | 118.2 | 2.01 | 57 | 130 | n.s. | 217 | 97 |
| | Milk (t/cow) | 10.7 | 118.3 | 1.97 | 30 | 140 | 1080 | 201 | 105 |
| | Milk (t/ha) | 7.5 | 118.2 | 1.99 | 30 | 139 | n.s. | 217 | 99 |
| | N-surplus (kg/ha) | 153 | 158.9 | 1.97 | n.s. | 140 | n.s. | 65 | 104 |
| | | | p<0.05 | p<0.01 | p<0.001 | | | | |

Space does not allow to go into all significant differences, so in appendix B the cumulative frequency at the largest difference of the two samples are given for all descriptors. In this section we explain a difference of each quadrant extensively to familiarize the reader with the information provided in table 5.

**Figure 4.** Cumulative distribution functions of N-fertilizer application. The population was split at the median hedge density of 73.1 m/ha, the largest difference was 0.13 at 105 kg N/ha (depicted by the solid black vertical line).
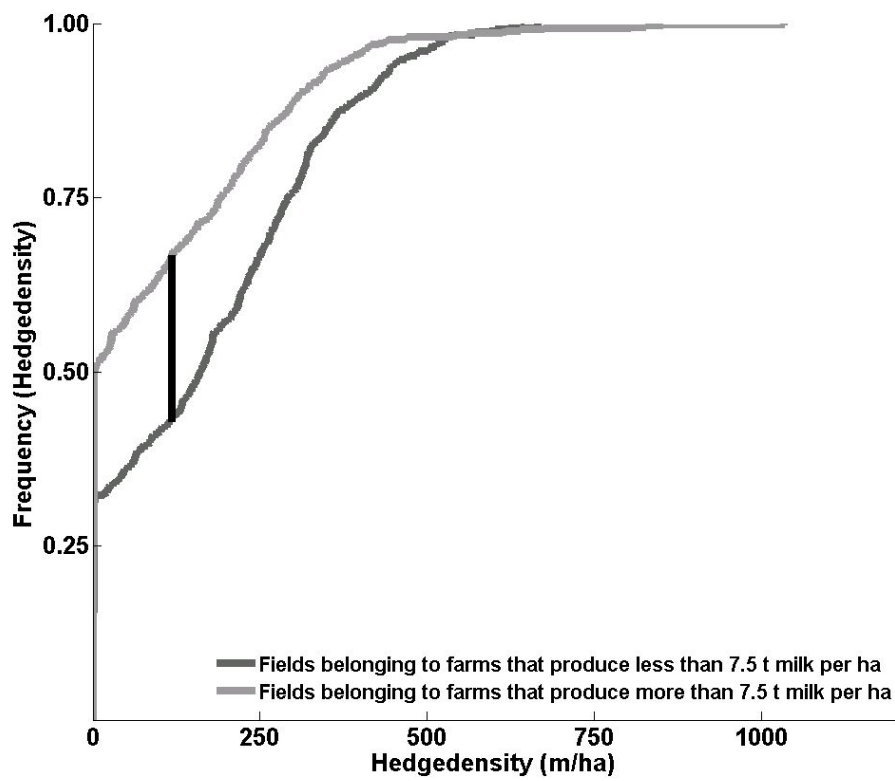
In Figure 3, two cumulative distributions of N-fertilizer application are plotted. The two distributions were generated by splitting the total populations of fields in two by the median hedge density of 73.1 m/ha. 73.1 m/ha is almost half of the total population average (Table 2) and means that less than two short sides were bordered by hedges. Fields that have less than 73.1 m hedge per hectare received on average more nitrogen fertilizer per hectare. The largest difference was found at 105 kg N/ha, which is 15 kg N less than the total population average (Table 2). The largest frequency difference between the two population samples was 0.13, depicted by the solid black vertical line in Figure 3. On 33% of the fields with a lower hedge density than 73.1 m/ha, less than 105 kg N/ha was applied, whereas 46% of the fields with a higher hedge density received less than 105 kg N/ha. Table 4 shows a negative association between hedgerow density and fertilizer application. Figure 3 shows that the difference is non-monotonic with the distributions crossing each other at 170 kg N/ha, indicating that hedge density related differences were mainly found for low N-fertilizer application rates.
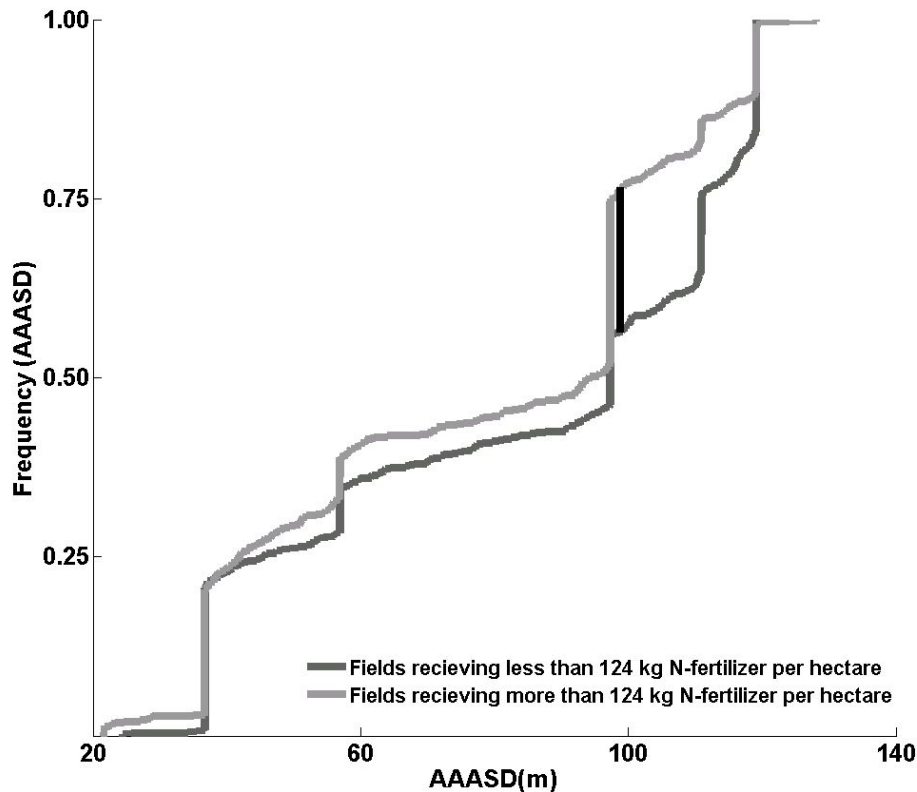
**Figure 5.** Cumulative distribution functions of accumulated aerated annual soil depth (AAASD). The population was split by the median fertilizer application of 124 kg N/ha, the largest difference was 0.20 at AAASD of 97 m (depicted by the solid black vertical line).
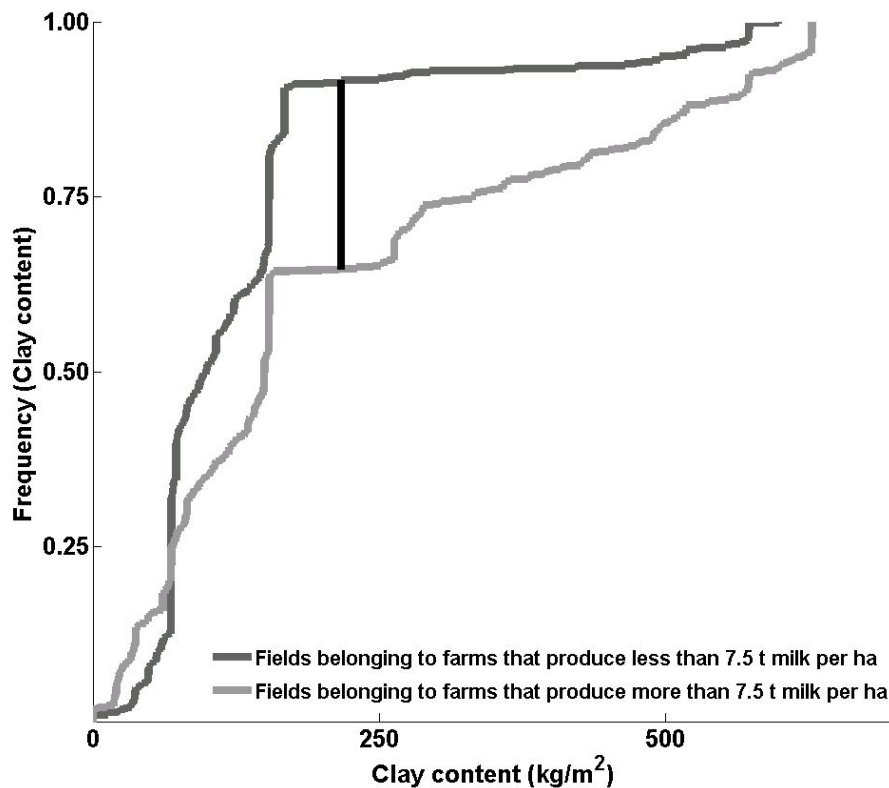
In Figure 4, the population of fields was split by the median fertilizer application of 124 kg N/ha and the cumulative distribution functions of AAASD are plotted. Fields that received less than 124 kg N/ha were on average found on better drained soils. 124 kg N ha is near the population average (Table 2) while the largest difference is found at 97 m AAASD, which is higher compared to the 80.3 m AAASD population average. Fields with more than 97 m AAASD had their mean groundwater table below 1.2 m in summer. Largest frequency difference between the two samples was 0.20. 56% Of the fields which received less than 124 kg N/ha had less than 97 m AAASD while 76% of fields receiving more than 124 kg N/ha had less than 97 m AAASD. Table 4 shows a negative association between fertilizer application and AAASD. Figure 4 shows that this association can be mainly contributed to the lower fertilizer application at the better drained fields.

*quadrant*

**Figure 6.** Cumulative distribution functions of hedge density. The population was split by the median milk production of 7.5 t/ha, the largest difference was 0.24 at a hedge density of 118 m/ha (depicted by the solid vertical black line).

In Figure 5, the population of fields was split by the median milk production of 7.5 t/ha and the cumulative distribution functions of hedge density are plotted. A milk production of 7.5 t/ha is near the population average of 7.3 t/ha (table 3). Fields that belong to a farm that produced less than 7.5 t milk/ha had on average more hedges per hectare. Largest difference was found at 118 m/ha, which are fields with a hedge on more than two short sides. Largest frequency difference between the two samples was 0.24. 43% of the fields with a lower milk production than 7.5 t/ha had less hedges than 118 m/ha, while 67% of the fields with a higher milk production than 7.5 t/ha had less hedges than 118 m/ha. Figure 5 shows that 50% of the fields belonging to more intensive farms had no hedge at all.

**Figure 6.** Cumulative distribution functions of clay content. The population is split by the median milk production of 7.5 t/ha, the largest difference is 27% at a clay content of 217 kg/m2 (depicted by the solid vertical black line).

In Figure 6, the population of fields was split by the same median milk production of 7.5 t/ha and the cumulative distribution functions of clay content are plotted. Fields that belong to a farm that produced less than 7.5 t milk/ha had on average less clay in their soils. Largest difference was found at fields with a clay content of 217 kg/m² , which are the fields found on marine soils. Largest frequency difference between the two population samples was 0.27. 92% of the fields with a lower milk production than 7.5 t/ha had a clay content of less than 217 kg/m², while 65% of the fields with a higher milk production than 7.5 t/ha had a clay content of less than 217 kg/m². Figure 6 shows the almost complete absence of fields of the less intensive farms on the marine soils.

## 4.4 Discussion

In agreement with our conceptual diagram (Figure 1), we found that in our study area, increasing milk production was linked to larger fields (3), fewer hedgerows (1), fewer

grazing days (5) and a higher use of N-fertilizer. This is closely linked to the N-surplus of the farm, indicating a decrease in nutrient use efficiency and nutrient cycling at farm level (8-21). These findings are in line with other studies on agricultural intensity and temperate grasslands (e.g. Pilgrim et al. (2010)). The degree of intensification was location specific. In 2006, significant differences in intensity were found for soil type (clay content) and soil drainage status (AAASD). The most intensive farms occurred more often on soils with a clay content of more than 200 kg/m² (marine soils), while having a much lower occurrence on the dry soils with an AAASD of more than 100 m (i.e. soils that have a mean lowest groundwater table of below 1.2 m). Furthermore, the long-term history of use added a spatial pattern on the bio-physical pattern of soil distribution and groundwater hydrology. The dry sandy soils used for mixed farming in the early twentieth century needed fencing to contain the animals and wind protection for their crops. The clayey and wetter areas could be enclosed by ditches and were mostly used for grazing and hay making. Consequently, hedgerows were almost exclusively found on the dry sandy soils (22-23) enclosing small fields (4). The effects of small fields and high hedgerow density originating from before 1930 were still visible in the lower milk intensity. The history of use expressed in the grassland age was influenced by clay content and AAASD (24-25) but also by the man-made pattern of hedges and field size. Low clay content and high AAASD favor tillage and cultivation of crops. Fields younger than 50 years were larger and had less hedges (data not presented). The increasing area of silage maize in the north of the Netherlands might further stimulate the future development of this pattern (CBS, 2012b). On top of these patterns, the current management takes place. Fields with more hedges, smaller fields or fields on sandy dry soils received less fertilizer and were grazed for longer periods of time.

Most importantly, this analysis shows that differences in milk intensity are interrelated with landscape pattern, which was not identified in previous studies in this area. Additionally, much might be learned from analyzing the value of the descriptor of the maximum differences of the two cumulative distribution functions. In Figure 3, the largest difference was located below the average N fertilizer application of 120 kg/ha, and there was no difference at applications above 170 kg/ha, indicating that only the farmer who was already carefully applying N-fertilizer is acknowledging the hedges.

The interrelations found in this study hint at a co-evolution (German, 2003) or co-production (Sonneveld et al., 2004) of landscape pattern and intensification. Co-evolution might cause a large diversity of trajectories of intensification followed, resulting in an

unique landscape pattern. From a co-evolutionary perspective the reoccurring values of descriptors in Table 5 give rise to intriguing questions. For example, why does the largest difference of N-fertilizer occur at 130-140 kg/ha for grazing days, AAASD, milk intensity and N surplus? What makes the clay content of more of 167 kg/m² so different to yield the largest differences of hedge density, hedge change, grassland age and N-fertilizer? Do the fields that have no access to groundwater in summer (an AAASD of >97, mean lowest groundwater table below 1.2 m) need such a different management that it results in the largest difference for grassland age, N-fertilizer, milk intensity and N-surplus? We speculate that these reoccurring values are related to tipping points for different trajectories of intensification in the Northern Frisian Woodlands. When passing a tipping point or critical threshold, a different set of feedbacks becomes dominant, and the system experiences a large, often abrupt change in structure and function. Such large, persistent changes in the structure and functioning of a system are often called 'regime shifts' (Kinzig et al., 2006). Although these have been conceptually defined for some agro-ecosystems (Kinzig et al., 2006), localizing and quantification of tipping points in complex landscapes is shown to be challenging. If we would be able to identify tipping points in such landscapes, this could be used to support resilience against undesired change, or to promote shifts to a more desired state.

Next to a need to improve our understanding of the location and value of the tipping points, method and data collection can be improved. The management data were collected for a different study, which might unconsciously lead to sampling bias. The management covered only 1 year leading and lack temporal variability. Moreover, fields belonging to one farm might receive the same type of management or might be close to each other resulting in spatial autocorrelation. Likewise, some descriptors were calculated from categorical maps or retrieved from the same source (historical maps), possibly resulting in a bias. To correct some of the caveats of spatial autocorrelation and farm-field correlations, data could be sampled with a stratified random sampling method (de Gruijter et al., 2006), with field ownership as stratification. Using continuous maps of groundwater and soils would reduce categorical effects. The Kolmogorov-Smirnov test quantifies and locates differences in patterns and processes without needing assumptions of linearity, and stationary of processes. Options to improve our method is the use of a multivariate version of the Kolmogorov-Smirnov test, however, these tests are generally seen as a challenge (Lopes et al., 2007) and there is no widely accepted test for comparing N-dimensional distributions (Loudin and Miettinen, 2003).

Neglecting feedbacks between landscape pattern and intensity potentially misinforms policy makers (Nicholson et al., 2009). For example, Table 4 shows many significant associations, which would hardly be considered policy relevant given their low values. Our analysis shows that recognizing the interrelations between intensity and landscape pattern leads to a complexity which cannot be captured by linear methods. These results support rural governance initiatives (Wiskerke et al., 2003) with the active participation of farmers (Vellinga et al., 2011) for their knowledge of local specific patterns.

## 4.5 Conclusions

Agro-ecosystems evolve via feedbacks between landscape pattern and management, resulting in non-linear dynamics and a complex landscape. The landscape pattern provided unequal positions for farms in the process of intensification of production. Our conceptual diagram of interactions between landscape and intensification of a Dutch dairy farming system was largely confirmed, but additional relations were uncovered, underlining the complexity of the system. We found that a higher milk production was linked to larger fields, fewer hedgerows, fewer grazing days, higher use of N-fertilizer and a decrease of nutrient cycling. These general observations can be differentiated by acknowledging landscape patterns. Significant differences in intensity were found for clay content and groundwater hydrology. On top of this landscape template, man-made patterns from before 1930 are still visible in the current differences of farm intensity. The current management involves choices of allowing cows to graze and applying N-fertilizer. These also have relations with the hedgerows, field size, clay content and groundwater hydrology. These relations implicate a co-evolution of landscape pattern and intensification. Largest differences between fields were found for similar values of clay content, groundwater hydrology and fertilizer use. These reoccurring values might indicate tipping points, that have implications for policies that deal with the future dynamics of such landscapes

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# Chapter 5

# Analysing soil fertility gradients at village scale in African smallholder farming systems: A scale mismatch?

**Abstract**

Many studies recognize that soil fertility gradients in smallholder farms in sub-Saharan Africa are important in determining the efficiency of crop response to nutrient inputs. To date, the spatial distribution of these fertility gradients at the village scale had not been determined. We set out to map soil organic carbon (SOC) content, as an indicator of soil fertility, at the village scale, and to relate the SOC content to farm scale management and landscape scale characteristics. Using digital soil mapping techniques and Landsat TM images we could explain 50% of the observed SOC variance. The village average values were estimated to be 1.5 % SOC content, although the sandy cropping area had a much lower average SOC content of 0.8 % and the red clays and valleys had higher average SOC content of 1.8%. The SOC variability could not be linked to farm management. No fertility gradients were observed, mostly due to a strong dominance of clay content on the spatial distribution of SOC. Clay content was able to explain 57% of the SOC variance, while farm area and labour size, typically used for farmer typology, were able to explain only an additional minor part of the SOC variance. This strong landscape scale effect needs to be included in future village-scale studies. We conclude that digital soil mapping of soil fertility gradients at the village scale has several scale issues that need to be addressed if the envisioned global digital soil map is to be relevant for smallholder farmers in sub-Saharan Africa.

## 5.1 Introduction

Food production in sub-Saharan Africa does not keep pace with population growth (Ray et al., 2013; Tittonell and Giller, 2013). Poor soil fertility is the primary bio-physical constraint that results in poor yields (Sanchez, 2010). Next to the inherent variability of soils and their fertility, management decisions result in the development of strong fertility gradients (Giller et al., 2006; Giller et al., 2011; Masvaya et al., 2010; Tittonell et al., 2013; Tittonell et al., 2007a; Tittonell et al., 2007b; Zingore et al., 2007b). These gradients are spatial patterns of soil fertility, resulting from inherent differences in parent material, position in the landscape and, above all, the preferential allocation of manure, compost, mineral fertilizers and labour on fields near the homesteads (Giller et al., 2011; Tittonell et al., 2013). As a result, soil fertility declines with increasing distance from the homestead. These gradients are considered a key entry point for increasing resource use efficiency of scarce fertilizers and thereby increasing food security in sub-Saharan Africa (Giller et al., 2011; Tittonell et al., 2013; Van Wijk et al., 2009).

In the infertile, ancient soils that dominate much of sub-Saharan Africa, soil organic carbon (SOC) is a key indicator of soil fertility. SOC has been identified as an essential natural resource in many land-based agro-ecosystems. It is considered the most important indicator of soil quality and agronomic sustainability, because of its impact on other physical, chemical and biological soil properties (Reeves, 1997). The accumulation of SOC is limited by the amount of C the field receives as unharvested biomass and manure. In turn, the amount of biomass and manure produced in low-external-input systems is dependent on the soil fertility and regulated by the SOC content.

Differences in soil fertility between fields on similar soils are induced by the strategic use of limited resources. Therefore, differences between farms in resource endowments, and hence in access to nutrient resources, lead to different gradients (Masvaya et al., 2010). Zingore et al. (2007a) showed that better-endowed farmers with ample access to manure, fertilizer and means of transporting manure have only slight fertility gradients, while farmers with a limited amount of manure or labour, preferably allocate such resources to the fields and gardens around their homesteads, resulting in a strong decreasing gradient of SOC. Farmers with no access to manure or with a scarce labour force and a limited cropping area, have no gradient with only depleted fields, as a result of prolonged cultivation with small applications of fertilizer and no organic nutrient resources.

Soil fertility gradients have a strong influence on resource use efficiency for crop production: the returns to investment in fertilizer and labour are substantially reduced in depleted soils (Giller et al., 2006; Zingore et al., 2009). Village level explorations of soil fertility and organic resources have been made (Rufino et al., 2011; Rusinamhodzi, 2013a; Zingore et al., 2011), which revealed that crop–livestock integration at village level results in the concentration of nutrients on farms with large herds of cattle. The small areas of high fertility soils close to the homesteads of wealthy farmers contributed the largest proportion of the total village maize yield, despite them occupying less than half the area of the depleted fields (Zingore et al., 2011). These studies assumed the same distributions of inherent soil characteristic between the farmer resource groups, and did not analyse the spatial distribution of soil characteristics across the landscape. As soil fertility plays a crucial role in food production at village level, there is a need to understand the spatial distribution of these fertility zones.

Changing the scale of observation from the farm to the village level is not as simple as it seems at first sight. New processes or relations can emerge. For example, it is well known from ecological studies that changing the scale of observation can influence inference (Dungan et al., 2002; Wu, 2004). Therefore, relationships at field scale or farm scale cannot be assumed to be representative of the village scale. However, as explained above, there is strong empirical and theoretical evidence that soil fertility gradients play a self-reinforcing role in determining the efficiency of response to inputs in smallholder farming systems of sub-Saharan Africa (Giller et al., 2006; Giller et al., 2011; Masvaya et al., 2010; Tittonell et al., 2007a; Tittonell et al., 2007b; Zingore et al., 2007b). Thus differences in farm resource endowment, soil type and number of years under cultivation lead to distinct gradients of SOC at the farm scale. We hypothesize that these gradients are also visible at the village scale and can be related to landscape and management characteristics.

We tested this hypothesis in two steps. Our first objective was to map SOC contents at the village scale. Secondly, we aimed to relate SOC content to farm-scale management and to inherent landscape-scale characteristics.

## 5.2 Materials and methods

### 5.2.1 Case study area

The study was conducted in the Murewa smallholder farming area, Zimbabwe (population density 104 people km$^{-2}$) located about 80 km east of Harare (17°49'S,

31˚34'E). The area has a sub-tropical climate and has relatively high potential for crop production. Murewa receives 750 to 1000 mm of rainfall annually between November and April. The soils are predominantly granitic sandy soils (Lixisols) with low inherent fertility. A smaller proportion of the area has more fertile red, dolerite-derived clay soils (Luvisols) that are considered the best agricultural soils in Zimbabwe (Nyamapfene, 1991). Farmers practice a mixed crop-livestock system dominated by maize (*Zea mays* L.). Cattle are the main livestock. In day time they are herded during the cropping season but they graze freely on communal rangelands in the dry season. Cattle are kept in kraals close to homesteads at night. Close interactions between crop and cattle production occurs through crop residues that are used to feed cattle and manure is used to fertilize crops, particularly at the fields closest to the homesteads. Only 6% of the households own around 10 head of cattle, while 35% own less than 10 heads. Some 33% of households own no cattle and have less than 1 ha of land. The remaining 26 % of the households do not own cattle and hold less than 2 ha of land (Rusinamhodzi, 2013a). The village has been intensively studied and fertility gradients at farms have been reported (Rufino et al., 2011; Rusinamhodzi, 2013a; Tittonell et al., 2007b; Zingore et al., 2007a).

### 5.2.2. Remote sensing data

To determine the spatial heterogeneity of SOC, Landsat Thematic Mapper (TM) satellite images were used. Three georeferenced datasets were downloaded from the USGS data portal. The images were acquired at 5 September 2008 and 11 and 27 November 2009. Of these images the image DN values (an 8 bit value reflecting the radiation of the earth surface) were used for the regressions. In addition, an ASTER digital elevation model (DEM) was downloaded from the same source.

### 5.2.3 Soil sampling

To investigate spatial heterogeneity of SOC, a stratified random sampling method (De Gruijter et al., 2006) was applied. The sampling area was located between 345400 and 349300 E and 8027200 and 8029350 S (UTM 36S). Three strata were defined on the basis of the Landsat TM satellite images from 5 September 2008. In Murewa, September is near the end of the dry season, when all biomass from the fields is removed and bare soil is visible. The strata were classified using the iso-cluster method and a maximum likelihood classification of bands 1 to 5 and 7  in ArcGIS. The classification was aggregated to a minimum area of 1 ha. The three strata roughly coincide with the cropping area in the sandy soils (302 ha), the red clay and valleys (337 ha) and a granite, stony 'kopje' (203 ha)

(Figure 1). The spatial coordinates of the sampling points were randomly generated in R (R Development Core Team, 2013) and subsequently assigned to a stratum by their location.

Fieldwork was carried out in December 2010. Sampling locations were located with a GPS. At each location an undisturbed volumetric sample was taken from non-stony soil at 5 to 15 cm depth. For every sample location, a description of the current land use was made. No measurement was taken when sample locations were on roads, compounds, kraals, water bodies and rock. These locations do not belong to the sampling population and were excluded. In total, 100 locations were sampled. For every tenth sample location a duplicate sample was taken, yielding in total eleven duplicate samples. These duplicate samples were used to compute laboratory measurement error. The volumetric samples were air dried and weighed to derive the bulk density. SOC was determined by the Walkley-Black method. Soil particle size distribution was determined using the Bouyoucos hydrometer method following Gee and Bauder (1986).

From the sampling data, the mean and standard errors of the SOC and clay contents were estimated for each of the three strata and for the sampling area according to Kempen et al. (2011). Each stratum mean is estimated as an unweighted average of the samples that are located in that stratum. The global mean, i.e. the mean of the sampling area, is estimated as a weighted average of the stratum means with weights equal to the relative areas of the strata. The stratum areas (Table 1) were estimated from the ratio between rejected and sampled locations (Table 1). This means that the global estimates of SOC and clay contents apply to the areas that could be sampled.

### 5.2.4 Soil property mapping

A digital soil mapping approach was used to map the SOC and clay contents (McBratney et al., 2003). The data on SOC showed strong positive skew (2.61), which was removed by transformation to natural logarithms. The log-transformed SOC contents were related to the bands 1 to 5 and 7 of the Landsat TM image of 11 November 2009, and the elevation and slope that were derived from the ASTER DEM using a linear regression model. The linear regression model was selected by the Akaike Information Criterion in a stepwise procedure. Regression modelling was implemented in R using the stepAIC function of the MASS package (Venables and Ripley, 2002). Default settings were used. Predictions were back-transformed to the original scale. A map of soil clay content was generated following the same procedure, using the Landsat TM image of 27 November 2009, to

prevent input dependency of the clay predictions with the predictions of SOC. Clay contents were transformed to natural logarithms as well.

The prediction models were validated using leave-one-out cross-validation (Brus et al., 2011; Hastie et al., 2008). Following Kempen et al. (2011) and De Gruijter et al. (2006) mean error (ME), mean absolute error (MEA) and root mean squared error (RMSE) were estimated. Estimates of these parameters are based on the prediction error. The prediction error is calculated as the difference between the predicted and observed values at a validation location. In addition, the root median square error (RMedSE) is estimated. For skewed distributions of squared errors, the median square error and its square root might be more robust statistics of the 'average' error.

*5.2.5 Landscape management and SOC interactions*

A separate dataset of farm characteristics (Rusinamhodzi et al., 2013b) was used to allocate management to the soil property maps. The dataset contains information on land ownership (area and time), area under cultivation, household size and available labour force and cattle ownership. Following Zingore et al. (2007a), resource groups (RG) were first separated on cattle ownership with RG 1 having more than 9 heads of cattle (in total 3 farms), RG 2 having 1 to 7 head of cattle (16 farms). Farms with no cattle were separated into two groups based on their area, with farms with 1 ha or more belong to RG 3 (13 farms) and those with less than 1 ha belonging to RG 4 (14 farms). Of the 80 households interviewed, 46 could be assigned to a geo-referenced location (Figure 2). The dataset was made spatially explicit via the location of the homestead and high-resolution imagery of Google Earth. Since some of the households were located outside the area where soil samples had been taken, the SOC and clay map was extrapolated for the whole village based on the LandSat TM images and DEM. The farms in Murewa mostly consist of one large field demarcated into smaller plots with only few farmers having detached plots far from homestead (Zingore et al., 2007a). With the use of Google Earth images, these adjacent fields could be assigned to a homestead (Figure 2). By combining the SOC and clay maps with the resource groups, interactions between management and landscape can be investigated.

To investigate the fertility gradients per resource group, first all pixels inside the farmers' fields were assigned to their resource groups. Subsequently these pixels were ranked regarding to their distance from the homestead. With intervals of 30 m the average SOC

was calculated. These averages were then plotted as a transect going from the homestead to the outfields for each resource group.

To further investigate the management-landscape interactions, partial least square regression (PLSR) was used (Wold et al., 2001). PLSR finds a linear regression model by projecting the management and landscape variables and the SOC into a new space. PLSR is insensitive to co-linearity of the predictors, the vectors of these predictors will have the same or opposite direction in the new projected space. PLSR explains the maximum variance of predicted SOC using all spatial and management data. In the partial least square regression nine variables were used to explain predicted SOC content of pixels belonging to farmers fields. The nine variables were distance, clay content, family size, labour size, time of cultivation, land area cultivated, land area owned, selling of own labour, and number of cattle.

## 5.3 Results

### 5.3.1 Village scale maps
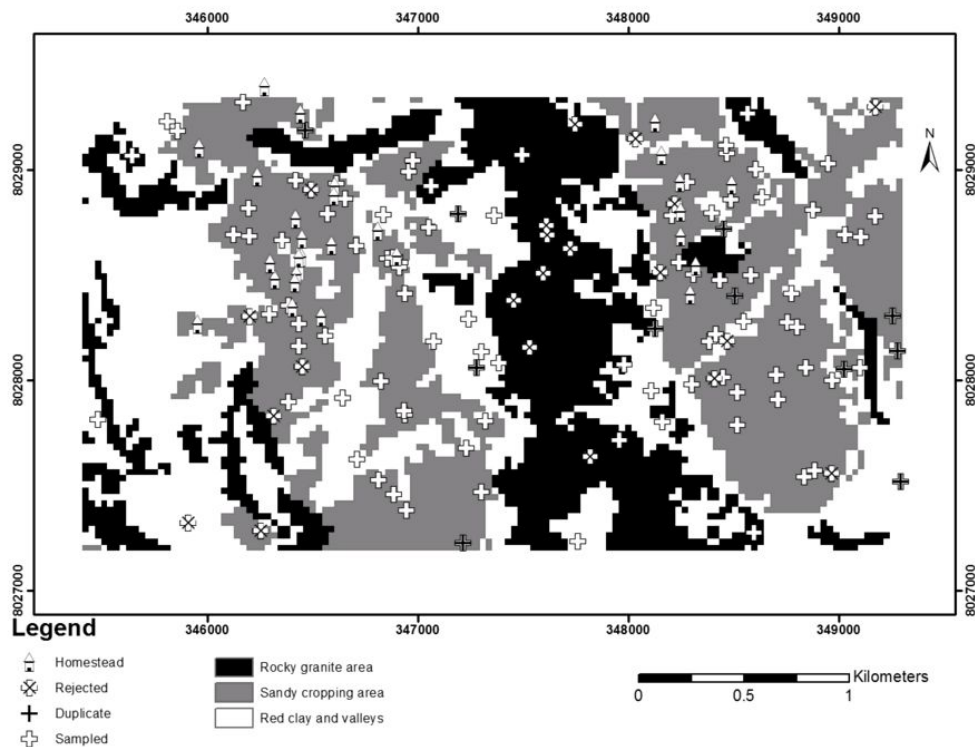


**Figure 7.** Location of sampling strata, sample locations and homesteads. Black is a rocky granite outcrop or kopje, grey represents the sandy cropping area, white the red clay and valleys. Plus signs represent sampling locations, black plus signs are locations of duplicate samples and crossed plus signs are rejected locations. Houses represent locations of known homesteads.

**Table 7.** Summary statistics of C and clay content per stratum based on measurements. Not all points visited could be sampled due to stoniness. Global mean and standard error are corrected for these rejected samples. Sampling error is based on 11 duplicate measurements

| | Rocky granite area | Red clays and valleys | Sandy cropping area | Global | Sampling error |
|---|---|---|---|---|---|
| Points visited | 15 | 23 | 83 | 121 | |
| Samples | 7 | 21 | 72 | 100 | |
| area (ha) | 203 | 337 | 302 | 842 | |
| **Soil organic carbon (%)** | | | | | |
| Mean | 2.70 | 1.77 | 0.84 | 1.54 | 0.57 |
| Standard error | 0.55 | 0.24 | 0.04 | 0.14 | 0.12 |
| Median | 2.46 | 1.60 | 0.74 | 0.88 | 0.26 |
| Minimum | 1.13 | 0.57 | 0.39 | 0.39 | 0.02 |
| Maximum | 5.61 | 4.74 | 2.51 | 5.61 | 1.53 |
| **Soil clay content (%)** | | | | | |
| Mean | 22.9 | 17.4 | 6.7 | 13.8 | 7.9 |
| Standard error | 4.4 | 2.6 | 0.4 | 1.3 | 1.9 |
| Median | 26.2 | 15.2 | 6.4 | 6.5 | 1.1 |
| Minimum | 5.3 | 3.5 | 1.0 | 1.0 | 0.0 |
| Maximum | 38.3 | 39.4 | 18.5 | 39.4 | 16.6 |

In total we sampled 72 points in the sandy cropping area and 21 points in the red clay and another 7 in the granite ridge area (Figure 1, Table 1). In total 100 locations were analysed for SOC content and 99 for clay content. The granite ridge along 347500 E was difficult to sample due to the rocky character of this area leading to a rejection of the majority of the samples. Most households are located on the sandy soils. The average SOC content of the village is estimated as 1.53%; the average clay content is estimated as 14%. Estimates by Zingore et al. (2011) for a neighbouring village (30 km to the east) are well within the 95% confidence limit of our estimates.
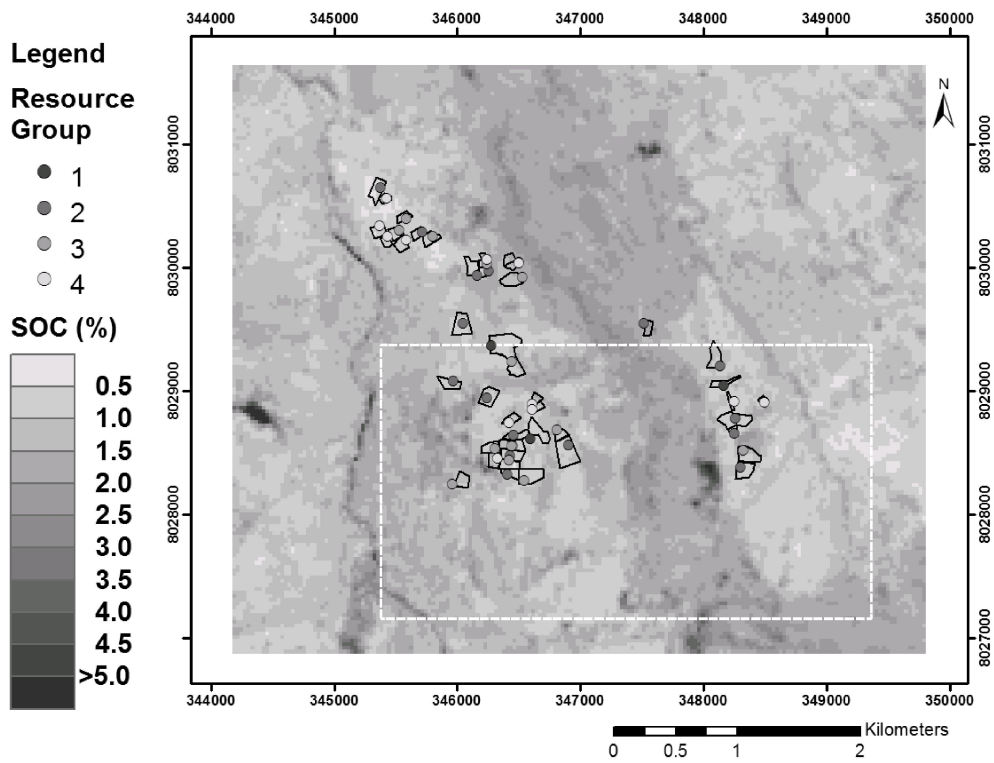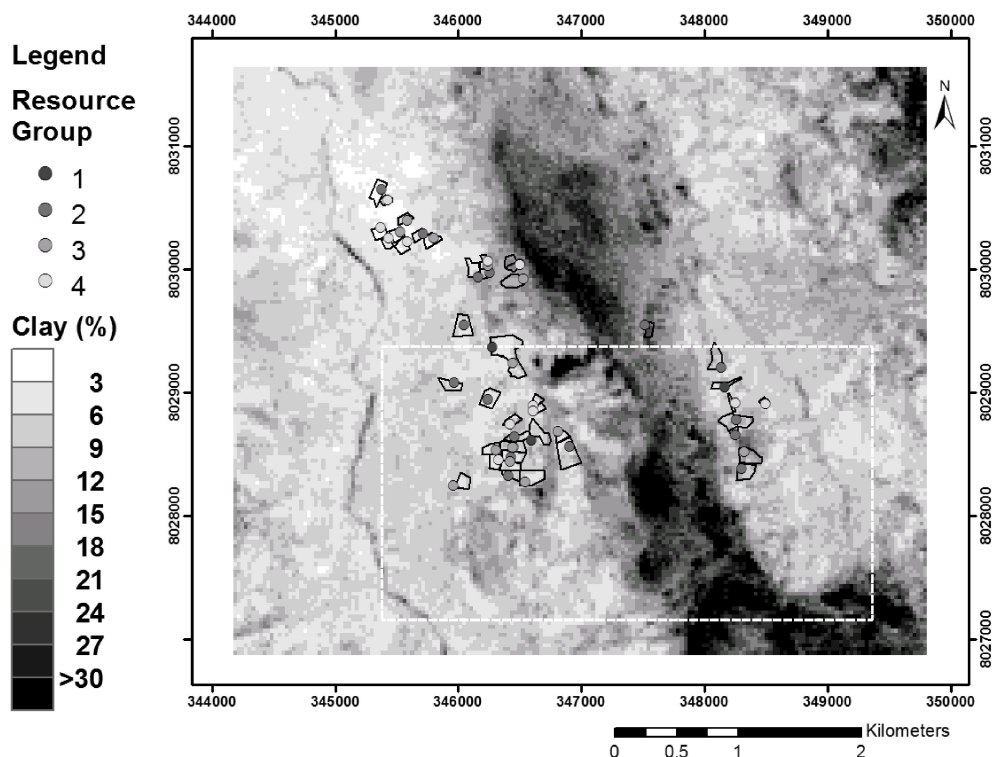
**Figure 8.** Predicted soil organic carbon (SOC) content (%), Houses indicate locations of known homesteads and solid black lines demarcate their adjacent fields. The white dashed line indicates the sample area.
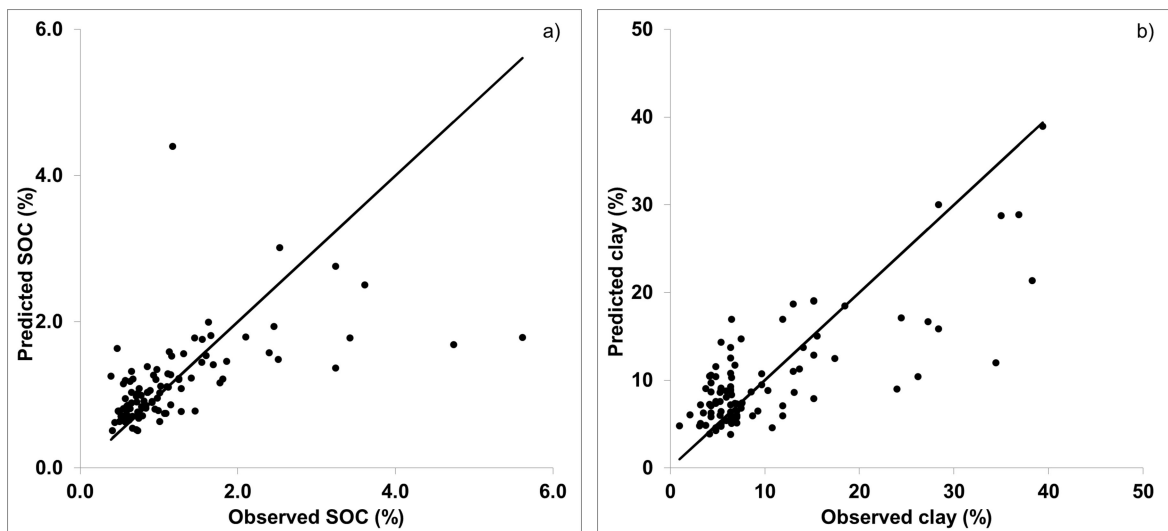


**Figure 9.** a) Soil Organic Carbon content (%) measured and predicted , b) Clay content (%)measured and predicted (%)

Stepwise linear regression of the SOC content on the Landsat TM image of 11 November 2009 and DEM derivatives resulted in the following model: SOC (log%)=2.98-0.022 × TM band 4-0.007 × TM band 5. This model explained 50% of the observed variation of SOC content. A map of the spatial distribution of the SOC contents is shown in Fig 2. SOC contents above 3 % were under-estimated (see Figure 3). Above this value, higher SOC values could not be differentiated by their DN-values, which is caused by the non-linear relation between surface reflectance and SOC content (Bartholomeus et al., 2008).



**Figure 10.** Predicted soil clay content (%), houses indicate the locations of known homesteads and solid black lines demarcate their adjacent fields. The white dashed line indicates the sample area.

Stepwise linear regression of the clay content on the Landsat TM image of 27 November 2009 and the DEM derivatives resulted in the following model: Clay (log%) = -9.631+ 0.012 × DEM-0.060 × TM band 2 + 0.064 ×TM band 3-0.027 ×TM band 4-0.023 × TM band 7. This model also explained 50% of the observed variation of clay content (see Fig 3). A map of the spatial distribution of the clay content is shown in Figure 4.

**Table 2.** Cross-validation results. ME is the mean error, MAE the mean absolute error, RMSE the root mean square error and RMedSE the root median square error.

| | Rocky granite area | Red clays and valleys | Sandy cropping area | Global |
|---|---|---|---|---|
| **Soil organic carbon (%)** | | | | |
| *n* | 7 | 21 | 72 | 100 |
| ME | -0.64 | -0.13 | 0.08 | -0.12 |
| MAE | 0.97 | 0.78 | 0.24 | 0.59 |
| RMSE | 1.53 | 1.19 | 0.33 | 1.01 |
| RMedSE | 0.48 | 0.37 | 0.19 | 0.33 |
| **Soil clay content (%)** | | | | |
| *n* | 7 | 20 | 72 | 99 |
| ME | -6.8 | 1.7 | 1.1 | -1.3 |
| MAE | 8.2 | 5.4 | 2.7 | 4.7 |
| RMSE | 10.4 | 7.6 | 3.6 | 6.9 |
| RMedSE | 7.3 | 4.4 | 2.1 | 4.3 |

The cross-validation results are presented in Table 2. SOC contents in the rocky granite area is under-estimated (indicated by the negative bias). A high SOC contents of 5.6% C is not well predicted by the model and results in a large prediction error. This biased predictions in rocky granite area inflates the global estimate of the ME to -0.12%. SOC is most accurately predicted for the sandy cropping area with a RMSE 0.33% C and least accurate for the rocky granite area with a RMSE 1.53%. As a result of a few large predictions errors there is a large difference between the global RMSE of 1.01% C and the RMedSE of 0.33% C. Prediction errors are generally larger for locations where relatively high SOC contents are predicted than for locations where relatively low SOC contents are predicted (see also Figure 3). The cross-validation $R^2$ for SOC is 0.47.

The results for clay content (Table 2) show biased predictions in rocky granite area. The predicted clay content is on average 6.8% too low. Globally, bias is -1.3%, which indicates a slight under-prediction of clay content. Like for SOC, the clay content is most accurately predicted for sandy cropping area with a RMSE 3.6% C and least accurate for the rocky granite area with a RMSE 10.4% C. Like for SOC contents prediction errors are generally larger for higher clay contents. The cross-validation $R^2$ for clay content is 0.47 as well.
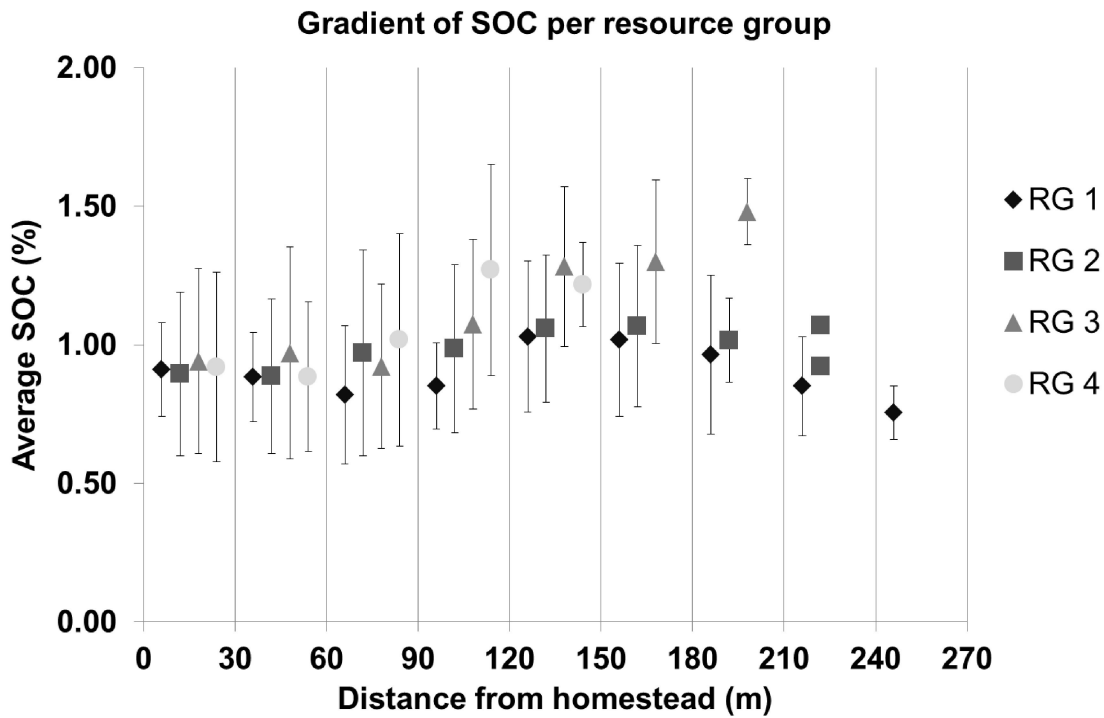
**Figure 11.** Average soil organic carbon (SOC) content (%) per 30 m for each farmer resource group (RG). Error bars are 1 standard deviation. Two points of one resource group in a 30 m segment are the only available data-points for that segment.

The SOC values were similar among the resource groups and no clear decreasing gradient of SOC from the homestead could be observed. The average SOC content of pixels within 60 m of the homestead are between 0.88 and 0.97% SOC, while pixels within 90-120 m of the homestead were on average 0.85 and 1.27% SOC
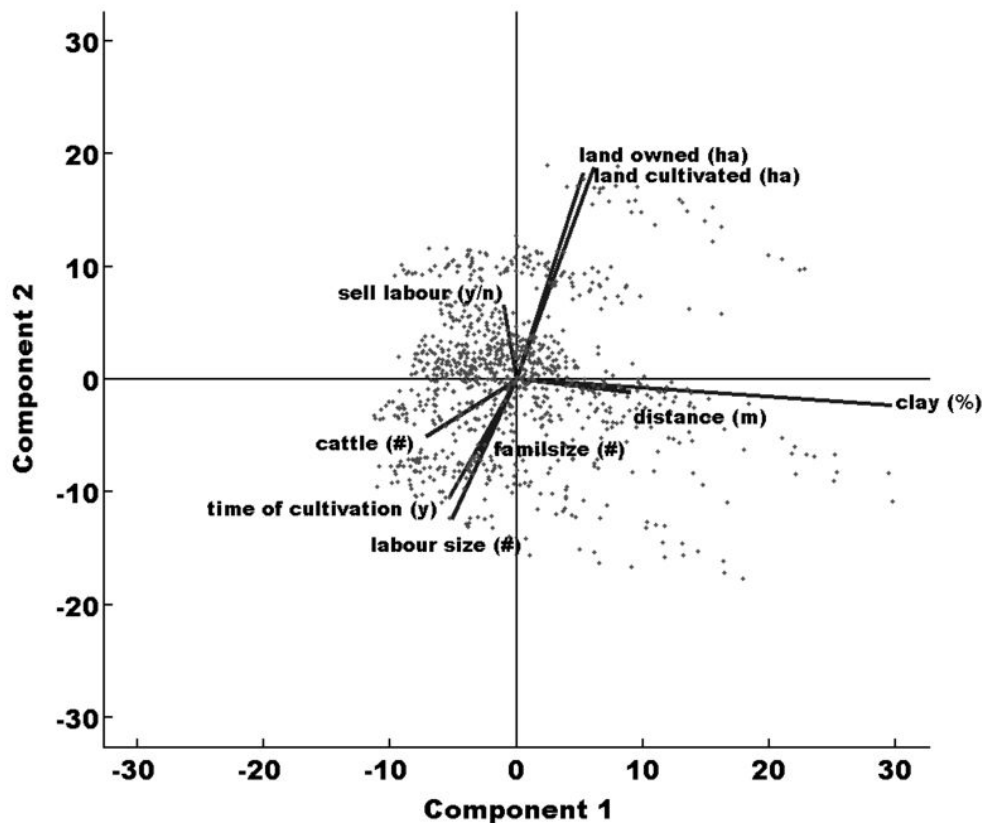
**Figure 12.** Bi-plot of partial least square regression (PLSR) used to estimate SOC content, with each normalized variable represented by a vector. The direction and length of the vector indicates how each variable contributes to the two components. The relative position of the each observation is in the component space is represented by a dot.

Re-projecting the nine landscape and management variables to nine components, 60% of the predicted SOC content could be explained. The first component was able to explain 54% and the second component contributed 5%. Component 1 was primarily related to the clay content (Figure 6) which was dominant in explaining the variability in SOC. This was confirmed by the measurements. The measured clay content explained 57% of the variation in the measured C content (see Figure 7).
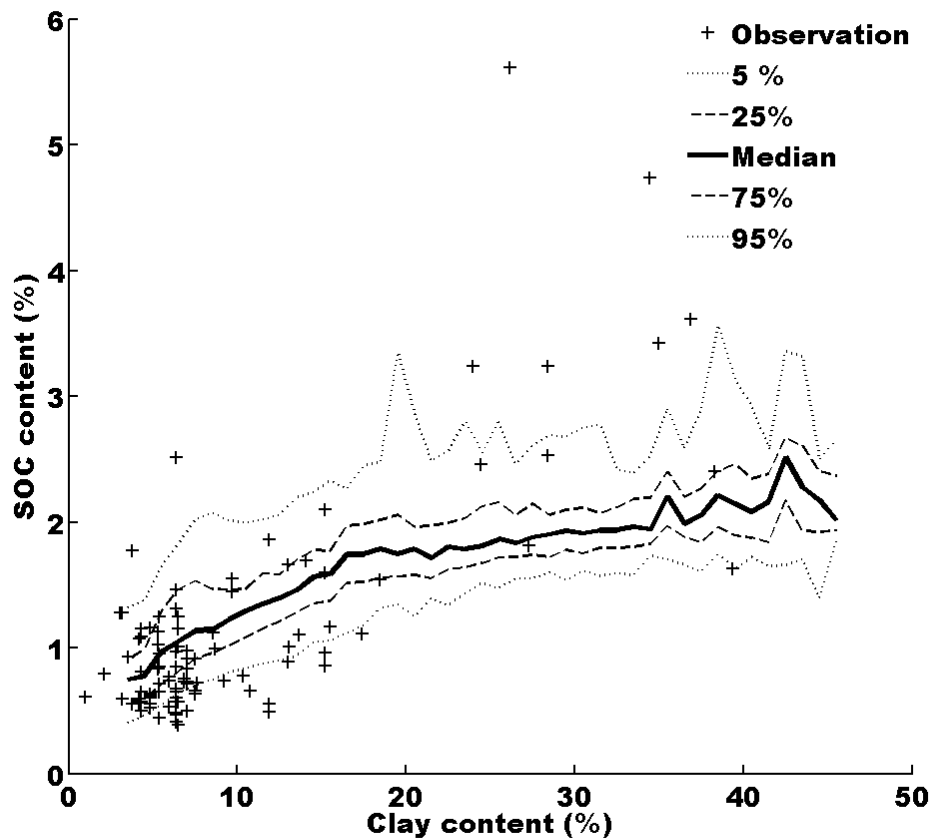
**Figure 13.** Observed and predicted relation of clay content and SOC. Black plus signs are the measurements of clay and SOC content. Lines represent 5, 25, 50, 75, 95% interval of predicted SOC contents per pixel, calculated per percentage of predicted clay contents.

## 5.4 Discussion

### 5.4.1 Mapping of SOC

By combining stratified random sampling and Landsat TM data we were able to quantify SOC contents and their associated uncertainty at the village scale. Data obtained by a random sampling design yields an unbiased estimate of the mean soil property values and the associated standard errors see table 1 For the sandy cropping area, the stratified random sampling yielded an almost unbiased prediction with high accuracy see table 2. Given the increasing availability of high resolution remote sensing data, supervised classification of cropping area, grazing area and natural vegetation might further improve the accuracy. Especially the predictions in the stratum that combined the red clays and valleys might improve from this classification. Furthermore a better estimate of SOC and

clay content might have been achieved when composite sampling of an area (e.g. a field or pixel) rather than single point sampling had been done.

The SOC regression model, that included only two of Landsat TM spectral bands, explained 50% of the variation, which can be considered a reasonably good result for a digital soil mapping exercise. Typically, $R^2$ values range between 0.40 and 0.60% (Adhikari et al., 2013; Hong et al., 2013; Kempen et al., 2011; Malone et al., 2009; Wiesmeier et al., 2011). Prediction accuracy might be further improved by considering additional covariates and by adding a kriging step. Although the current sample area was only 800 ha, the method can be readily scaled up to neighbouring areas with similar agricultural systems and soils.

*5.4.2 Detection of SOC gradients*

Figure 5 shows no large differences between resource groups (RG). The fertility differences between RG in Figure 5 clearly differ from fertility gradients reported by Zingore et al. (2011) and Rufino et al. (2011). Zingore et al. (2011) reported large difference between RG's for the neighbouring village. The homefields in the neighbouring village of resource group 1 and 2 were between 0.8% C for sandy soils to 1.6% C for clay soils. For RG 1 soil carbon content decreases towards the outfields to values between 0.5% C for sandy soils and 1% C for clay soils. While For RG 2 carbon content decreases towards the outfields between 0.4% C for the sandy soils and 0.7% C for the clay soils. For RG 3 and 4 all fields were considered to have the same carbon between 0.4% C for the sandy soils and 0.7% C for the clay soils. For a part of our case study area Rufino et al. (2011) reported for all fields of all resource group SOC values between 0.6 and 0.2% C. With RG 2 having the most pronounced gradient from 0.6 % C in the homefields decreasing to 0.2% C in the outfields. The SOC contents seems to increase with distance from the homestead for RG 3 and 4, this is caused by pixels at the borders of the fields, which also include grazing grounds or natural vegetation with higher SOC content (see Figure 2).

In summary contrary to our hypothesis that strong gradients of high SOC contents close to the homestead compared with low SOC content in the outfields would be found, these could not be observed at village scale. This is remarkable given that Zingore et al. (2007a) reported strong gradients for farms in the same village. There are several factors that may contribute to this discrepancy. First, our method may be unsuitable to detect gradients of SOC. Since 50% of the variance is explained by the regression and it might miss the

variance caused by management. The predicted SOC content is however most accurate with a RMSE 0.33% C and table 2 in the cropping area which is most likely to have management effects. Another contributing factor may be that the 30 m resolution of the Landsat images is coarse in relation to the plot sizes of 0.1 to 0.5 ha (Rusinamhodzi et al., 2013b). As such, our results might suffer from the 'ecological fallacy' or 'spatial transmutation', that is, the aggregate is not representative of the different separate elements (sensu (Wu, 2004). In our study, the aggregation of plots to a pixel might not capture individual SOC contents of plots.

Likewise, the aggregation of variation in SOC to pixels may have resulted in another scale effect: the modifiable areal unit problem (see for example Dungan et al. (2002)). This phenomenon occurs when changing the boundaries to which the variation is aggregated results in changes in the "observed" relationships. For our study, the aggregation of point measurements to pixels may have masked the gradients across different plots that are observed at farm scale. Finally the lack of gradients may be an observational bias. Gradients can be observed within the farm but these disappear when studied at village scale. The increased landscape heterogeneity at higher scales can dominate the variance of SOC. This is in agreement with the results of the partial least square regression where the second component is dominated by management factors but only contributes 5% in explaining the variance in SOC values.

The strong relationship between clay and SOC content shows that variation in clay content cannot be represented by just two classes of sandy and clay soils at the village scale as done by Rufino et al. (2011); Zingore et al. (2011). Neither can they be assumed identical for homefield, midfields and outfields across a village as done by Rufino et al. (2011). Subtle differences in clay content among farmers' fields are important in determining differences in SOC among farms. For example, within the sandy soil class variation clay content ranged between 2 and 10%, which can account for a difference in average SOC content of 0.5 % (Figure 7). In these sandy soils, this is equivalent to a doubling of total SOC that potentially can lead to more than a doubling of maize yields (Rusinamhodzi, 2013a).

The lack of observed gradients at village scale prohibits the further exploration of possible interactions between landscape and management. The results do show, however, that fertility gradients are scale sensitive. At higher scales of aggregation the gradients observed at farm scale disappear. Such scale problems of the 'ecological fallacy' and 'the modifiable areal unit problem' (Dungan et al., 2002) do not necessarily disappear with a

finer resolution of the satellite images or with a denser sampling scheme. Although at a finer resolution part of the aggregation effect might disappear, new patterns might also be detected (e.g. shadows, surface roughness etc.) that might cause bias. A farm-scale focused dense and aggregate sampling scheme as applied in Tittonell et al. (2013) might be able to determine farm scale patterns of SOC. However, this method cannot readily be applied to the village scale when free grazing is important. The scale of aggregation (in contrast with the farmers' fields) for communal grazing is unknown. At the village scale processes interact at different spatial scales. The dynamic management of plots, communal grazing and landscape heterogeneity cause an unstable pattern and make it problematic to determine the most appropriate scale of analysis.

Digital soil mapping of SOC and clay with satellite imagery has good potential for explaining spatial variation. Thus there are high expectations of the envisioned global digital soil map which is being developed using similar methods. Sanchez (2010) expects it will help farmers to pinpoint which forms of mineral and organic fertilizers are needed in each field. However, the same 30 m resolution is expected to be sufficient for smallholders (Sanchez et al., 2009), yet our results suggest that such a resolution may miss soil variability associated with past and present soil management – the soil fertility gradients – that have been shown to be very important in explaining crop response to nutrient inputs.

## 5.5 Conclusions

Our results demonstrate that fertility gradients are scale sensitive. Fertility gradients could not be observed at the village scale, and aggregations from the farm scale to the village scale cannot readily be made. Digital soil mapping of SOC with satellite imagery has a high potential. Yet, the digital mapping of soil fertility gradients at the village scale has several scale issues that need to be addressed for the global digital soil map to be relevant for smallholder farming systems in sub-Saharan African.

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## Chapter 6

# From 'Panarchy Rules!'
# to 'Panarchy Rules?'

## 6.1 Introduction

When I started my PhD in the end of 2006, resilience was an emerging concept, which was in the process of being picked up by more mainstream sciences with key publications in journals such as Global Environmental Change (Folke, 2006) and a special issue in Ecology and Society (Walker et al., 2006) on the progress of resilience perspective since the publication of the book Panarchy (Gunderson and Holling, 2002).

The resilience perspective offered a new conceptualisation of system dynamics which was shown to be useful in analysing social-ecological systems and which, therefore, might shed light on the functioning of agro-ecosystems as well. Consequently, the general objective of this thesis was to employ a resilience perspective to agro-ecosystems and to derive an increased understanding of agro-ecosystem functioning. In this synthesising chapter I focus on how the resilience perspective shaped my research. I first give a chronological account how concepts, methodology and methods were adapted during my research to align with ideas I derived from the resilience perspective on agro-ecosystem functioning. Subsequently I evaluate the perspective and suggest an adapted resilience heuristic that better fits agro-ecosystems dynamics.

## 6.2 The resilience perspective chronologically put to the test

### 6.2.1 Panarchy as a leading heuristic

At the beginning of the research that led to Chapter 2 'Panarchy rules', my objective was to identify multiple stable states of dairy farms in Northern Frisian Woodlands. Differences in nutrient use efficiency were thought to be caused by difference in feedbacks in the nitrogen cycle at farm level. One fast feedback loop from fertiliser or urine to the grass plant, then to the livestock and back to inorganic nitrogen via urine and mineralisation of faeces and unharvested biomass. This fast feedback loop is dominant for farms characterised by high external inputs and contrasts with "rebalancing" farms, that were characterised by a slower feedback loop via soil organic matter (SOM). The rebalancing idea was to decrease fertiliser input, which would lead to a higher root/shoot ratio of the grass and feed lower crude protein and higher crude fibre content which would lead to an increase of the carbon to nitrogen ratio (C/N) of manure which in turn, would lead to an increase of the SOM content. I was confident that I would be able to find the different states since the prerequisites were in place; that is a change of dominant feedbacks and the two different states of high and low efficiency seemed to be locally

stable (Beisner et al., 2003). Instead, I found that long-term dynamics rather than stable states were the likely cause of different farm efficiencies. More importantly, these long-term dynamics were not considered within the institutional setting of environmental legislation and the self-governance experiment that needed fast and measurable results. We claimed panarchy as a leading heuristic to analyse such scale mismatches in agro-ecosystems.

*6.2.2 The importance of slow variables*

Panarchy suggests that dynamics at a focal scale can only be understood by taking into account the scales above and below it. The focal scale is connected to these scales via cross-scale interactions. Kinzig et al. (2006) uses a multi-scale framework to connect dynamics at patch farm and region scale with the ecological, economic and socio/cultural domain. The interactions between these scales might result in cascading events; the collapse of one level induces other thresholds to be crossed as well (Kinzig et al., 2006). Following this framework I expected to be able to locate "hotspots" in the landscape of farms having a high nutrient use efficiency.

For Chapter3 'Landscape Asymmetry', I therefore collected SOM measurements at field scale and combined these with detailed soil (-hydrology) maps and land use history. SOM content provided the long-term memory of management and landscape interactions at a lower scale. Higher scale dynamics of the interaction between the economic and cultural dynamics were later described in a separate paper (Hermans et al., 2012). The spatial-temporal variability of SOM contents was linked to landscape position and land use history represented in the landscape asymmetry. This asymmetry in the landscape was linked with the small composing elements of the landscape, and thus the identity of the landscape (Antrop, 2005). Landscape identity provided a connection to the resilience of the landscape.

My initial goal, however, of linking a high nutrient use efficiency at farm level to locations in the landscape was not reached. Following the effect of small differences in texture and soil hydrology the SOM content was very heterogeneous within a farm. This within farm heterogeneity caused a scale mismatch with the nutrient use efficiency calculated at farm scale. This farm scale efficiency is the product of a temporal and spatial diverse management (grazing, mowing, maize cultivation) at field level and internal feedbacks within the farm. Since the relation between SOM and fertilisation and yield is non-linear this farm aggregate data could not be used to explain efficiencies.

### 6.2.3 Co-evolution of agro-ecosystems

The multi-scale interactions I identified in Chapter 3, 'Landscape Asymmetry' showed that a strategy of farm intensification and re-balancing strategy can be characterised by different positive feedbacks at field, farm and regional scale. Within the resilience perspective, a particular combination of dominant feedbacks is referred to as a regime. Since land use history and landscape position are related (Figure 5 and 6 Chapter 3, 'Landscape Asymmetry' and Sonneveld et al. (2004)) and the large role of SOM I expected to able to locate regimes by relating them to patterns in the landscape.

Indeed, clear indications of interrelationships of farm intensity and landscape came to the fore in Chapter 4, 'Co-evolution'. The results showed that heterogeneity of farming practices change together with the landscape. Conceptually the results were more challenging. Although individual farm examples of the regimes could be identified, no clear regimes at a landscape level were found. Despite differences in dominant feedbacks between landscape and management of the two regimes these did not lead to exclusive patterns in the landscape. This can be explained by out of equilibrium dynamics with the landscape pattern only responding slowly to management changes. But if management and landscape indeed co-evolve, regimes might not be the most appropriate concept. The concept of regimes assumes that over time dominant feedbacks give rise to self-organisation and thus level formation. Co-evolutionary thinking, however, would assume that landscape and management do not evolve to predetermined regimes but would respond to (stochastic) changes in each other's behaviour. If self-organisation of dominant feedbacks is unable to shape its corresponding pattern, no level is formed and the proper scale of analysis remains unknown.

### 6.2.4 Linking patterns to processes, a scale mismatch

In the Chapter 5 'scale mismatch' I tried to work the other way around by first investigating the landscape pattern or asymmetry, subsequently linking this to agro-ecosystem functioning. The case study of Zimbabwe seemed ideal since the economic collapse of Zimbabwe was known to have had major impact on farming practices in terms of availability of fertilisers, while the patterns to investigate, soil fertility gradients, were well documented. Moreover, a critical threshold of SOM was already identified (Mtambanengwe and Mapfumo, 2005). The initial hypothesis for this paper was that lack of fertilisers would lead to less biomass returned to the fields, which would lead to steeper gradients. We further hypothesized that these changes in gradients could then be related

to increasing spatial autocorrelation which was said to indicate decreasing resilience (Dakos et al., 2010). Yet, despite trying multiple different statistical methods, I failed to link SOM patterns to management, which led to the conclusion of a scale mismatch. This work particularly shows that pattern is also scale dependent and therefore that pattern analysis does not provide a method to avoid having to deal with the unknown scale problem of agro-ecosystem analysis identified in the previous chapter.

*6.2.5 Current regimes do not shape current patterns*

In summary, my research shows that to improve our understanding of agro-ecosystem functioning, location and its history play a key role for its management. Yet, management does affect the landscape pattern but more slowly, even to such an extent that self-organisation caused by the management interactions is not fast enough to shape the landscape pattern. This de-coupling of management and process, causes that a regime is not able to shape the pattern by which it would be characterised. This lack of a regime means that no level of self-organisation emerges and as such no proper scale can be identified.

## 6.3 Evaluating the resilience perspective

In evaluating the resilience perspective I first discuss how at first I claimed panarchy as a leading heuristic and how empirical results challenged this claim. Subsequently, I suggest how we can focus the lens of the resilience perspective for agro-ecosystem analysis.
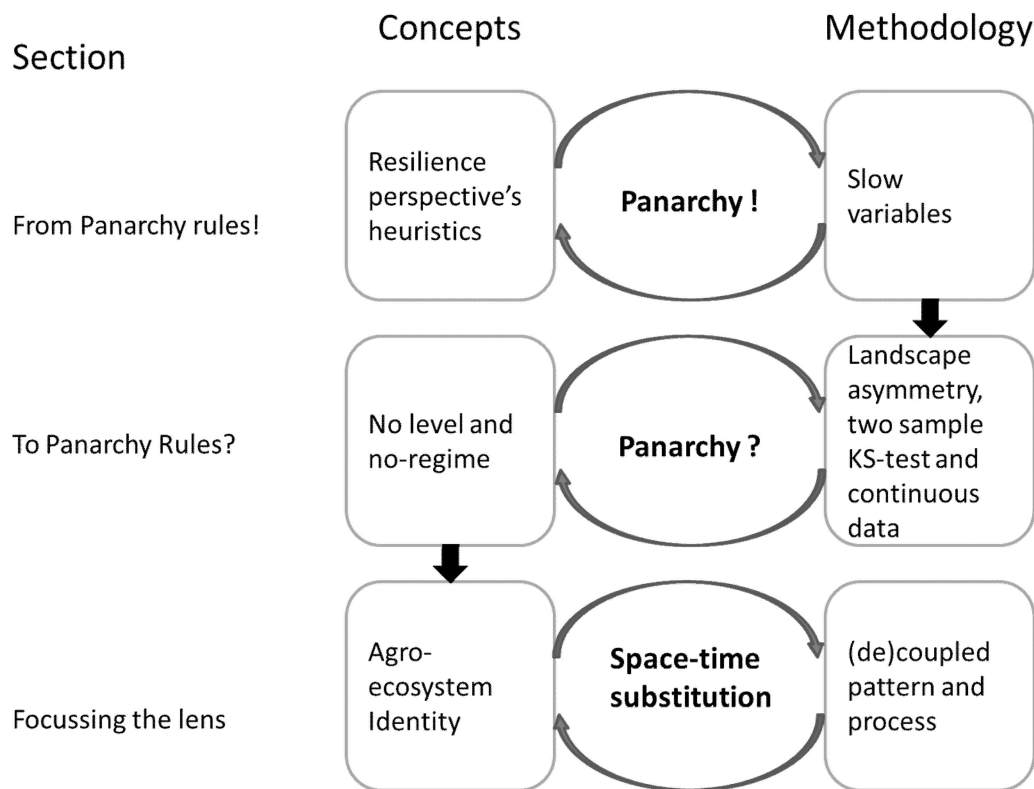
**Figure 14.** Progress of my thinking of the interactions between concepts used and methodology applied.

### 6.3.1 From Panarchy rules!

Panarchy suggests the importance of taking into account the cross-scale influences of the processes from the scales above and below the focal scale. As my focal scale I chose the scale above the individual farm. Including the processes at a larger scale that influence farm management showed that slow variables and memory play a key role in the understanding of agro-ecosystems functioning. Historic management gave rise to differences in SOM, field size and hedgerows. These slow variables in turn were linked to landscape asymmetries of environmental variation. In the Northern Frisian Woodlands and in Murewa clay content showed to be a dominant variable that determined SOM content. These asymmetries, however, might be hard to detect with the intrinsic variation of farm management masking the underlying asymmetry. The asymmetries that arise from continuous environmental variation can therefore easily go unnoticed (see Chapter 3, 'Landscape asymmetry'). Aggregations over landscape asymmetries (for example per soil type) might miss the slow variables that shape the potential of an agro-ecosystem. Analysing continuous data rather than classified data is therefore insightful (see Chapter 3, 'Landscape asymmetry' and Chapter 4, 'Co-evolution'). The difficulty to detect

asymmetries also shows that landscape asymmetry has no direct relation with current management. This decoupling has important implications for system analysis. When current pattern do not reflect current management, interference providing an interval or ratio scale is incorrect. Using non-parametric statistics (i.e. ranking) somewhat mitigates this error by providing a direction of change rather than absolute change. Moreover the de-coupling of management and pattern makes a normal distribution unlikely. Instead of assuming a normal distribution, the actual distribution provides much more insight in the systems response (see Chapter 3, 'Landscape asymmetry' and Chapter 4, 'Co-evolution').

### 6.3.2 To Panarchy rules?

Although my scale of analysis showed the importance of larger scale slow variables, I did not define clear boundaries around my system and thus where the larger scale starts. Giller (2013) recognised that problem in defining farming systems as a scale above the farm system. He concluded that the diversity within and among farms precludes large-scale generalisations but was unable to define a farming system at lower scales. The difficulty or impossibility of defining boundaries to agro-ecosystems might be a common characteristic with landscapes (Cumming, 2011a) and complex systems in general (Gomiero et al., 2006).

The adaptive cycle assumes that a particular combination of dominant feedbacks give rise to a regime. This regime is characterised by pattern-process feedback that give rise to the level of self-organisation. The slow variables of soil organic matter, field size and hedgerows are examples of the patterns of self-organisation. However, these patterns are not the result of current management but from past management. As such management and pattern are de-coupled and no regime emerges. This decoupling would also explain why I in Chapter 4 'Co-evolution' I was able to observe the thresholds without being able to separate the regimes. This lack of a regime destabilizes the level of self-organisation making the proper scale of analysis unclear.

This lack of a level of self-organisation challenges the fundament of the resilience heuristics. If there is no level, dynamics cannot be described by the adaptive cycle. Likewise, a panarchy cannot be formed by multiple adaptive cycles. Moreover, the heuristic of resilience is very much linked to a level; if there is no level it becomes hard to analyse. Although adaptability and transformability are considered key heuristics for the resilience perspectives (Folke et al., 2010), I could hardly elaborate on them. This was certainly not by intent, but their application appeared to be hard for systems without a

regime. It is for me unclear how these heuristics would help if there is no clear regime that needs to be maintained or to be re-configured.

### 6.3.3 Focusing the lens of the resilience perspective

An additional heuristic: identity

The resilience perspective offers a set of heuristics that helped me to think about social – ecological interactions. To focus the lens of the resilience perspective for agro-ecosystem analysis I suggest to rethink its heuristics. I think it makes sense to study resilience as a general concept of how complex systems such as agro-ecosystems persist over time. However, defining this complex system is the difficulty. I suggest to define an agro-ecosystem's resilience by using its identity. Cumming and Collier (2005) define system identity by its key components and relationships that are maintained continuously in space through time. While Antrop (2005) defines the identity of cultural landscapes by its coherence. Coherence can be thought of as the landscape asymmetry. Integrating these two definitions of identity for agro-ecosystems leads to a combination of landscape asymmetry and the conceptual models as used in Chapter 4 'Co-evolution' that relates management with asymmetries.

Recoupling management and landscape asymmetry

When landscape asymmetry is (re)coupled to the management a regime can emerge through self-organisation and positive feedbacks can be exploited. Graphically, agro-ecosystem dynamics can be depicted by a broad and shallow basin in which multiple marbles (farms) roll and bounce. The gradient of the basin is not steep enough to adjust for internal dynamics in the marble or outside changes. However, when multiple marbles align a new basin (regime) is formed by the interactions of the marbles (see Figure 2). Identity of these aligned marbles can be maintained in space through time shaping a pattern of which management is coherent with the landscape asymmetry.
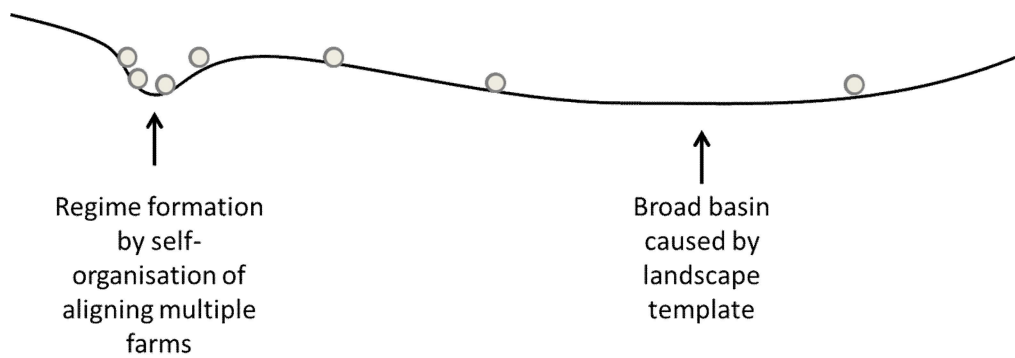
**Figure 15.** Ball in cup representation of an agro-ecosystem. Landscape characteristics provide a broad basin, in which multiple farms interact (the balls). When multiple farms align their behaviour a regime might emerge.

In modern human-dominated agro-ecosystems patterns and process are de-coupled. As such patterns as captured by maps or pixels cannot be assumed to match current management. Understanding agro-ecosystem functioning needs to include both the pattern or asymmetry that reflect the slow variables in the system and the current management. Re-coupling management with an asymmetry offers potential benefits of positive feedbacks that are under exploited by conventional management. Landscape asymmetries are typically shaped by slow variables and as such are hard to experiment with. However agro-ecosystems are spatially structured systems. Using resources from multiple location to a single location create a substitution of space with time and a way to experiment. The anthropogenic soils studied in this thesis provide a good examples of how larger areas can subsidize smaller areas to exploit positive feedbacks of soil organic matter and nutrient use efficiency.

## 6.4 Future research and concluding remarks

This thesis was a thesis of largely, failed initial hypotheses. I started out with rather strong ideas or perhaps even beliefs on agro-ecosystems and resilience. Time and again, results that were obtained both through modelling and through data collections gave rise to the need to reject the starting idea. Yet, at the same time new ideas and suggestions surfaced.

It is my hope that this thesis contributes to the emerging fields of landscape agronomy (Benoît et al., 2012) and spatial resilience (Cumming, 2011b). In the coming years I hope to contribute to these emerging fields by testing the idea of aligning asymmetry with identity. The (re)coupling of management with asymmetry offers potential benefits of positive feedbacks than can be exploited. Furthermore I am eager to make the move from

describing and explaining to exploration and design of agro-ecosystems (Giller et al., 2011). Key lessons I will take on board for this future research are:

- Agro-ecosystems are spatially-temporally structured systems

  Future analyses including both the temporal and spatial dimension of agro-ecosystem functioning are required.

- In agro-ecosystems patterns and processes are uncoupled

  The lack of the emergence of a level means that agro-ecosystems are out of equilibrium but not random or chaotic. Assumptions of normality, stationary and independence of data cannot be made. In fact deviations from these assumptions yields much information.

- In analysing agro-ecosystems diversity should be pursued rather than reduced

  I will attempt to build on continuous data rather than aggregated data. I hypothesise that aggregations hide potential asymmetries that can be exploited.

In short, the resilience perspective offers a set of heuristics that help to think about social-ecological interactions. However, for agro-ecosystems the current set of heuristics cannot be used to deal with a de-coupling of pattern and process. Agro-ecosystems identity offers a perspective that relates the slow variables of landscape asymmetry with the current management. Aligning asymmetries with management through, for example, space-time substitutions offers a promising experimental framework for future research.

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# English summary

Agriculture is faced with new challenges while at the same time conceptualisations of agricultural systems are shifting. The resilience perspective offers a new conceptualisation of system dynamics which might shed light on the functioning of agricultural systems. An improved understanding of agricultural system functioning can contribute to overcome these challenges. The general objective of this thesis is to employ a resilience perspective to agro-ecosystems and to derive increased understanding of agro-ecosystem functioning. In the separate chapters I try out several approaches and methods to test if the resilience perspective is useful for analysing agro-ecosystems.

In Chapter 2 'Panarchy rules', the objective was to identify multiple stable states of dairy farms in Northern Frisian Woodlands. Literature as well conceptual models suggested the existence of a state with high nutrient use efficiency and one with low nutrient use efficiency. I analyse the dynamics in the Northern Frisian Woodlands by the five heuristics of the resilience perspective and a dynamic farm model. The resilience perspective proved to be especially insightful in addressing interacting long-term developments expressed in the panarchy. Panarchy created a heterogeneity of resources in the landscape providing local landscape-embedded opportunities for high N-efficiencies. The dynamic farm model showed that modern conventional dairy farms short-cut the adaptive cycle by frequent grassland renewals, resulting in high resilience and adaptability. This comes at the cost of long-term accumulated ecological capital of soil organic matter and transformability, thus reinforcing the incremental adaptation trap. Our analysis revealed that long term dynamics such as the accumulation of soil organic matter were not considered within the institutional setting of environmental legislation. We therefore claimed panarchy as a leading heuristic to analyse these kind of scale mismatches in agro-ecosystems.

In Chapter 3, 'landscape asymmetry', the objective was to link the high nutrient use efficiency at farm level to locations in the landscape. I modelled soil organic matter (SOM) dynamics of grassland soils to identify dominant long-term drivers and combine and analyse land use history and landscape characteristics to explain the spatial variability of SOM contents. Sensitivity analyses showed that the dominant parameter for attainable SOM content is the mineralization rate of SOM. Results furthermore indicated, that SOM content is related to temporal variability in land use and to spatial variability of groundwater hydrology and soil texture. I conclude that the landscape asymmetry of SOM provides windows of opportunities for farmers who wish to

reduce fertilizer input. However, connecting landscape asymmetry to other scales also reveals potential cascades of events that might undermine agro-ecosystem resilience.

In chapter 4 'co-evolution' I set out to localize regimes of production intensifying farms and farms that aim to reconcile farming and landscape. The previous chapter showed that a strategy of farm intensification and the re-balancing strategy can be characterised by regimes of positive feedbacks at field, farm and regional scale. I identified relations between landscape patterns and production intensity, collect field scale data and analyse their relation with non-parametric statistics. I found that a higher milk production was significantly linked to larger fields, fewer hedgerows, fewer grazing days, higher use of N-fertilizer and a decrease of nutrient cycling. Furthermore, production intensity was found to differ with the landscape pattern of clay content and groundwater hydrology. On top of this landscape template, man-made patterns of field sizes and hedgerows from before 1930 are still visible in the current differences of milk production intensity. Current farm management was found to have relations with the hedgerows, field size, clay content and groundwater hydrology. These relations hint at a co-evolution of landscape pattern and agricultural intensification. Interestingly, the largest differences between descriptors of landscape pattern and intensity were found for similar values of clay content, groundwater hydrology and fertilizer use. We speculate that these similar values indicate the existence of tipping points for diverging trajectories of intensification. Identification of such tipping points have implications for policies that deal with the future dynamics of rural landscapes.

In chapter 5 'scale-mismatch', I investigate the landscape pattern or asymmetry at village scale In Zimbabwe. I map soil organic carbon (SOC) content, as an indicator of soil fertility, at the village scale, and aim to relate the SOC content to farm scale management and landscape scale characteristics. Using digital soil mapping techniques and Landsat TM images we obtain reasonably good results. However, the SOC variability could not be linked to farm management. No fertility gradients were observed, mostly due to a strong dominance of clay content on the spatial distribution of SOC. Clay content was able to explain the majority of the SOC variance, while cattle ownership, farm area and labour size, typically used for farmer typology, were able to explain only an additional minor part of the SOC variance. I conclude that this strong landscape scale effect needs to be included in future village-scale studies. I furthermore conclude that digital soil mapping of soil fertility gradients at the village scale has several scale issues that need to be addressed if the envisioned global digital soil map is to be relevant for smallholder farmers in sub-Saharan Africa.

In the final chapter 'to Panarchy rules ?' I aim to highlight the increased understanding of agro-ecosystem functioning by employing the resilience perspective. Paradoxically the empirical results of my thesis challenge the fundaments of the resilience perspective. The de-coupling of pattern and process in agro-ecosystems leads to mismatch with the current set of resilience heuristics. I therefore suggest an additional heuristic of identity in order to focus the lens of the resilience perspective for agro-ecosystem analysis. Agro-ecosystems identity offers a perspective that relates the slow variables of landscape asymmetry with current and future management. Aligning asymmetries with management via for example via space-time substitutions offers a promising experimental setup for future research

# Nederlandse samenvatting

De landbouw staat voor nieuwe uitdagingen, terwijl tegelijkertijd ons begrip van landbouwsystemen aan het verschuiven is. Het resilience (veerkracht) perspectief biedt een nieuw kader, dat ons kan helpen om de dynamiek van landbouwsystemen beter te begrijpen. Dit betere begrip van landbouwsystemen kan helpen om de uitdagingen waar de landbouw momenteel voor staat, te overwinnen.

In dit proefschrift analyseer ik verschillende benaderingen en methoden om te onderzoeken of het resilience perspectief nuttig is voor het analyseren van agro-ecosystemen.

Het doel van hoofdstuk 2 'Panarchy Rules' was om meerdere stabiele toestanden van melkveebedrijven in Noordelijke Friese Wouden identificeren. Zowel de wetenschappelijke literatuur als conceptuele modellen suggereerden dat er twee stabiele toestanden waren: een toestand met een hoge efficiëntie van nutriëntgebruik en een toestand met een lage efficiëntie van nutriëntgebruik. Ik heb de dynamiek van deze stabiele toestanden geanalyseerd door de vijf principes van het resilience perspectief en een dynamisch boerenbedrijfsmodel te combineren. Om de interactie van lange-termijn ontwikkelingen weer te geven bleek het resilience principe van 'panarchy' cruciaal. Een panarchy van verbonden processen op verschillende schalen zorgden voor een geschakeerd landschap waar in de mogelijkheden voor hoge stikstof efficiëntie ingesloten zijn. Het dynamische boeren bedrijfsmodel suggereert dat moderne conventionele melkveebedrijven de 'adaptive cycle' afsnijden door regelmatig het grasland te vernieuwen. Dit resulteert in een hoge resilience en hoog aanpassingsvermogen, maar dit gaat ten koste van het traag opgebouwde ecologisch kapitaal, de bodem organische stof, en 'transformability'. De geleidelijke aanpassing van efficientie leidt dus tot een valkuil. Uit mijn analyse bleek dat de lange termijn dynamiek, zoals het vastleggen van organische stof, niet binnen het institutionele kader van de milieuwetgeving werd meegenomen. Ik suggereer 'panarchy' als het belangrijkste principe om dit soort schaal problemen in agro-ecosystemen te analyseren.

Het doel van hoofdstuk 3, 'Landscape Asymmetry', was om de hoge efficiëntie van nutriëntgebruik op bedrijfsniveau te koppelen aan locaties in het landschap . Om de trage dominante variabele in graslandbodems te identificeren modelleerde ik de dynamiek van bodem organische stof (SOM). Uit de gevoeligheidsanalyse bleek dat de dominante parameter voor het haalbare SOM-gehalte de mineralisatiesnelheid van SOM is. Echter het huidige SOM gehalte hangt sterk samen met de leeftijd van de graszode. Om de ruimtelijk variabiliteit van SOM te

verklaren werden daarom de landgebruiksgeschiedenis met landschappelijke kenmerken die mineralisatie bepalen gecombineerd. Deze empirische gegevens bevestigen dat het SOM gehalte gerelateerd is aan de temporele variabiliteit in landgebruik, de ruimtelijke variabiliteit van het grondwater en de bodem textuur. Ik concludeer dat de asymmetrie van SOM in het landschap locatie-specifieke kansen biedt voor boeren die de kunstmestgift willen verminderen. Het koppelen van de asymmetrie in het landschap met de andere schalen daarentegen, liet zien dat de resilience van het agro-ecosysteem kan worden ondermijnd als bepaalde gebeurtenissen elkaar opvolgen.

In hoofdstuk 4 'Co-evolution' ben ik op zoek gegaan naar regimes van intensive bedrijven en kringloop boeren, dat zijn bedrijven die zich richten op sluiten van kringlopen op hun bedrijf. Uit het vorige hoofdstuk bleek dat een strategie van intensivering en de kringloop strategie kunnen worden gekarakteriseerd door regimes van positieve terugkoppelingen op veld, boerderij en landschaps-niveau. Eerst heb ik relaties tussen landschapspatronen en productie-intensiteit geïdentificeerd, daarna verzamelde ik gegevens op veldniveau en tot slot heb ik relaties tussen patronen en productie met niet-parametrische statistiek geanalyseerd. Hieruit bleek dat een hogere melkproductie significant samenhing met grotere velden, minder heggen, minder dagen dat de koeien buiten grazen, een hoger gebruik van stikstof en een verminderde nutriëntenkringloop. Daarnaast hing de productie-intensiteit af van het kleigehalte en de grondwaterstand. De huidige verschillen tussen huidige intensiteit van de melkproductie zijn nog te koppelen aan perceel oppervlak en heggen van vóór 1930. De huidige bedrijfsvoering bleek verder samen te hangen met velden die omzoomd zijn met heggen, het perceel oppervlak, het kleigehalte en het grondwater. Deze relaties wijzen op een co-evolutie van het landschapspatroon en de intensivering van de productie. Opvallend was dat de grootste verschillen tussen het landschapspatroon en productie-intensiteit gevonden werden bij dezelfde waarden van kleigehalte, grondwater hydrologie en kunstmest gebruik. Ik speculeer dat het feit dat deze waarden gelijk zijn, mogelijk wijst op kantelpunten voor uiteenlopende trajecten van intensivering. Het identificeren van dergelijke kantelpunten heeft gevolgen voor beleid dat zich bezighoud met de toekomst van het landelijk gebied.

In hoofdstuk 5 'Scale-mismatch', onderzocht ik de landschaps-asymmetrie op dorpsniveau in Zimbabwe. Hiervoor heb ik een kaart gemaakt van bodem organische koolstof (SOC), als een indicator van de bodemvruchtbaarheid. Daarna heb ik deze kaart gekoppeld aan verschillende bedrijfsvoeringen en landschapskenmerken. Met behulp van digitale bodemkarteertechnieken en

Landsat TM satelliet beelden kreeg ik redelijk goede resultaten . Toch kon de variatie van SOC niet worden gekoppeld aan de bedrijfsvoering. Ik vond namelijk geen gradiënten in bodemvruchtbaarheid. De ruimtelijke verdeling van SOC bleek vooral bepaald te worden door de dominante rol van het kleigehalte van de bodem. Het kleigehalte in de bodem verklaarde het merendeel van de variatie van SOC, terwijl het bezit van koeien, bedrijfsgrootte, arbeidsbeschikbaarheid, typische factoren die vaak gebruikt worden om bodemvruchtbaarheid binnen bedrijven te verklaren, slechts een klein extra deel van de variantie van SOC konden verklaren. Ik concludeer dat dit sterke schaal-effect op landschapsniveau moet worden meegenomen bij toekomstige studies op dorpsniveau. Daarnaast heeft het digitaal in kaart brengen van de bodemvruchtbaarheids-gradiënten op dorpsniveau verschillende schaalproblemen. Om de beoogde wereldwijde digitale bodemkaart relevant te maken voor kleine boeren in Afrika, moeten deze schaalproblemen erkend worden.

In het laatste hoofdstuk 'Panarchy Rules?' benadruk ik het verbeterde begrip van het functioneren van agro-ecosystemen door het gebruik van het resilience perspectief. Paradoxaal genoeg weerspreken de empirische resultaten van mijn thesis juist de fundamenten van het resilience perspectief. De ontkoppeling van het patroon en het proces binnen agro-ecosystemen past niet binnen de set van principes van het resilience perspectief. Ik stel daarom een extra principe voor: identiteit. Identiteit kan het resilience perspectief richting geven bij de analyse van agro-ecosystemen. De identiteit van agro-ecosystemen biedt een perspectief dat de trage variabelen van de landschap asymmetrie koppelt aan het huidige en het toekomstige beheer. Het koppelen van de asymmetrie met het management bijvoorbeeld via ruimte-tijd verwisselingen biedt een veelbelovende experiment voor toekomstig onderzoek.

# Acknowledgements

The metaphor of a journey is probably the most tired metaphor for the process of writing a thesis. I find it however wrongly used by focussing on the physical geography of journey (mountains to climb etc,) rather than on the people you meet. Without all people that supported me through this journey of more than 7 years my PhD would have lacked identity. I started to write out the names of all the people that have at some stage contributed to the identity of this thesis, however I ended up with a list that would precisely lack identity because of its length. Therefore I chose to group these people without wanting to devaluate their valuable input. I would like to thank all the folks of the Soil Geography and Landscape group, the Plant Production Systems group, the Santa Fe Complex Systems SummerSchool 2008, the Stockholm Resilience Institute, the Geochemistry Group, the PE-RC PhD Council, and de Grindhorst for giving identity to my journey. However I wish to thank a few people specifically, who have been vital for the success of this journey.

First, I have to say I travelled literally and figuratively with giants: it was easy to talk high level as the shortest of my supervisors was over 1.9 m. If I describe their role I think about the Sherpa's, an ethnic group in Nepal. They are widely renowned for their hardiness, expertise, and experience at very high altitudes. My supervisory team gave me all the freedom to discover my own direction, but coached and took over some of the load when I needed it.

I started with two promotors, Prof. Ken Giller and Prof. Tom Veldkamp. You took me on this journey of discovery, and with varying intensity you both coached me when I was at a loss. Dear Ken, you qualified what would become my first chapter as "luchtfietserij".and you probably never realised that it would result in lots of emperical work in the remainder of the thesis. And dear Tom, thank you for your support to choose to continue with this "luchtfietserij" to see where it would land.

My guide in daily matters Dr. Kasper Kok. Almost nine years ago I entered the big room at BenG to have chat for a potential MSc-thesis on scale and complexity. Now, with the completion of my PhD thesis, our intensive interactions have for the moment come to an end. You guided me for a quarter of my life, a period that has been life-changing. At all most the same time, we met our partner, got married and our kids were born. I am grateful to have had you as my guide and friend and for sharing with me these important moments in our lives.

Marthijn Sonneveld became my co-promotor when Tom left to Enschede. However, just after Christmas last year Marthijn passed away after a short but devastating illness. Dearest Marthijn, I cannot write this without becoming entirely grief-stricken. Losing you at the end of my travels puts a gloom over the final stage of my thesis. This thesis carries your enthusiasm for science and your honest and open view on science and life in general. It will remain to inspire me. You are dearly missed.

When my companions Frans and Joost finished their PhD projects, I did not finish mine yet and had to take a job-wise detour while in need of funds. This thesis would still be in its final phase (as it has been for the last two years), if Prof. Lex Bouwman would not have showed up. Lex, thank your for giving me a post-doc position while allowing me to finish my thesis. However, more than then the needed funds, you are my example of the perfect boss. Every morning at 7:00 sharp we start with an espresso and discuss first what is on our mind personally, where after we talk science. If I ever get into a position to lead, you will be my example.

Hans Schiere has been my mentor in complexity thinking for over a decade now. I once asked him how to see patterns in agroecosystems, when you lack experience. I guess this thesis contains some efforts worth discussing. Hans thank you for inspiring me.

I want to especially thank Bas Kempen, Frans Hermans, Chrispen Murungweni and Bas Allema who have become good friends during my PhD. Thank you for your company during this journey.

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Having children is a bliss, however there are times they can become a burden. Dear Eddy and Elly, thank you being opa and oma, when the load became overwhelming.

Dear Pa and Ma you have been existential to this thesis in more than one way. Thank you, for showing me the important values in live.

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# Curriculum Vitae

Dirk Frederik van Apeldoorn was born on 23 April 1980 in Deventer, The Netherlands, where after he, his brother and parents quickly returned to Naivasha, Kenya. In 1983, they migrated back to Heerde, the Netherlands. Where he obtained his VWO degree in 1999. Since in 1999 the last cohort of the study tropical landuse in Wageningen started, plans for exploring the world were postponed. He almost immediately joined the education committee to safeguard the quality of his study and got into the national news when he complained about exams that were too easy. In 2000, he co-founded a development-oriented student organisation "Patio". But left Netherlands in 2002 for his internship at an NGO in Mexico to co-develop a GIS of a multi-scale sustainability evaluation framework. When he returned to the Netherlands in 2003, he temporarily stopped his studies to become the education specialist of the student union of Wageningen. In 2004, he continued his studies with a joint MSc project of "explorations of intransitive relations in a multi-agent model" at the department of Mathematics and Statistics and Plant Production Systems group, while continuing to work for the national student union "LSVb" on education quality. In 2005, he started his second MSc project with a thesis on "Multi-scale Modelling of Small-holder System Dynamics in Southern Mali" at the department of Soil Inventarisation and Land Evaluation Group and the Plant Production Systems group. In 2006, he graduated (*Cum Laude*) with an MSc degree in tropical landuse with a specialisation in agronomy. In December 2006, he started a joint PhD at Land Dynamics group and Plant Production Systems group. As PhD representative, he became member of the board of PE-RC research school and coordinated the PhD discussion group on Math, Stats and Models. In 2008, he went to the homeground of complexity thinking by participating in the complex systems summer school of Santa Fe. In 2009, a prolonged sickness put a stop to his PhD study, but in 2010 he was able to continue his PhD work. In 2012 he joined the Geochemistry group in Utrecht as a post-doctoral researcher, to model global and regional nutrient dynamics, meanwhile finishing his thesis. Since January 2014 he combines the global modelling work with a post-doctoral position at the Farming Systems Ecology group in Wageningen. He is now involved in the design and analysis of spatial-temporal diversity of agroecosystems at the field, farm and landscape scale.

# Publications

van Apeldoorn, D. F., B. Kempen, H. M. Bartholomeus, L. Rusinamhodzi, S. Zingore, M. P. W. Sonneveld, K. Kok and K. E. Giller ((submitted)). "Analysing soil fertility gradients at village scale in African smallholder farming systems: A scale mismatch?" Geoderma.

van Apeldoorn, D. F., B. Kempen, M. P. W. Sonneveld and K. Kok (2013). "Co-evolution of landscape patterns and agricultural intensification: An example of dairy farming in a traditional Dutch landscape." Agriculture, Ecosystems & Environment 172(0): 16-23.

Hermans, F., D. Van Apeldoorn, M. Stuiver and K. Kok (2013). "Niches and networks: Explaining network evolution through niche formation processes." Research Policy 42(3): 613-623.

van Apeldoorn, D. F., M. P. W. Sonneveld and K. Kok (2011). "Landscape asymmetry of soil organic matter as a source of agro-ecosystem resilience." Agriculture, Ecosystems & Environment 140(3-4): 401-410.

van Apeldoorn, D. F., K. Kok, M. P. W. Sonneveld and T. A. Veldkamp (2011). "Panarchy rules: Rethinking resilience of agroecosystems, evidence from Dutch dairy-farming." Ecology and Society 16(1): 39, [online] URL: http://www.ecologyandsociety.org/vol16/iss31/art39/.

Beers, P. J., A. Veldkamp, F. Hermans, D. van Apeldoorn, J. M. Vervoort and K. Kok (2010). "Future sustainability and images." Futures 42(7): 723-732.

PE&RC Training and Education Statement

With the educational activities listed below the PhD candidate has complied with the educational requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)
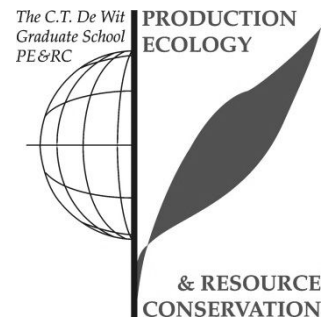
**Review of literature (5.6 ECTS)**
- Resilience of agro-ecosystems

**Writing of project proposal (4.5 ECTS)**
- Modelling resilience of agro-ecosystems

**Post-graduate courses (7.5 ECTS)**
- Land science: bringing concepts and theory into practice; PE&RC (2007)
- Complex systems summer schools; Santa Fe institute, New Mexico, USA (2008)
- Analysing farming systems and rural livelihoods in a changing world: vulnerability and adaption; PE&RC, Zimbabwe (2008)
- Uncertainty analysis; SENSE (2008)
- Spatio-temporal analysis and big data processing using free and open source software; PE&RC and SENSE (2013/14)

**Laboratory training and working visits (1.4 ECTS)**
- Regimeshifts in agro-ecosystems; Resilience Institute, Stockholm, Sweden (2011)

**Invited review of (unpublished) journal manuscript (2 ECTS)**
- Agriculture, Ecosystems and Environment: integrated soil fertility management (2012)
- Ecology and Society: panarchy (2012)

**Competence strengthening / skills courses (2.3 ECTS)**
- Interdisciplinary course: understanding complex social ecological systems; PE&RC and CERES (2007)
- The latest technologies for literature and information searches; Wageningen UR Library (2009)
- Interdisciplinary course: experiments to innovate during great transformations; SG and SENSE (2010)
- Career assessment; WGS (2011)

**PE&RC Annual meetings, seminars and the PE&RC weekend (1.5 ECTS)**
- PE&RC Weekend (2007)
- PE&RC Day (2009)
- PE&RC Day (2010)

**Discussion groups / local seminars / other scientific meetings (6.5 ECTS)**
- TransForum meetings (2006-2010)
- Statistics , maths and modelling in Production Ecology and Resource (2007-2010)
- Farming Futures in Sub-Saharan, Africa (2008)
- Food Group; Resilience Institute, Stockholm, Sweden (2011)

**International symposia, workshops and conferences (8.5 ECTS)**
- International Resilience Symposium, Stockholm, Sweden (2008)
- ALIFE XI (2008)
- NAEM (2011)
- Resilience of cultural landscapes, Berlin (2011)