Cranfield University

F.G.A. Verheijen
2005

On-farm benefits from soil organic matter in England and Wales

Faculty of Environment

Ph.D.

Cranfield University

Faculty of Environment

PhD

2005

F.G.A. Verheijen MSc (physical geography)

On-farm benefits from soil organic matter in England and Wales

Supervisors:

Prof. M.G. Kibblewhite

Prof. P.J.L Loveland (initial 6 months)

This degree is submitted in partial fulfillment of the requirements for the Degree of Doctor of Philosophy.

ABSTRACT

Soil organic carbon (SOC) is increasingly recognised as an important component in the global carbon cycle and as a potential C sequestration pool for mitigation of the enhanced greenhouse effect. Recent appeals have prompted research into the potential of storing C in arable fields and the concomitant impact for on-farm economics. This project was instigated to answer the question "*Does soil organic matter (SOM), or its management, provide arable on-farm benefit, in England and Wales?*". A methodological design was developed which integrates social science with soil science.

From the National Soil inventory (NSI) database, attainable SOC ranges were estimated for different SOC physiotopes, i.e. landscape units for which the environmental factors governing SOC contents are similar. Significant differences were found, e.g for a dry-sandy physiotope and a wet-clayey physiotope, the ranges were estimated at 0.5-1.6% and 2.0-5.4% SOC (w/w), respectively.

A list of qualified 'SOM benefit' indicators was developed using an iterative process involving the scientific literature and interviews with 'expert farmers'. Perceptions of the indicators were investigated within a stratified random sample of commercial farmers. On balance, farmers perceived that benefits of SOM outweighed the disbenefits (i.e. lodging, weeds, and slugs). N fertiliser reduction, increased yield quantity, and enhanced ease of tillage were recognised as the most valuable benefits. However, the values were low to moderate, and perceived to be influenced substantially by physiotope, crop type, and SOM management type.

Farmers' perceptions and valuations were investigated for 101 fields on commercial farms, selected from the NSI database to represent the attainable SOC content ranges. No correlations were found between SOC and any performance indicator. The full range of reported performances was found for fields with similar SOC contents. This implied that SOC contents and SOM management may have little importance to on-farm economics when compared to the quality of overall farm management.

These results expose the marginal extent of on-farm benefits from increased SOC contents and SOM management. Implications for future research and policy are discussed.

ACKNOWLEDGEMENTS

Many people have contributed to this thesis, in many different ways. It would be impossible to list them all, but the following people I wish to thank explicitly:

Professor Mark Kibblewhite has not only been an excellent mentor, but also superseded his supervisor duties in personal support and development. Discussions during 'progress meetings' often digressed to domains as diverse as (inter)national politics, the 1960s, Catch 22, the Templar Knights in 13th century Portugal, and many more (wonderfully obscure) topics… It has been an enjoyable education (and I never shall split infinitives in scientific texts again!).

Professor Peter Loveland inspired as supervisor in the initial 6 months and has provided useful feedback as chairman of the Thesis Committee. Professor Joe Morris aptly pointed me in the right direction for social science methods. Dr. John Gaunt was constructively thought-provoking as project manager, and, together with the other members of the inter-disciplinary project team (Dr. Gil Yaron, Dr. Cathy Butcher, Dr. Saran Sohi, Helen Yates, and Chris Brett), a dynamic communication and collaboration was achieved. Chris Brett deserves a special thank you for many, many long days spent together on the road, in B&B's, and each other's houses. It was an epic journey, stretching to (I believe) every county in the land, which never became boring thanks to Chris's company and ever-ready conversation.

Marije Overmars in Amsterdam suffered my endless organic matter chatter over the telephone, energetically helped to create a reference library, and supported me superbly through episodes of Ph.D. blues. My parents, Arnie Klaren, and Sorche O'Keefe all accompanied me in the field on occasion. My office mates, Bashir Nwer and Sorche O'Keefe, formed a source of unrelenting optimism and the best company imaginable.

My NSRI colleagues made me feel very welcome. Pat Bellamy helped with statistical work (and showed me how to catch sheep…). Margit Liedberg entered 1667 cases from old, paper files into digital format. Roy Newland helped me surf the Internet for farmer contacts. The lab crew was professional and flexible.

The Department of Food and Rural Affairs (Defra) funded the research project. The British Soil Science Society (BSSS) provided grants for conference attendance, and the European Science Foundation (ESF) financed workshops, as well as a summer school in the Dolomites.

Finally, a thank you to Cat for putting up with my absentmindedness during the write-up, and for our scientific pillow talk, without (seemingly) ever finding it strange or too much…

Frank Verheijen

Summer 2005

This thesis is dedicated to the soil surveyors of the (former) Soil Survey of England and Wales and the participating farmers, without whose hard work, and kindly offered time, respectively, this work would not have been possible.

Frank Verheijen
2005

GLOSSARY

FYM	Farm Yard Manure
NSI	National Soil Inventory
OM	Organic Matter
Physiotope (in the context of SOM)	A unit in the landscape where environmental conditions that govern SOC are similar
SOC	Soil Organic Carbon
SOCIMR	Soil Organic Carbon Indicative Management Range
SOM	Soil Organic Matter
SOMFIE (indicator)	Soil Organic Matter on-Farm Impact on Economics
SSI	Semi Structured Interview

TABLE OF CONTENTS

LIST OF FIGURES

Chapter 1

Chapter 2

Chapter 3

Chapter 4

Chapter 5

Chapter 6

LIST OF TABLES

Chapter 2

Chapter 3

Chapter 4

Chapter 5

Chapter 6

LIST OF BOXES

Chapter 1

Chapter 3

CHAPTER 1

INTRODUCTION

"We're all gonna be just dirt in the ground."
Tom Waits (1992)

This chapter states the relevance of the research aim. It also describes the thesis structure and provides a thesis route map.

1.1 ORGANIC CARBON AND THE NATURAL AND POLITICAL ENVIRONMENTS

Political developments are focusing attention on the importance of soil carbon in the global carbon cycle and the potential for carbon sequestration in soil to mitigate the enhanced greenhouse effect, and on the possible economic benefits and disbenefits linked to soil organic matter in farming, particularly in relation to future reform of the Common Agricultural Policy (CAP). It is important that policies aimed at more appropriate management of SOM (Box 1.1) are based on sound scientific evidence. However, knowledge gaps exist both on attainable SOC contents in agricultural soils, and on the relationship between SOC and the agro-production function.

Box 1.1 SOM and SOC

The terms Soil Organic Matter (SOM) and Soil Organic Carbon (SOC) are both used in the literature. By convention, when SOC is measured, SOM is calculated as: 1.724 SOC. The actual conversion factor can range from 1.4 to 3.3 (Körschens, 1998). In this thesis, SOC is used when referring to measured values and SOM is used when describing or discussing qualitative data.

De Groot *et al.* (2000) classified 23 ecosystem functions into four primary functions: regulation (n=11), habitat (n=2), production (n=5), and information (n=5). Ecosystem functions are defined as “the capacity of natural processes and components to provide goods and services that satisfy human needs, directly or indirectly”. For arable soils the production function has a relatively high economic value. Costanza *et al.* (1997) estimated the ‘food production’ function represents more than half of the total value of the ecosystem services of arable soils.

Increasingly, soil is recognised as a vital environmental compartment. The organic component of soil has received particular attention. It is important to understand the factors that control SOC contents, both because SOC is considered to be an important component in agronomic systems and because SOC has a key role as a carbon reservoir in Earth systems (see Appendix 1). Globally, soil is estimated to hold more organic carbon (1,100 Gt) than the atmosphere (750 Gt) and the terrestrial biosphere (560 Gt) (Post *et al.*, 1990; Sundquist, 1993). Assessment of carbon stocks within soils, and the definition of policy measures for SOC management, are problematic. This is mainly due to large spatial and temporal variability in SOC contents and the variety of factors controlling SOC contents.

In the Kyoto Protocol of 1997 (formally known as the United Nations Framework Convention on Climate Change), Article 3.4 allows organic carbon stored in arable soils to be included in calculations of net carbon emissions. It speaks of the possibility of subtracting the amounts of CO_2 removed from the atmosphere into agricultural sinks, from the assigned target reductions for individual countries. SOC sequestration in arable agriculture has been researched (Schlesinger, 2000; Smith *et al.*, 2000a, b; Freibauer *et al.*, 2002; West & Post, 2002; Sleutel *et al.*, 2003; Janzen, 2004; King *et al.*, 2004; Lal, 2004) against the background of organic carbon (OC) credit trading schemes (Brown *et al.*, 2001; Johnson & Heinen, 2004). However, fundamental knowledge on attainable SOC contents (relative to variation in environmental factors) is still in its infancy, and it is mostly approached by modelling (Falloon *et al.*, 1998; Pendall *et al.*, 2004).

To develop appropriate policies for the purpose of sequestering SOC in arable soils, knowledge of the accompanying benefits for farmers (derived from having a greater OM contents in their soils) is essential. For example, if there is no on-farm benefit, policy options may need to include incentives. On the other hand, if there is substantial on-farm benefit, policy may focus more on knowledge-transfer of benefits to farmers. However, although some consensus exists on the (mainly off-farm) relationship between SOM and environmental quality and human health other than atmospheric CO_2 concentrations (Deportes *et al.*, 1995; Oliver, 1997; Gerke *et al.*, 1999; Condron *et al,* 2000; Hansen *et al.*, 2001; Wang *et al.*, 2004), the (on-farm) relationship between SOM and economics of the agro-production function is less clear.

1.1.1 Soil organic carbon and the agro-production function

SOC has been proposed as an indicator of soil quality (Defra, 2003), but no consensus exists on its relationship to agronomic and other variables, such as crop yield (Loveland & Webb, 2003). Critical or threshold levels of SOC in relation to soil physical properties and nutrient supply to crops have been researched extensively (Greenland *et al*., 1975; Watts & Dexter, 1997; Chenu *et al*., 2000; Six *et al*., 2000a; 2000b; Carter, 2002; Shepherd *et al*., 2002). The absence of clear relationships reflects the many possible mechanisms by which SOC interacts with the soil, water and plant system, as well as the wide spatial and temporal variation in SOC contents and composition. These variations arise from differences in soil properties, climate, land use and soil management. Finally, sampling and analytical errors can be substantial in relation to observed differences in SOC contents and so may obscure underlying relationships.

1.2 THESIS OBJECTIVES

This project aims to decrease the knowledge gap regarding the relationship between SOC and the agro-production function and SOC contents in agricultural systems, within England and Wales. The specific objectives (see 3.2 for more detail) are:

- To investigate the environmental variables that govern SOC variation, and to define 'SOC Indicative Management Ranges (SOCIMRs)' for arable ecosystems
- To develop indicators of on-farm benefit from SOM and investigate farmers' perceptions and valuations (i.e. estimations of the worth of the benefits) relative to environmental conditions and SOM management
- To qualify and quantify the 'SOM benefit indicators' for fields along the SOCIMR, and/or under different SOM management.

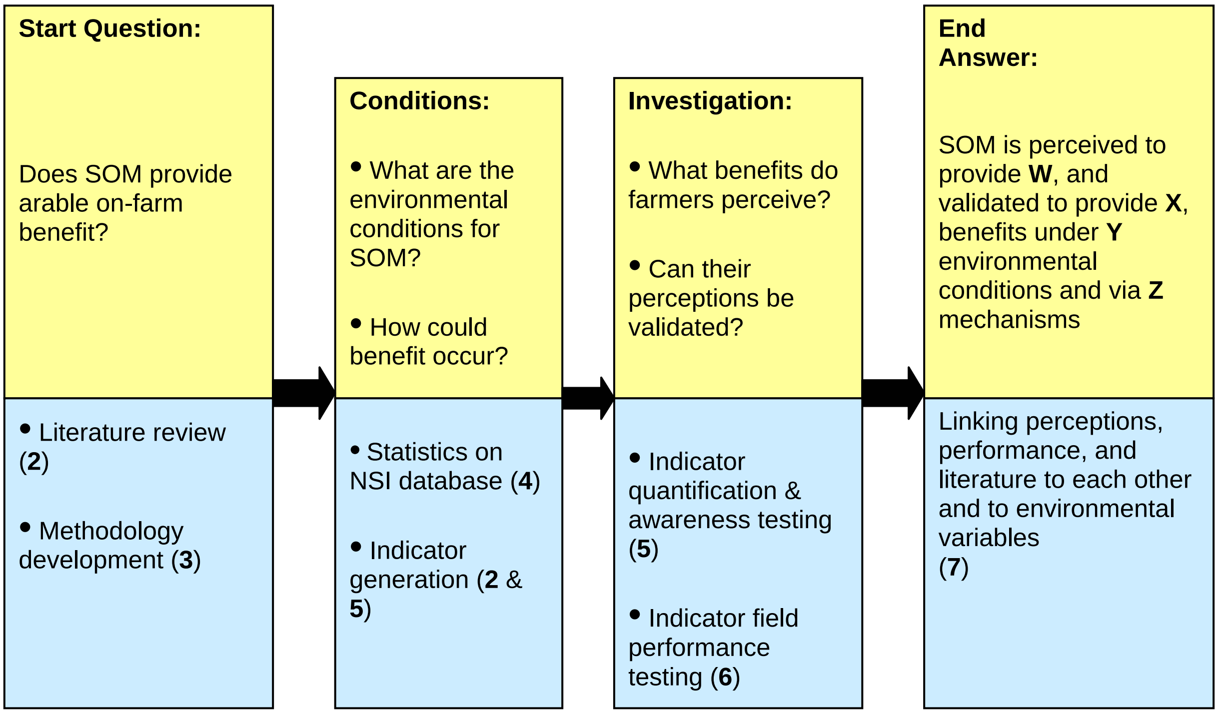
Integration of these objectives will provide an answer to the over-arching research question:

Does SOM, or its management, provide arable on-farm benefit, in England and Wales?

The results presented and discussed in this work, aim to extend understanding of the dynamics and value of SOM in farming systems, SOM-to-farming processes, and the interactions of these with environmental factors. It is hoped that the results will contribute to a sound scientific basis for future policy development.

1.2.1 Thesis structure

This work stands on three main pillars. The first is a determination of a conditional framework for SOC contents. It forms the physical geographical element of the research. The second pillar is the development of a quantified and qualified indicator list, i.e. indicators of how SOM impacts on arable farming. It forms the socio-economic backbone of the research. The third pillar is the development and application of a methodology linking the first two pillars. Integrative discussion of the pillars will provide answers to the over-arching research question (see section 1.2).



Start Question:	**Conditions:**	**Investigation:**	**End Answer:**
Does SOM provide arable on-farm benefit?	• What are the environmental conditions for SOM? • How could benefit occur?	• What benefits do farmers perceive? • Can their perceptions be validated?	SOM is perceived to provide **W**, and validated to provide **X**, benefits under **Y** environmental conditions and via **Z** mechanisms
• Literature review (**2**) • Methodology development (**3**)	• Statistics on NSI database (**4**) • Indicator generation (**2** & **5**)	• Indicator quantification & awareness testing (**5**) • Indicator field performance testing (**6**)	Linking perceptions, performance, and literature to each other and to environmental variables (**7**)

Figure 1.1 **Thesis route map with chapter numbers in parentheses. The top (yellow) part gives the route map in questions. The bottom (blue) part shows the matching thesis processes. NSI = National Soil Inventory. For a detailed thesis flow chart see Chapter 3.**

Figure 1.1 shows the route map of the research described in this thesis. A more detailed description can be found in Chapter 3. Chapter 1 briefly introduces relevant aspects of soil organic carbon. Chapter 2 reviews the scientific literature on SOC, focusing on environmental controls and impacts on the agro-production function. It is a reference base for all subsequent chapters. Chapter 3 reviews the possible approaches to deliver a sound answer to the critical question, and discusses the evidence to support the argument for the selected methodology. Chapter 4 determines which environmental factors govern SOC contents and defines SOC Indicative Management Ranges (SOCIMRs). Chapter 5 details the development of the qualified SOMFIE indicator list and discusses farmers' perceptions of SOM value. Chapter 6 analyses field performance of the indicators, and provides relevant case studies. Chapter 7 considers the fundamental research questions, discusses the significance of the results on an integrated level, and makes recommendations for future research and conditions for policy design.

CHAPTER 2

A REVIEW OF SOIL ORGANIC MATTER, ITS CONTROLS AND FRACTIONS, AND ITS IMPACT ON FARMING

> *"The humus problem of soil is very complex"*
>
> Kononova (1958)

This chapter gives a brief overview of SOM knowledge, with specific attention to controls on SOM dynamics. SOM impacts on the agro-production function are reviewed, and an initial indicator list is developed. Finally, experiential science is reviewed as an alternative information source.

2.1 SOM – DEFINITION AND DYNAMICS

SOM has been a major research topic throughout the history of soil science, which is generally regarded to have been ongoing for approximately a century (Sollins *et al.*, 1996; Six *et al.*, 2004), although the first chemical fractionation of SOM was made by Achard as far back as 1786 (Kononova, 1958).

SOM is a standard parameter (measured by SOC, see box 1.1) in nearly all soil, and soil-related research. Despite its ubiquitous application, a consensus definition of SOM is not apparent in the literature (Carter, 2001). Sollins *et al.* (1996) defined SOM as "all dead material in or lying on the soil that contains organic carbon (OC)". Schnitzer (1991), however, defined SOM as "the sum total of all OC-containing substances in soil". Two disparities are immediately apparent: i) the inclusion of living soil biomass (edaphon); and ii) the inclusion of the ectorganic profile (aboveground litter, fragmentation and humification layers). Other workers introduced soil processes in defining SOM; Oades (1988): "the mixture of recognizable plant and animal parts and material that has been altered to the degree that it no longer contains its original structural organization"; SSSA (1987): "the organic fraction of the soil exclusive of undecayed plant and animal residues." These definitions exclude living soil biomass and fresh OM additions to the soil.

A third disparity, or ambiguity, is presented by the term OC. In chemistry, 'organic carbon' is defined by the existence of hydrogen-carbon bonds. Therefore, soil compounds like calcium and magnesium carbonates (limestone or dolomite) are excluded and regarded as 'inorganic carbon'. SOM decomposition products can be organic or inorganic, e.g. CH_4 or CO_2.

Using a strict chemical definition, both carbohydrates and hydrocarbons are considered organic. Charcoal, coal, or soot fragments in soil also contribute to estimates of SOM contents. A relatively recent approach to SOM definition has been to differentiate between organic matter and its partly mineralized (i.e. incompletely oxidised) products, which are referred to as Black Carbon. Black C was found to constitute up to 35% of the total SOC content for five soils from long-term agricultural research sites across the U.S.A. (Skjemstad *et al.*, 2002). The water retention and nutrient supply functions of Black Carbon are believed to be unimportant, although it has been suggested that it may contribute to the fertility of highly weathered tropical soils, by increasing nutrient retention and improving soil structure (Glaser *et al.*, 2002).

SOM could be defined functionally as “the sum total of all organic carbon-containing substances in soil that are not Black Carbon”. Practically, however, methods for measuring only SOC, or only Black Carbon, have not been established. The recovery of Black Carbon is incomplete (particularly for particles larger than clay size), and highly variable between methods and soil types (Skjemstad and Taylor, 1999; Schmidt *et al.*, 2001).

2.1.1 SOM fractionation

When using its widest definition, SOM consists of both living and non-living organic matter: alive and dead soil flora and fauna (edaphon); alive and dead plant roots; and input from dead above ground biomass. In addition, it includes the metabolites of the edaphon and roots, and microbiological and chemical breakdown products of all non-living components.

Ever since soil science came into existence, attempts have been made to simplify this very complex SOM system. Traditionally, it would be divided (by chemical fractionation) into (i) humic and (ii) non-humic substances (see Section 2.1.1.1), although many other fractionation methods (including physical and biological fractionation) have been developed.

2.1.1.1 Humic substances

Humic substances (HSs) constitute between 60 and 80% (w/w) of the organic matter in most mineral soils (Schnitzer, 1989). Although HSs have been researched for a relatively long time, a consensus on their definition has not been reached (MacCarthy, 2001, and Hayes and Clapp, 2001). MacCarthy (2001) gives the following definition of HSs: "*an extraordinary complex, amorphous mixture of highly heterogeneous, chemically reactive yet refractory molecules, produced during early diagenesis in the decay of biomatter, and formed ubiquitously in the environment via processes involving chemical reaction of species randomly chosen from a pool of diverse molecules and through random chemical alteration of precursor molecules*."

Although HSs from different sources display remarkable uniformity in their elemental composition, it is not possible to write a molecular structure, or set of structures, that fully describes molecules of a humic substance (MacCarthy, 2001). Burdon (2001) looked at suggested structural formulae of HSs in the literature, and concluded that they are so different from each other that all could not be correct. The complexity of HSs is illustrated in Figure 2, which shows a two-dimensional representation of a possible structure for a HS. Chemical identification has been described as being "akin to identifying people in a stadium when all of them shouted out their names at once" (Hayes *et al.*, in Christopher, 1996).

It has been proposed that humic substances can be regarded as a "super mixture", i.e. a mixture having a degree of complexity and heterogeneity equivalent to that of a large ensemble of molecules where no two molecules are identical, where the molecules are essentially devoid of a regularly recurring, extended skeletal entity and display a high degree of molecular diversity (MacCarthy, 2001).

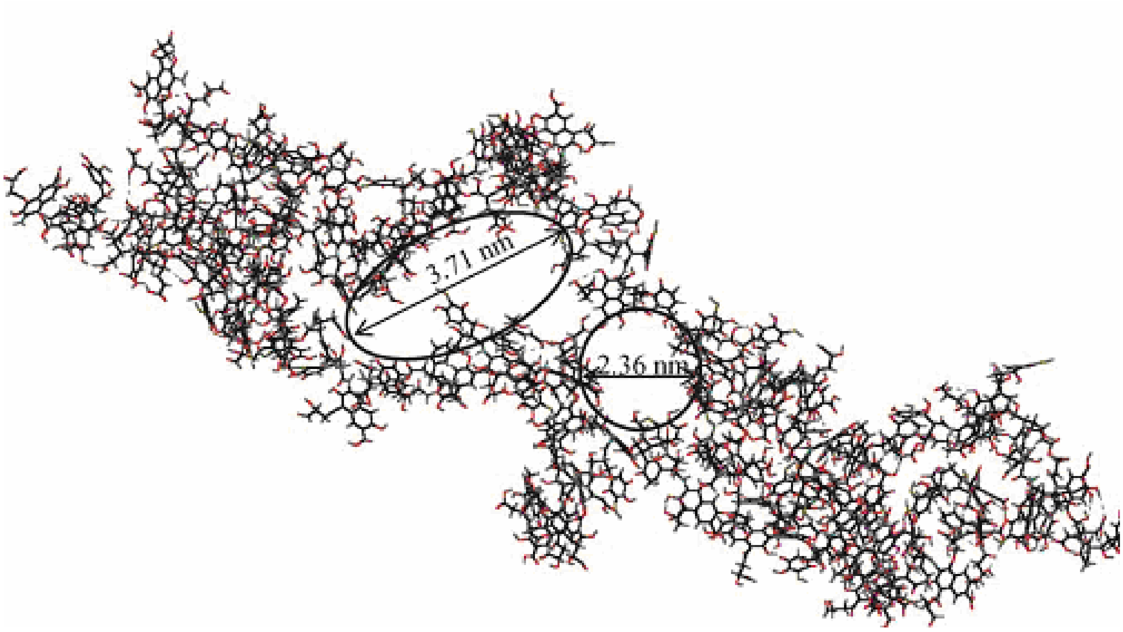


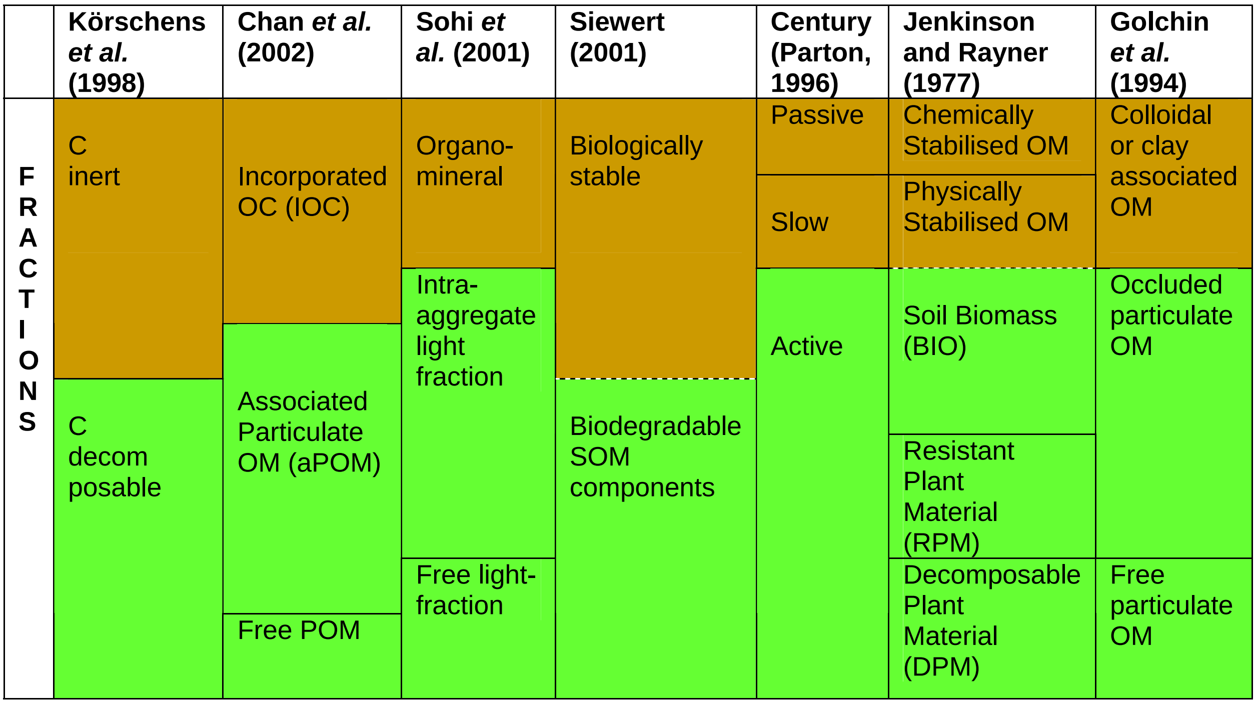
Figure 2.1 Possible structural formula of a Humic Substance (Alvarez-Puebla *et al.*, 2005)

The conversion rate of fresh OM to HSs is strongly dependent on its composition. Higher percentages of cellulose and lignin slow decomposition. A high content of N-containing compounds (e.g. proteins) enhances the rate of decomposition. Humification is more complete and faster with lower C:N ratios in fresh OM. In addition, external factors – such as temperature, soil moisture content, soil aeration (gas phase distribution), pH and the presence of nutrients – all affect decomposition rates.

2.1.1.2 Physical-chemical-biological fractionations

A wide array of SOM fractionation methods have been developed (see Appendix 2). These can most easily be divided into chemical, physical and biological methods, although some methods encompass more than one category. Different workers, employing different fractionation methods, use different terminology when describing SOM dynamics. Table 2.1 depicts the terminology discussed in this work. For simplification, green represents the 'active' and brown represents the 'stable' SOM. The relative borders between the fractions of the different schools indicate how they overlap. Where dashed lines are used the overlap with respect to other pools is uncertain.

Table 2.1 Terminology of different SOM pools by different schools. An estimation of relative pool sizes is shown.



	Körschens *et al.* (1998)	**Chan *et al.* (2002)**	**Sohi *et al.* (2001)**	**Siewert (2001)**	**Century (Parton, 1996)**	**Jenkinson and Rayner (1977)**	**Golchin *et al.* (1994)**
FRACTIONS	C inert	Incorporated OC (IOC)	Organo-mineral	Biologically stable	Passive	Chemically Stabilised OM	Colloidal or clay associated OM
					Slow	Physically Stabilised OM	
			Intra-aggregate light fraction		Active	Soil Biomass (BIO)	Occluded particulate OM
		Associated Particulate OM (aPOM)					
	C decom posable			Biodegradable SOM components			
						Resistant Plant Material (RPM)	
			Free light-fraction			Decomposable Plant Material (DPM)	Free particulate OM
		Free POM					

Jenkinson (1977) used ^{14}C labelled OM to investigate the decomposition of plant material in soil. Jenkinson and Rayner (1977) used those data in conjunction with SOM data from the Rothamsted classical field experiments to derive a model in which five pools of SOM are separated:

- Decomposable plant material (DPM); $t_{1/2}$ = 0.165 years
- Resistant plant material (RPM)); $t_{1/2}$ = 2.31 years
- Soil biomass (BIO)); $t_{1/2}$ = 1.69 years
- Physically stabilised organic matter (POM)); $t_{1/2}$ = 49.5 years
- Chemically stabilised organic matter (COM)); $t_{1/2}$ = 1980 years

Several dynamic SOM models identify different pools of SOM with different turnover times. Century is one of the most widely used and defines five organic matter pools, two representing litter and three representing SOM (see also Figure 2.2):

- An active fraction consisting of microbial biomass and metabolites (1.5 years turnover rate)
- A slow (intermediate or protected) fraction, representing stabilised decomposition products (25 years turnover rate)
- A passive fraction, representing highly stabilised, recalcitrant SOM (1000 years turnover rate) (Parton, 1996)

The ‘active’ fraction of the Century model roughly corresponds to the sum of the DPM, RPM and BIO pools of Jenkinson’s method. It is this ill-defined ‘active’ fraction, with its fast turnover rate, that is thought to be most important in determining performance of soil functions. The living biomass of soil organisms, other than plants, ranges from 0.2 to 4% of the total SOC (Tate, 1987 in: Amundson, 2001).

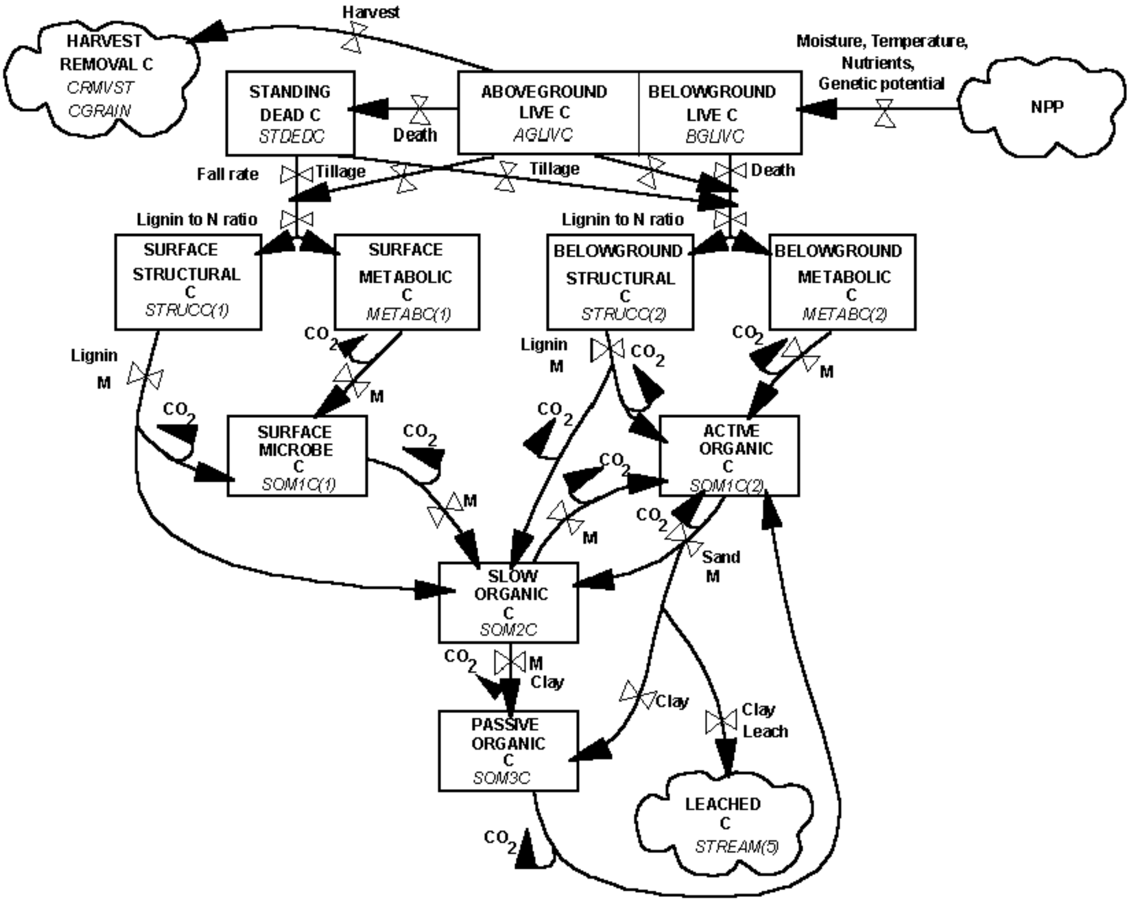


Figure 2.2 **Flow diagram for the SOM sub-model in Century (Parton, 1996)**

Given the different pools and dynamics of OM in the soil, it is self-evident that OM can be stored in the soil in different ways and for different periods of time. The residence time of SOM varies greatly between pools. The most stable pools are viewed as being largely 'inert' with long half lives. In the short term (decades) additional net OC storage or loss would be to or from the active pools. OM storage is dynamic, i.e. the larger the pool, the greater its yearly output will be and so the greater the corresponding input will have to be to maintain the size of the pool.

SOM is often seen as *the* most important primary factor determining soil quality/health, and measurements of total SOC contents have been used in many studies. Total SOC contents have been correlated with a wide variety of other soil parameters, ranging from soil water repellency (Doerr *et al.*, 2000; DeBano, 2000; Verheijen, 2001) to aggregate stability (Tisdall and Oades, 1982). However, coefficients of determination (r^2) between total SOC and soil functions are generally low. From the above, it is clear that there are many different definitions of active C, as well as methods to measure it.

Wallace (1994) quantified the active fraction: "Fifty percent, more or less, of the SOM from farm lands has been lost. The remainder is perhaps more resistant […] but that which has been lost was perhaps the most important half – it resisted erosion, it made soils permeable, it increased water holding capacity and it produced healthy crops".

The fifty percent, however, is a generalisation without sound scientific backing, and large variations can be expected for different ecosystems, soils and landuse. Loveland and Webb (2003) reviewed the literature on critical levels of total SOM and found little evidence of such critical levels, but recommended more research in 'active' SOM as this fraction might correlate better with other important parameters.

2.1.2 Environmental controls on SOM

The most important environmental controls on SOM and its dynamics are soil temperature and moisture regime, texture, and pH. The processes of control and their interactions are complex, which has been the topic of considerable debate in the scientific literature regarding the relative importance of environmental controls.

National soil survey data (Belgium, Germany, USA, UK, New Zealand) have been used to demonstrate that SOC content and soil clay content are correlated positively (Russel & McRuer, 1927; Spain *et al.*, 1983; Burke *et al.*, 1989; Loveland *et al.*, 1997; Körschens *et al.*, 1998; Sparling *et al.*, 2003; Lettens *et al.*, 2004). Experimental data corroborate this relationship (Freitag, 1980; Körschens *et al.*, 1980; Parton *et al.*, 1987; Hassink, 1997; Rühlmann, 1999). A physical stabilisation mechanism, as discussed in Section 2.1.1, is the most accepted theory for explaining this correlation. Verberne *et al.* (1990) modelled four fractions of SOM and found that the mineralization rate in fine-textured soils is slower than in coarse textured soils. It was concluded that in fine textured soils a larger proportion of the SOM may be protected physically.

In addition to clay contents, relationships between SOC and clay mineralogy have also been found. Powers and Schlesinger (2002) investigated the relationships between SOC and environmental variables for 35 forest plots in a diverse landscape in northeastern Costa Rica and concluded that a larger proportion of the variation in SOC contents was explained by clay mineralogy than by clay contents, or other environmental variables. Wattel-Koekkoek *et al.* (2003) found significantly different turnover times (by determining the ^{14}C age) of SOC associated with kaolinite (360 years, n=6) to smectite (1,100 years, n=6) in savanna systems.

SOC contents have been shown to be related positively to precipitation and negatively to temperature. Combinations of these two factors vary widely and can have complex impacts on SOC dynamics. The relative importance of precipitation and temperature, and more specifically the potential positive feedback of a warming climate on SOC decomposition rates have been the topic of scientific debate (Jenkinson *et al.*, 1991; Giardina and Ryan, 2000; Knorr *et al.*, 2005; Powlson, 2005). A consensus on this matter has not been reached.

Nichols (1984) studied 65 equally spaced pedons in the Southern Great Plains. Land use was grassland, precipitation ranged from 330 to 1140 (mm yr^{-1}) and mean annual temperature from 14 to 23.3 (°C). The simple linear regression of mean annual temperature on SOC was not significant. The simple linear regression of clay content and SOC content was highly significant (correlation coefficient – $r = 0.86$, $p<0.001$). The relationship of percent clay and mean annual precipitation with organic C was significant (coefficient of multiple determination - $R^2 = 0.90$, p not given). The multiple linear regression equation was:

$$\%OC = -0.50 + 0.0098 \text{ clay} + 0.06 \text{ mean annual precipitation} \qquad [2.1]$$

Spain (1983) performed a multiple regression analysis of SOC with environmental variables on a database of 3652 compiled soil records in Australia. For all climatic regions, precipitation showed the highest coefficients of determination of all environmental variables (tropical: R^2=36.5; sub-tropical: R^2=33.7; cool temperate: R^2=51.8, p not given). Temperature correlated weakly negatively with SOC, and the cause of this was suggested to be a restricted range of temperature classes in some regional groupings.

Burke *et al.* (1989) analysed statistical relationships between SOC and climate for 500 grassland and 300 cultivated soils in the National Soil Survey pedon database in the Central Plains, USA. Similarly to Spain (1983), they found SOC contents to be correlated negatively to temperature ($R= -0.827$, $p<0.0001$) and positively to precipitation ($R=0.127$, $p<0.0001$). Temperature was the most significant variable for both grassland and cultivated soils.

Soil pH has also been shown to influence SOC contents. Motavalli *et al.* (1995), and Muneer and Oades (1989), showed that Ca might be a more important factor controlling SOC decomposition rates than clay in limestone-derived soils. Calcium carbonate additions to soil (liming) have been shown to increase SOC contents by amelioration of Al and Mn toxicity (and/or alleviation of Ca deficiency) and thereby increasing OM returns from above and below ground biomass, when sufficient amounts are applied in the long-term (Haynes and Naidu, 1998). Spain (1983) showed that pH was equally strongly correlated to SOC contents as temperature, for cool temperate regions.

2.1.3 Management controls on SOM

SOM increases when OM inputs exceed OM outputs, i.e. when assimilation exceeds mineralization. There are three main ways by which management may increase SOM contents: i) increased OM inputs, ii) reduced tillage, and iii) decreased drainage.

i) OM inputs to soils are provided by crop roots; crop residues; manure applications (often partly generated by animal consumption of the crop residues); and application of off-farm sourced OM (Table 2.2). The rate of OM inputs by roots and crop residues is partly determined by crop management. Different crops have very different root structures and below ground and above ground biomass. Nitrogen fertilisation can increase SOC contents by increasing Net Primary Production (Alvarez, 2005) and OM inputs.

ii) Apart from adding OM to soil directly, soil and crop management can enhance the OM content of soil by modulating SOM dynamics to alter equilibrium SOM levels. Reduced tillage systems increase SOM contents by decreasing aeration (related to soil structural disturbance) and thereby decreasing microbial decomposition rates. Reduced tillage systems vary from shallow inversion tillage to discing and no-till systems. Several workers have shown that less intense tillage results in a higher SOM content in a humid, temperate climate (Dick, 1983; Franzluebbers *et al.*, 1994; VandenBygaart *et al.*, 2003), although Franzluebbers and Arshad (1996) found that not to be the case for soils in a cold, semi-arid climate.

iii) Section 2.1.2 discussed the relationship between precipitation and SOC contents. Wetter soils are less aerated and microbial decomposition rates are reduced under anaerobic soil conditions. Precipitation has a major but not the only influence on the soil moisture regime. In agricultural systems this is 'managed' (e.g. by installing drainage and mole ploughing, seasonal flooding, or groundwater regulation).

Table 2.2 Examples of OM inputs, C:N ratios, and occurrence

Direct OM inputs in agricultural soil	Type	C : N	Occurrence
crop residues (stubble)	F	M	very common
crop residues (straw)	F	M	very common
farm Yard Manure (FYM)	PD	L	very common
FYM mixed with straw	F/PD	L/M	very common
slurry	D	M	common
ley grass	F	L	common
poultry manure	PD	L	small scale
sewage sludge	D	M	small scale
paper pulp	PD	L	small scale
waste from the food industry	PD	H	small scale
office waste paper	D	H	experimental

F = fresh, PD = partly decomposed, D = decomposed, M= moderate, L = low, H = high

The capacity of soil and crop management to increase OC contents in arable soils has been reviewed in relation to soil quality (Reeves, 1997) and SOC sequestration (Franzluebbers, 2005, Martens *et al.*, 2005). For the southeastern USA a SOC sequestration rate of 0.42 (± 0.46) t ha^{-1} yr^{-1} was found for 62 paired-field experiments with conventional and no-tillage treatments (Franzluebbers, 2005). The large standard deviations indicate substantial variation in sequestration rates, potentially caused by environmental and previous land use factors. Martens *et al.* (2005) reviewed the impact of tillage practice on SOC contents in the dry (i.e. potential annual evaporation exceeds annual precipitation) southern USA and found a lower SOC sequestration rate of 0.28 t ha^{-1} yr^{-1} for reduced tillage compared to conventional tillage.

Environmental variables may have substantial impact on the effectiveness, or success, of SOM management aimed at increasing SOC contents. This was illustrated by Stumpe *et al.* (2000) who reported low SOM build-up with FYM applications on a sandy loess soil covering glacial till in the central German arid region. Fifty years of 30 t ha^{-1} y^{-1} of FYM application increased SOM by only 0.2% at 0-20 cm depth, and 0.1% at 20-40 cm depth.

2.1.4 SOC ranges

Understanding of environmental and management controls on SOC dynamics should enable formulation of potential, or attainable, ranges of SOC for different land-soil combinations. SOM fractionation methods (see Section 2.1.1) could provide greater insight into SOC dynamics and SOC ranges, although method standardisation appears the missing factor for progress. SOC ranges have been explored by statistical interpretation of soil sample analyses (see Table 2.3); by establishing and running SOC models; and by gathering ‘expert opinion’.

There appears to be a baseline of SOC contents in soils closely related to the clay (< 2 μm) or the clay + (fine) silt (< 6.3 or 20 μm) fractions. Körschens (1980) determined the baseline (slope - m= 0.047) using 11 long-term field experiment soils and numerous arable soils. A later paper by Körschens *et al.* (1998) produced a different lower limit (m=0.068) by plotting the SOC content against the clay content of the 'nil plots' (not receiving fertilisers) of 21 long term field experiments. In both cases the particle size fraction <6.3 μm was used.

Table 2.3 Overview of SOC limit estimates relative to clay contents.

Publication	Slope (m) of lower limit	Slope (m) of upper limit	Related soil particle size (μm)	n	Related environmental conditions	Sample, landuse and region
Körschens (1980)	0.04	ND	<6.3	11	Loess soils and temperate continental climate	Long term experimental 'nil' plots (Germany)
Körschens *et al.* (1998)	0.068	ND	<6.3	21	Loess soils and temperate continental climate	Long term experimental 'nil' plots (Germany)
Körschens *et al.* (1998)	0.035-0.045[a]	0.035-0.05[a]	<6.3	ND	Loess soils and temperate continental climate	ND
Hassink (1997)	0.037 (0.04[b])	ND	<20	39 (32[b])	Temperate and tropical climates	Uncultivated and grassland experimental sites (worldwide)
Loveland *et al.* (1997)	0.04	ND	<2	1261	Variety of soils and range of precipitation in temperate climate	Soil profile survey of arable and grassland soils on commercial farms (England and Wales)
Freytag (1980)	0.047	0.069	<2	numerous		Germany

[a]=determined from published data, [b]=excluding Australian soils, ND=Not Determined

Loveland *et al.* (1997) produced a minimum line (m=0.04), based on a statistical estimation of soil profile data (n=1261) for England and Wales (Figure 2.3). They made a comparison between the SOC content of the Broadbalk exhaustion plots at IACR-Rothamsted (ca. 1% SOC) with that predicted by the lower limit estimate, using the measured clay contents of representative A horizons of Broadbalk soils. The predicted SOC contents of 1.01% and 1.09% were remarkably close to the measured value.

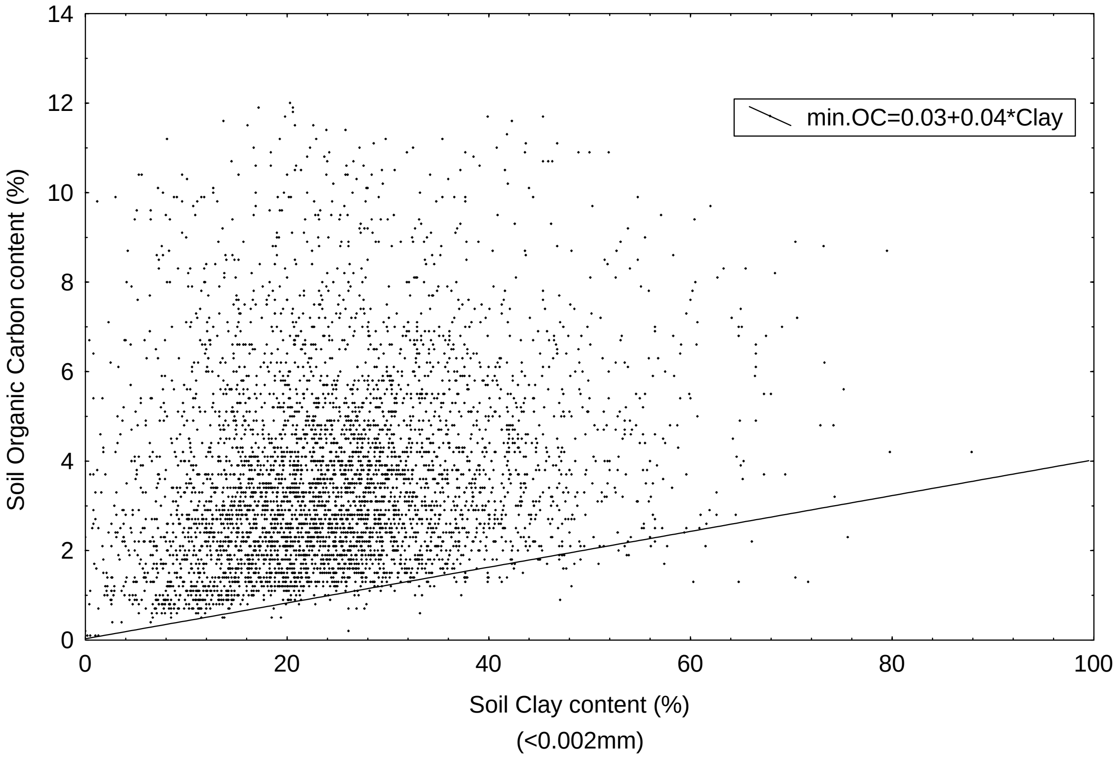


Figure 2.3 **Distribution of soil organic carbon to clay content in England and Wales (Loveland *et al*., 1997).**

Hassink (1997) fitted a regression between SOC (in the particle size fraction < 20 μm) and the percentage of soil particles < 20 μm of 39 sites from uncultivated and grassland soils (of research farms) of temperate and tropical regions to estimate the capacity of soils to preserve SOC by its association with clay and silt (m=0.037).

Körschens *et al*. (1998) also used analytical data for 12,000 farm soils, together with experiments on the ameliorative effect of organic fertilisers, to produce guideline values for the optimal SOM content of loamy and sandy soils without groundwater influence (Table 2.4). The lower limit was set at 0.5 % decomposable OM, the higher limit at 0.9 % decomposable OM. From the work of Körschens *et al.* (1998) lower limit slopes were determined to allow comparison with other studies. The slopes ranged from 0.035 to 0.05 (Table 2.4).

Considering the methodological differences employed (e.g. survey and experimental sites, temperate and tropical climates, various particle sizes), the slopes of the lower limits are remarkably similar, indicating a burgeoning consensus regarding the magnitude of the relationship between lower SOC content limits and fine earth measurements (i.e. clay and -very- fine silt). The most accepted causal mechanism for this relationship is physical stabilisation of SOC by clay and silt (see Section 2.1.2), although chemical and biological stabilisation are likely to be related to texture.

Two publications report a SOC range (both upper and lower limits) interpreted as a 'desirable range'. Körschens *et al.* (1998) calculated the upper limit by adding an amount theorized to be 'needed' (0.5 to 0.9% %SOC) to the lower limit. The theorized amount was an interpretation of a combination of experimental and survey data (Table 2.4). Statistical determination of both upper limits and lower limits on the same data populations (surveys and experimental sites) is needed to provide environmental representation. Freytag (1980) estimated the lower limit (m=0.047) and upper limit (m=0.069) of approximately 170 soils from the Halle-Leipzig area in Germany. Statistical significance was not determined, as the lower limit was constructed by forcing a straight line through zero and increasing the slope until a visual 'jump' in the frequency of data points falling below the line was observed. The upper limit was constructed by adding experimentally derived indications of desirable 'active' SOC quantities to the lower limit. Both approaches have a high degree of arbitrary terms and do not necessarily represent reality.

Table 2.4 SOC 'guideline values' (Adopted from Körschens *et al.*, 1998)

	Sandy soils		Loamy soils	
Clay + fine silt %	**upper value**	**lower value**	**upper value**	**lower value**
4	1.5	1.0		
5	1.5	1.0		
6	1.5	1.0		
7	1.5	1.0		
8	1.6	1.1		
9	1.7	1.2		
10	1.7	1.2	2.0	1.3
11	1.8	1.3	2.1	1.4
12	1.9	1.4	2.2	1.4
13	1.9	1.4	2.2	1.5
14	2.0	1.5	2.3	1.6
15	2.1	1.6	2.4	1.7
16	2.1	1.6	2.5	1.8
17	2.2	1.7	2.6	1.8
18	2.3	1.8	2.7	1.9
19	2.3	1.8	2.8	2.0
20	2.4	1.9	2.8	2.1
21	2.5	2.0	2.9	2.1
22	2.5	2.0	3.0	2.2
23	2.6	2.1	3.1	2.3
24	2.7	2.2	3.2	2.4
25	2.8	2.2	3.3	2.5
26			3.4	2.5
27			3.4	2.6
28			3.5	2.7
29			3.6	2.8
30			3.7	2.8
31			3.8	2.9
32			3.9	3.0
33			4.0	3.1
34			4.1	3.2
35			4.1	3.2
36			4.2	3.3
37			4.3	3.4
38			4.4	3.5

Sparling *et al.* (2003) examined three approaches for defining 'desired SOM contents': i) statistical investigation of the New Zealand soil database, ii) model predictions (using Century) and iii) an expert panel approach. They focused on four soil orders only, which had limited observations (ranging from 5 to 31 for each soil order) thereby disabling comparison to larger scale investigations.

However, a clear disparity was found between the statistical and modelling approach on the one hand and the expert panel approach on the other hand. The expert panel (consisting of 24 scientists), without being aware of the other methods' results, expressed the view that minimum C contents should be allowed to be a factor 2.5-4 smaller than suggested by the statistical and modelling methods, without seriously compromising production. For environmental rather than production criteria the panel's recommendations were approximately doubled.

2.2 SOM'S IMPACT ON THE AGRO-PRODUCTION FUNCTION

If on-farm benefits from SOM are to be investigated then their influence on the agro-production function needs to be formalized. The main soil functions influenced by SOM, which are important to the agro-production function, are:

- Water retention
- Soil structural stability (aggregate stability, micro/macro aggregate formation and stability)
- Soil porosity (through soil meso and macro fauna)
- Nutrient retention
- Nutrient source for vegetation by decomposition (mineralization).

The literature indicates that on-farm economic impacts of higher SOM levels can be both beneficial and deleterious. The same is true for off-farm economic impacts (externalities). True economic impacts can be grouped by mode of impact, and are linked to different agro-production sub-functions, as summarised in Table 2.5. Some sub-functions have multiple or overlapping modes of impact: 'Seed rate' could also be classed as 'crop-related', however, because of its conditional relationship to yield (no yield with a seed rate of zero) it was classed as being a direct impact on yield. Seed-bed preparation is crop dependent at crop type level (combinable or root crop), but relatively independent to crops of the same type and therefore classed as 'non-crop-related.

Table 2.5 SOM impacts on agro-production sub-functions

Mode of impact	Agro-production sub-functions
direct impacts of SOM on yield	yield, seed rate
crop-related impacts of SOM	crop establishment, fertiliser use, disease and chemical use
non-crop-related on-farm impacts of SOM	workability/trafficability, seedbed preparation, irrigation
external impacts of SOM	erosion, groundwater quality, surface water quality, carbon sequestration

The magnitudes of these impacts vary greatly between different studies, reflecting large differences in methodologies and systems examined. Both qualitative and quantitative approaches have been applied, different variables have been considered and compared (e.g. different environmental units), and potentially, yield results have been masked by fertiliser inputs, or by the use of total carbon rather than an 'active' fraction of soil carbon (see Section 2.1.1).

Each agro-production sub-function has one or more possible SOMFIE indicators. SOMFIEs are defined as indicators of **S**oil **O**rganic **M**atter on-**F**arm **I**mpact on **E**conomics. Impacts of SOM on arable farming are often tacit, unclear, or not explored. SOMFIEs offer a way to make tacit ideas tangible; they aid exploration of ideas and help to crystallise these into more clearly defined propositions. SOMFIEs may represent both positive and negative impacts of economic or other types of value.

SOMFIEs have been known to land users for decades (or centuries) in terms of experience (e.g. reflected in farming systems) and the relative importance of

SOMFIEs has changed over time according to changes in socio-economics, land use, societal demand, and technology. Some SOMFIEs may have disappeared completely (and others appeared) during these changes. Step-changes have been delivered by technological progress during the 18th, 19th and 20th century (Brunt, 2004). Figure 2.4 shows the change in crop grain yields in the Rothamsted experimental plots over the last ca. 150 years against the introduction of rotational cropping, inorganic fertilizers, new crop varieties, and biocides.

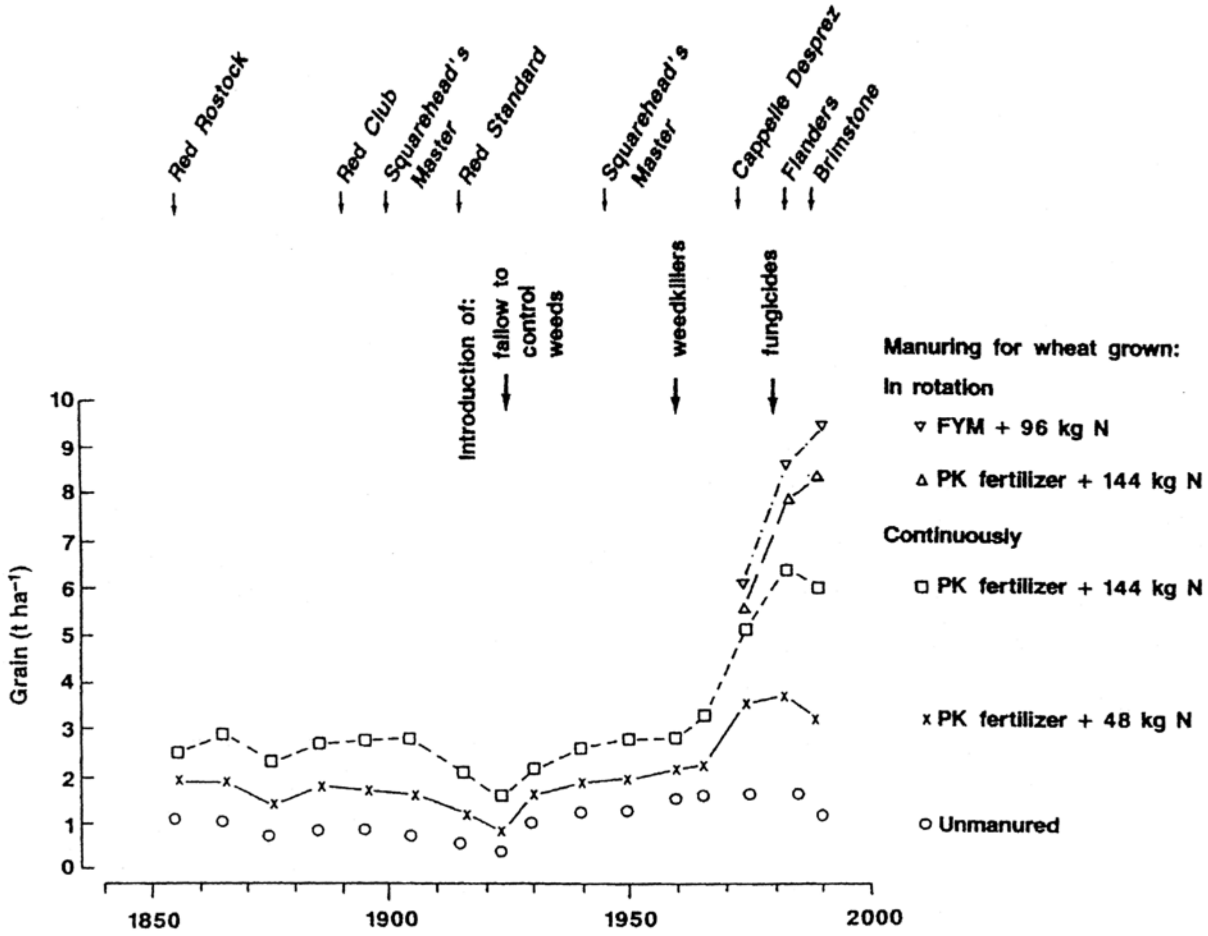


Figure 2.4 **Yields of winter wheat grown on Broadbalk, Rothamsted, from 1852 to 1990 with fertilizers and with farmyard manure, showing the effects of changing cultivars and the introduction of weed control, fungicides, and crop rotations to minimise effects of soil-borne pathogens. Reprinted from Johnston (1994)**

It is likely that the relative, and in some cases absolute, SOMFIE importance changed according to the step changes in agriculture, i.e. some SOMFIEs may have disappeared, others may have been introduced, or have become stronger or weaker. Although SOMFIEs have been known for probably as long as man has worked the soil (i.e. since the first Agricultural Revolution ca. 12,000 years BP), the knowledge was tacit and little quantified. A more formal description is proposed below (see Sections 2.2.1 to 2.2.4, and Table 2.7 for an overview).

2.2.1 Direct impact of SOM on yield

Evidence for active SOM increasing yield can be inferred from the correlation between FYM application and yield. When FYM is introduced to soil (ploughed in) it enhances the active fraction of SOM, and provides nutrients (mostly N) to the following crop. After the fertilising effect, it is the build-up of another active C pool (e.g. intra-aggregate) over several years (or decades) that is thought to improve soil fertility, due to greater background N-mineralization and micronutrient release, better soil structure, possibly disease suppression, and greater water retention leading to less water stress on crops. Research on semi-arid ecosystems has shown water availability to be a limiting factor in crop productivity, and crop yields have been correlated to dry growing seasons. Diaz-Zorita *et al.* (1999) performed stepwise regression analysis between wheat yields and soil properties and found different relationships in different years. In a year without a water deficit, N and P influenced yield, in drought years however, yields were correlated to water availability and OM as shown in Equations 2.2 and 2.3 respectively:

$$\text{Yield (1992)} = 183.1 + 2.05 \cdot \text{WR} + 120.7 \cdot \text{TOC} \qquad R^2 = 0.58,\ n = 25,\ P < 0.01 \qquad [2.2]$$

$$\text{Yield (1994)} = 362.0 + 4.8 \cdot \text{WR} + 49.5 \cdot \text{TOC} \qquad R^2 = 0.59,\ n = 71,\ P < 0.01 \qquad [2.3]$$

with yield in kg ha^{-1}, water retention as 'WR' (g kg^{-1}) and total OC as 'TOC' (g kg^{-1}).

An impact of these magnitudes of OM on yields is not to be expected in temperate ecosystems, although drought stress may occur in a substantial part of arable England/Wales in the summer months, i.e. before cereal harvesting (see Soil Water Regime, Section 2.2.2).

Bauer and Black (1994) investigated soils in temperate North America and found that an additional tonne of OM per hectare led to a 15.6 kg ha^{-1} increase in grain yield. However, as Loveland and Webb (2003) point out, in two of the four years fertiliser-N applications masked the effects of SOM on yield.

Stumpe *et al.* (2000) investigated the effects on yields of total SOM and FYM for a sandy loess soil over glacial till in the central German arid region. Their main conclusion was that differences in total C content do not affect yields on soils in good physical condition if there is an appropriate compensation by mineral-N additions (see also Fertiliser use, Section 2.3.2).

Grace *et al.* (1995) found a gradual increase in grain yields from the 1960s in the continuous wheat plots at the Permanent Rotation Trial in South Australia. With 9-year increments starting from 1955, the yields were: 0.52, 0.65, 0.92, and 1.09 t ha^{-1}. They hypothesise that this was the result of a gradual build-up of light fraction organic material, although this was not quantified.

2.2.2 Crop-related on-farm impact of SOM

CROP ESTABLISHMENT

Stibbe and Terpstra (1982) researched the effect of penetration resistance on emergence and early growth of silage maize in a laboratory experiment. Root penetration is related to soil strength, which for a given bulk density, increased as the matric potential decreased (Taylor and Gardner in: Stibbe and Terpstra, 1982). Penetration resistance below and beside the planting slot increased linearly with the time between planting and emergence of 50% of the number of seeds planted. Percentage of emerged seedlings, increase in plant height and dry matter yield during early growth decreased linearly with increasing penetration resistance. Because of the short growing season (6 months), quick emergence and rapid early seedling growth are thought to be important to obtain optimal dry matter yields. The effect of SOM was not investigated in this work, but SOM can influence penetration resistance through its impact on soil bulk density (dilution effect, see Section 2.2.3).

The amount of solar radiation that reaches the soil surface (as affected by slope and vegetation cover) and the specific heat of soils, largely control the rate at which soils warm up in the spring, and so the emergence of seedlings. Soil colour and soil moisture content are the main factors determining the specific heat of soil. For pure water the specific heat is about 4.18 J g^{-1} K^{-1}; that of dry soil is about 0.8 J g^{-1} K^{-1}. Therefore, although soils high in SOM content are usually dark in colour, the associated extra energy absorption is often countered by a high water content, which causes the soil to warm up much more slowly (Brady, 1990).

FERTILISER USE

As discussed in Section 2.2.1, the application of organic amendments provides N for crops. Most farmers apply less inorganic N in years when they apply organic amendments. Stumpe *at al.* (2000) found possible inorganic-N reductions of > 60 kg ha^{-1} for root crops, and about 20 kg ha^{-1} for cereal crops, for FYM application rates of 40 t ha^{-1} yr^{-1}.

In practice many farmers simply apply standard amounts (as in the Code of Good Agricultural Practice for the Protection of Water, MAFF, 1998), without considering differences in OM levels. However, ‘precision farming’ systems do take account of OM differences.

An adverse effect on fertiliser use occurs when SOM enhances soil water repellency (WR); applied fertiliser nutrients are leached through preferential flowpaths, resulting in both costs to the farmer and to the environment. Although the relationship between SOM and WR is not straightforward, many workers have reported a positive correlation between SOM content and soil WR. The extent of soil water repellency is not limited to semi-arid ecosystems (Ritsema and Dekker, 1996) or long dry spells in temperate ecosystems. Recent research has shown water repellency to occur at a relatively large soil moisture range (De Jong et al, 1999 and Verheijen, 2001). Although the mechanisms of soil water repellency in agricultural soil are well studied and modelled, the magnitude of the impact on nutrient leaching is poorly documented.

DISEASE AND CHEMICAL USE

Many different types of diseases are encountered in agricultural systems, ranging from mild forms of leaf spot to take-all disease in winter wheat, which causes 5-20% yield losses in half of UK wheat crops– costing farmers up to £60 million yearly (HGCA, topic sheet 49, 2001). The causative agents can be viruses, fungi, bacteria, protozoa, nematodes and insects. A first practical division is between soil-borne and air-borne diseases. SOM would be expected to have most influence on soil-borne diseases, although there may be an indirect mechanism of SOM influencing the impact of air-borne diseases through effects on crop health and associated disease suppression characteristics.

Focusing on the soil-borne diseases, many papers in the literature investigate the effect of one particular pathogen. Although useful in explaining particular mechanisms of disease suppression, this does not answer the more general question of SOM's disease-suppressive effects. Drinkwater *et al.* (1995) used a system-level approach (whole-farm level) to compare conventional (CNV) and organic (ORG) systems with respect to disease. They found the species richness of predators and parasitoids to be on average 75% greater in ORG systems. The ORG soils had slightly greater SOM levels, which they ascribed to increases in labile C pools, since indicators of active C (N mineralisation potential and microbial activity) were three times greater in ORG than in CNV soils. These results indicate that soil biological processes may compensate for reductions in pesticide use.

Akhtar and Malik (2000) reviewed the role of organic soil amendments in the biological control of plant-parasitic nematodes and found the effectiveness of nematode suppression by organic amendments to depend on the amount of amendment used, C:N ratio, and time of decomposition. Organic amendments with C:N ratios < 20 release NH_4^+ or NO_3^- during mineralization, which can be taken up by plants, whereas C:N ratios > 20 lead to temporary soil N immobilisation in microbial tissue. They list several mechanisms for disease control of which the release of toxic compounds (certain nemato-toxic proteins) and/or the modification of the soil microflaura are most relevant. Tilston *et al*. (2002) investigated the effect of OM compost types on disease suppression in agricultural crops. Disease severity of *Fusarium culmorum* (one of several *Fusarium* species to cause Fusarium ear blight in wheat) was analysed relative to compost chemistry, which showed nitrate to mainly suppress disease.

Rodgers-Gray and Shaw (2000) found another mechanism behind disease suppression. Contrary to the suggestion that straw (as crop residue) is a source of inoculum that exacerbates diseases, they found that at the end of the season, winter wheat plants from straw-treated plots had consistently reduced *Septoria tritici* blotch, powdery mildew, brown rust and root rot. They also found a significantly higher leaf silica content in straw–treated plants, late in the season ($P < 0.001$) and suggested an interaction between silicon nutrition (from SOM) and secondary resistance. However, only one site was studied and the results could depend on soil type.

Locke and Bryson (1997) review herbicide interactions with plant residues. They state that organic carbon, pH, texture, nutrient status, soil moisture, and microbial populations play an important role, and name four mechanisms:

1. actual chemical or microbial transformation of the herbicide
2. dissipation, i.e. disappearance of herbicides from a soil's system
3. persistence, i.e. the longevity of a herbicide in soil
4. carry-over, i.e. concentrations of herbicide that are phytotoxic to a following crop.

Herbicide sorption on plant residues (in reduced tillage systems) may render herbicides less bioactive or physically separate from soil, thereby disabling the herbicide's potential capacity to inhibit weed emergence in the soil. SOM may increase the residence time of herbicides in soil, although this also depends on the half-life of the herbicide and the system of soil management. In contrast, for some herbicides, retention by organic residues and soil components at the soil surface can increase volatization, and photodecomposition, and reduce persistence.

Lock and Bryson (1997) conclude that concentrations of herbicide in runoff are sometimes higher for reduced tillage (more OM near soil surface), but in terms of total herbicide loss, lower runoff volume from reduced tillage soils tends to offset the higher herbicide concentrations.

Pesticides can be bound to SOM through sorption (Van der Waals forces, hydrogen bonding, hydrophobic bonding), electrostatic interactions (charge transfer, ion exchange or ligand exchange), covalent bonding or combinations of these reactions (Bollag *et al.*, 1992). The mineral part of soil can also bind pesticides, although this is ignored by the widely used organic-matter-normalised-sorption coefficients (K_{om}). Sheng *et al.* (2001) found that smectite clays can contribute as much as SOM to pesticide retention in soil. This review indicates that benefits of lower pesticide requirements from enhanced biological activity in soils with higher SOM contents may be offset by increased pesticide retention. Furthermore, investigations into pesticide retention capacity in relation to SOM need to control for clay mineralogy in their experimental approaches.

Most research on disease suppression is performed on experimental plots, with associated environmental conditions. Extrapolation of results to other environmental conditions is not straightforward as disease suppression characteristics are known to vary with environmental variables. Gill *et al.* (2000)

found that finer textured soils suppressed root rot of wheat seedlings better than coarse textured ones. Soils of several clay contents were infected with root rot and dry root weights were measured as an indicator for disease suppression. Dry root weights (for wheat) in soils infected with root rot, of 0.9, 12 and 24 %clay were 91, 55 and 28% lower than in control uninfested plots ($P < 0.003$). Persson and Olsson (2000) found a relationship between clay mineralogy and disease suppression. Suppressive soils contained a higher ratio of vermiculite-smectite to illite-kaolinite (Figure 2.5). Only one pathogen – *Aphanomyces* root rot – was researched.

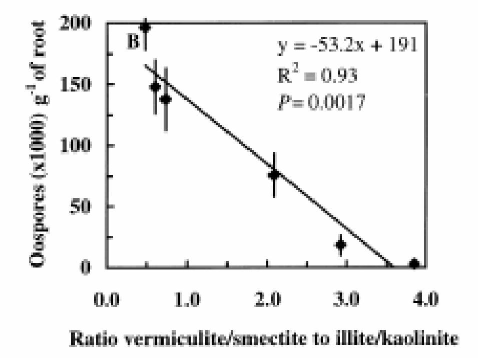


Figure 2.5 Relationship between clay mineralogy and disease suppression (Reprinted from Person and Olsson, 2000)

SOIL WATER REGIME

Hudson (1994) stated that the consensus view of the relationship between SOM and available water content (AWC) is incorrect. His review of the literature suggests that many studies failed to demonstrate a relationship between SOM and AWC because they were not designed properly. Effects were masked by variations in soil texture, stone content, and other properties that are known to affect AWC. In order to minimise these variations, Hudson performed moisture retention analysis using different moisture retention values on several textural groups. Relatively high coefficients of correlation were found. The results show that within all textural groups, as SOM increased from 1 to 3% the AWC approximately doubled. When it increased to 4% it accounted for more than 60% of the total AWC in all three textural groups (see Equations 2.4 – 2.6).

Sand

$\text{AWC} = 3.8 + 2.2\,(\text{OM}) \qquad r = 0.79,\ p=0.0001,\ n = 20$ [2.4]

Silt loam

$\text{AWC} = 9.2 + 3.7\,(\text{OM}) \qquad r = 0.58,\ p=0.0001,\ n = 18$ [2.5]

Silty clay loam

$\text{AWC} = 6.3 + 2.8\,(\text{OM}) \qquad r = 0.76,\ p=0.0001,\ n=21$ [2.6]

With available water content (AWC) as water held at 10 kPa for sands and 33 kPa for other textures minus the water held at 1500 kPa, and organic matter (OM) as gravimetric percentages.

Loveland and Webb (1997) reviewed critical thresholds of SOM and concluded that soil water holding capacity (WHC) at various suctions is influenced by SOM, but often only contributes <10% to the known variance of this property, especially at large suctions.

Much of the improvement in WHC is attributed to active SOM (Loveland and Webb, 1997). Theoretically, a higher active C content should diminish the necessity for irrigation, or reduce crop water stress – and therefore enhance disease suppression and yields. This should be most apparent in rainfed agriculture. In irrigated agriculture, possible reductions in irrigation could cut costs substantially.

Droogers *et al.* (1997) argue that, apart from measuring the "available" water, it is also important to look at its "accessibility". Available water is often defined as the amount of soil water between field capacity and wilting point. It is not, however, likely that all "available" soil water is "accessible" to roots, especially when water is held in coarse aggregates which are strong enough to impede root growth. They found that OM played no role in the water accessibility: sites with 1.7 and 5.0% SOM showed 95 and 94% accessibility, where the site with 3.0% SOM showed 68% accessibility. This study shows that the effect of soil management on soil water dynamics can outweigh SOM effects. Since the three sites were chosen on their soil management – in the same soil series, it is not known what the relationship between SOM and water accessibility is within one management type on one soil series.

Under relatively wet conditions, SOM could provide a benefit by better drainage because of a better soil structure (see Section 2.3.3). Veron *et al.* (2002) correlated above ground net primary productivity (ANPP) of wheat (from remotely sensed data) with mean annual precipitation (MAP), in the Argentine Pampas. The ANPP decreased as MAP increased. Precipitation variability accounted for 49% of wheat ANPP. SOM was not considered in this study, but could have an impact through its role in the soil water regime.

2.2.3 Non-crop-related on-farm impact of SOM

Droogers *et al.* (1996) define trafficability as: "the period during the year when soil traffic is possible without causing unfavourable compaction" and workability as: "the period during the year when tillage is possible with positive effects on soil structure". Therefore, if land is considered trafficable, then it is deemed suitable for non-soil-engaging operations, e.g. fertiliser application and crop protection (Earl, 1997). Workability is concerned with soil-engaging operations and can be split up into (1) the workability window - i.e. the number of days per year the soil can be worked – and (2) the ease of cultivation, i.e. how fast or with how much energy (fuel) the soil can be worked. Trafficability and the workability window are both state variables - measured in number of days - with different measures (Droogers *et al.*, 1996, Earl, 1997), i.e. standard units to express the degree, amount or size of something. The ease of cultivation is a rate variable – measured in time and/or fuel per hectare for a given cultivation practice – and is more difficult to measure. Some authors use the term 'soil tilth' meaning: 'the physical conditions of the soil as related to its ease of tillage, fitness as a seedbed and its impedance to seedling emergence and root penetration' (Karlen et *al.*, 1990; Watts and Dexter, 1994).

SOM has an ambivalent influence on the resistance – or shear strength - of the soil. Soil shear strength increases with bulk density and inter-particle bonding, while it decreases with moisture content (Stibbe and Terpstra, 1982). OM reduces bulk density and increases moisture retention - both of which reduce shear strength, but it can increase the inter-particle bonding. This is shown by Ekwue (1990) who compared the influences of different types of OM on soil shear strength. Peat OM and OM under grass reduced bulk density and increased moisture retention. OM under grass, however, increased soil shear strength from 19.17 to 24.44 kN m^{-2}, while peat OM reduced it from 15.47 to 11.90 kN m^{-2}. The behaviour of SOM under grass was explained by improved aggregate stability which increased soil shear strength. The peat only made the soil aggregates fall apart and reduced the shear strengths.

Soil compactibility is closely related to soil bulk density. Soane (1990) reviewed the effect of OM on compactibility, and proposed several mechanisms by which OM may influence the ability of the soil to resist compactive loads:

Binding forces between particles and within aggregates. Many of the long-chain molecules present in SOM are very effective in binding mineral particles. This is of great importance within aggregates which "…are bound by a matrix of humic material and mucilages" (Oades in Soane, 1990).

Elasticity. Organic materials show a higher degree of elasticity under compression than do mineral particles. The relaxation ratio – R – is defined as the ratio of the bulk density of the test material under specified stress to the bulk density after the stress has been removed. Relaxation effects of materials such as straw are therefore much greater than material like slurry or sewage sludge.

Dilution effect. The bulk density of SOM is usually appreciably lower than mineral soil. It can however differ greatly, from 0.02 t m^{-3} for some types of peat to 1.4 t m^{-3} for peat moss, compared to 2.65 t m^{-3} for mineral particles (Ohu *et al.* in Soane, 1990).

Filament effect. Roots, fungal hyphae and other biological filaments have the capacity to bind the soil matrix.

Effect on electrical charge. Solutions/suspensions of organic compounds may increase the hydraulic conductivity of clays by changing the electrical charge on the clay particles causing them to move closer together, flocculate and shrink, resulting in cracks and increased secondary – macro - porosity (Brown and Thomas, 1987).

Effect on friction. An organic coating on particles and organic material between particles is likely to increase the friction between particles (Beekman in Soane, 1990).

These mechanisms contribute in varying degrees to changes in compactibility, depending on the type and distribution of organic matter present. OM additions to soil, other than roots, are multiform (Table 2.2). Crop residue, straw and grass would, because of their high relaxation ratios, have a much greater effect on the elasticity than slurry or poultry manure. Sludge and slurry will have a more pronounced effect on the electrical charge, because of the relatively high mineral concentrations. Schjønning et al. (1994) looked at the different soil physico-chemical impact of FYM and mineral fertiliser treatment after 90 years of treatment. The FYM field had a higher SOM content, and CEC, lower bulk density and was friable at higher water contents. The mineral fertilised soil was more compact than the FYM soil at large stresses. Munkholm *et al.* (2001) performed two case studies; soil tilth was better for an annual cropped system than a diversely cropped organically farmed system, both receiving FYM and not differing significantly in C content. Soil tilth was better for a diversely cropped organically farmed system with FYM application (3.4% SOM) compared to a cereal cropped conventionally farmed system without FYM application (2.5% SOM).

From the above it can be concluded that intra-aggregate SOM may be important for compactibility (vertical stress) and free SOM for workability (horizontal stress) – in the sense of "ease of cultivation". Tillage on wet soils can induce 'smearing', which is a form of compaction. Trafficability and the workability window would profit from both types of SOM. It is likely that the free and intra-aggregate pools of SOM will increase simultaneously, thereby aiding both compactibility and soil shear strength. The extent to which this occurs is likely to differ between soil textures and the type of OM added.

Watts and Dexter (1994) add two variables that have a large impact on workability: increased traffic intensity and lower water content resulted in larger aggregates and higher energy requirement for ploughing. Another term frequently used is soil friability. Friability has been defined as the tendency of a mass of unconfined soil to disintegrate and crumble under applied stress into a particular size range of smaller fragments (Utomo & Dexter, 1981). Friability – a desirable feature when producing a seedbed during tillage – also indicates the soil's structural condition (Watts & Dexter, 1998). They also concluded that: "Friability reaches a maximum at water contents around the lower plastic limit, that mechanical disturbance of wet soil by tillage reduces the friability, and that friability is strongly positively correlated with the organic carbon content of the soil:

$$\text{Friability} = 0.086 + 0.196\ \text{SOC},\ (r^2 = 0.970) \qquad [2.7]$$

At the more practical end of the research spectrum there has been remarkably little work. Low and Piper (1973) were told by farmers that they were able to plough in a higher gear when ploughing fields that were recently out-of-grass compared with those which had been arable for many years, with other factors such as the day, previous crop and harvesting conditions being the same. After experimental research they concluded that there is a reduction in draw-bar pull (measured in kN) when ploughing arable soils that were recently under grass for a period of years; the greater the number of years, the greater the reduction. They also stated that there are indications that the reduction is related to the pore space, the organic matter content of soils and to the sticky point. McLaughlin *et al.* (2002) showed a 13 to 18% lower tractor fuel consumption on fields that received very high manure rates (100 Mg ha^{-1}). A more realistic application of 50 Mg ha^{-1} had approximately half the impact.

According to Droogers *et al.* (1996) the workability window in a loamy soil in the Netherlands (precipitation = ca. 800 mm y^{-1}) is smaller in an ecological (organic) farming system than in a conventional system. Threshold values for workability, determined by the lower plastic limit, occurred at matric potentials of -120 and -45 cm for the ecological and conventional systems, respectively. The corresponding trafficability threshold values, obtained by penetrometer, were -160 and -15 cm matric potential. These values were translated into probabilities of being able to sow or plant at what is considered the optimum date by agronomists. For the conventional field this probability is 77% for cereals and 93% for potatoes and sugar beet. For the ecological field it is 0% and 17% respectively. Thus, despite the higher SOM content (3.3 vs 1.6%) and lower bulk density (1.47 vs 1.68 Mg m^{-3}) and higher porosity (0.42 vs 0.36 m^3 m^{-3}), the ecological system has a significantly smaller workability window. The potential productivity was higher due to an increased moisture supply to the soil, but the risk of compaction was higher as well due to a higher probability of performing field operations under wetter conditions, putting relatively high demands on the management abilities of organic farmers.

It should be noted that the two soils differed in clay content – 15% and 20% for the organic and conventional fields, respectively. At different clay contents the impact of SOM on the workability window is likely to differ.

2.2.4 External economic impacts of SOM

Organic matter can influence erosion in several ways. Firstly, OM binds soil particles and aggregates; it holds the soil together against the erosive impact of wind and water. Secondly, through the positive influence on structure in terms of aggregate stability the SOM provides easier infiltration, thereby reducing Hortonian overland flow and its associated erosion. LeBissonnais and Arrouys (1997) showed that the development of surface sealing and infiltration capacity were related to aggregate stability, which was itself a function of organic carbon content.

2.2.5 SOMFIEs relative to SOM fractions

Probably, different SOC fractions have varying influences on each of the SOM functions (see Section 2.2). A general difficulty with SOC research is the spatial and temporal heterogeneity of SOC in agricultural soil. Leinweber *et al.* (1994) investigated seasonal variations of SOM in a long-term agricultural experiment and found SOC concentration decreased by 0.24% in the unfertilised plot and 0.43% in the fertilised plot (NPK + FYM) between June and August (p < 0.01, see Figure 2.6). The seasonal fluctuation in SOM could be ascribed to the 'active' SOM pool, or root formation.

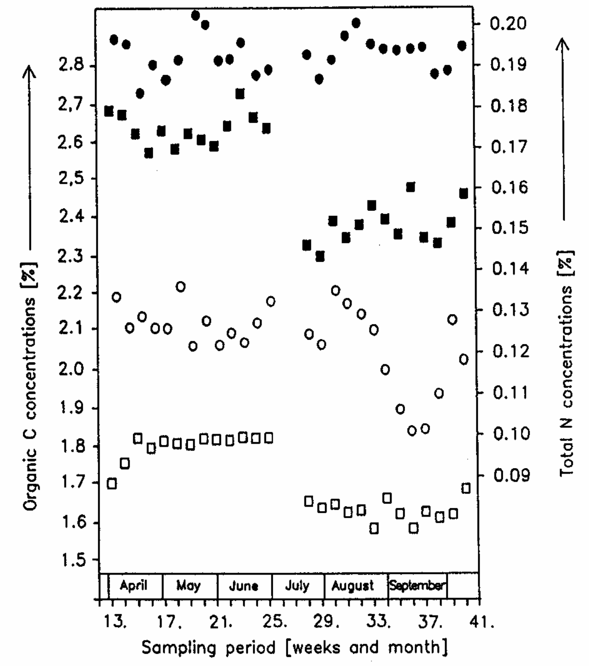


Figure 2.6 **Seasonal variation of SOC. Open symbols = untreated, filled symbols = NPK + FYM, Squares = SOC, circles = N (Adopted from Leinweber *et al.*, 1994)**

Based on the literature review (integrating Sections 2.1.1 with 2.2.1-2.2.4) an attempt can be made to relate SOMFIE indicators, representing agro-production sub-functions, to fractions of SOM. Table 2.6 sets out a possible set of relationships.

Table 2.6 SOM fractions and agro-production sub-functions

SOM fraction	Impact on agro-production sub-function	SOMFIEs
Free	Most important fraction for reduction in fuel consumption. Nutrient input by fast turnover rates. Important fraction in disease suppression, although consistent evidence for beneficial impact is weak.	Workability (effort) Fertiliser use Biocide use
Intra-aggregate	Most important fraction for resisting compaction. Background nutrient release. Important for short term carbon sequestration.	Workability (window) Fertiliser use Externalities
Organo-mineral	Important for long term carbon sequestration and as a pollutant sink.	Externalities

Other agro-production functions – irrigation, yield and crop establishment – are related to the free and intra-aggregate SOM fractions combined, but the literature does not provide sufficient evidence to discern which fraction is most important.

Therefore, this review indicates that, when researching SOM-to-farming interactions, selecting one ‘active SOC’ method will not provide adequate information.

2.3 FARMERS’ EXPERIENCE AND PERCEPTIONS

The scientific method, as described in the above Sections, uses scientific knowledge of soil processes and their interactions with farming as a basis for hypothesis formulation, and subsequent testing in laboratory studies, field experiments, or case studies. By 1900 this pattern of analytical thought was set (Warkentin, 1999) and it has grown into the main 'knowledge provider' for farmers.

Another body of knowledge on the interactions between soil and farming exists in the form of experience in the farming community. Knowledge is gained by trial and error and passed onto subsequent generations. This process of 'knowledge building' by 'experiential science' (Baars, 2002, Zimmer, 1994) does not have the direction and efficiency of experimental science. However, experiential science in farming has been ongoing and accumulating for substantially longer (i.e. since the first agricultural revolution, ca. 12,000 BP) than experimental science in academic research, and it has not been confined to selected environmental conditions. Therefore, valuable knowledge on how SOM impacts on farming potentially exists in the farming community and could be harnessed, and integrated with (and validated by) experimental science.

Knowledge based on experiential soil science has been given many different names in the literature, i.e. indigenous, local, folk, farmers' and people's soil knowledge (Zimmerer, 1994, Sillitoe, 1998, Winklerprins, 1999). The study of this knowledge, is often referred to as ethnopedology (Winklerprins, 1999, Barrera-Bassols and Zinck, 2003).

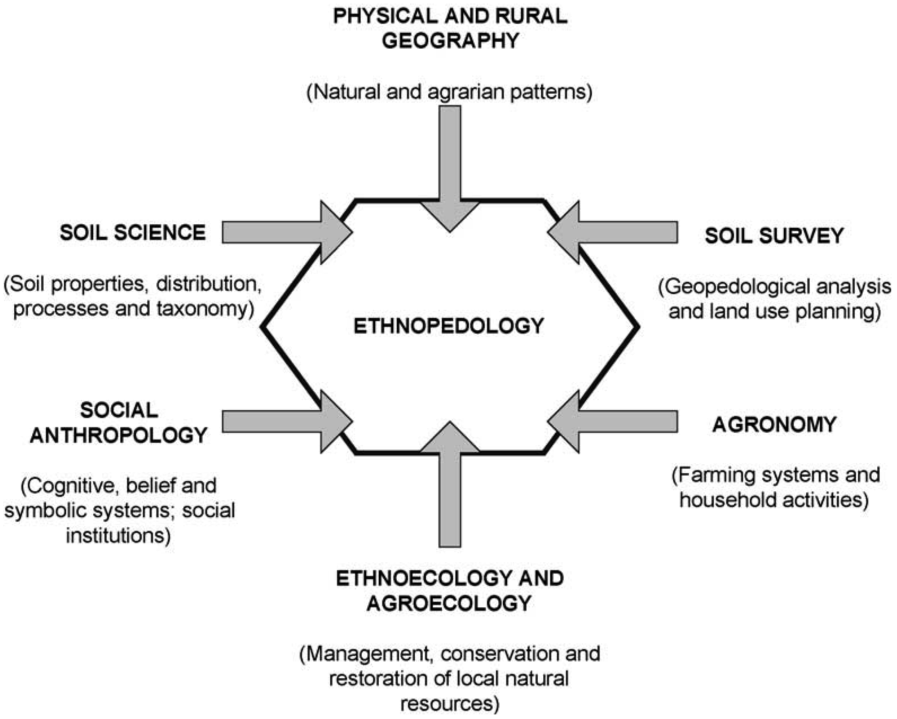


Figure 2.7 **Ethnopedology as a hybrid discipline (adopted from Barrera-Bassols and Zinck, 2003)**

Ethnopedology is a hybrid discipline of natural and social sciences, and it aims to understand the local approaches to soil perception, classification, appraisal, use and management (Barrera-Bassols and Zinck, 2003, see Figure 2.7). The wide range of topics are centered on ethnographical work, nomenclature work, and more utilitarian work. The first two operate on the basis of soil type recognition or description, and vernacular classification schemes, respectively. The utilitarian work moves towards incorporating local soil knowledge into development issues, and is the category of interest for gaining understanding of how SOM interacts with arable farming.

Winklerprins (1999) pointed out that much work is poorly accessible, i.e. in 'grey' literature (e.g. technical, project, and progress reports), and, when published in peer-reviewed journals, has not been synthesized comprehensively. However, a more recent special issue of Geoderma (vol. 111, 2003) has provided a degree of synthesis.

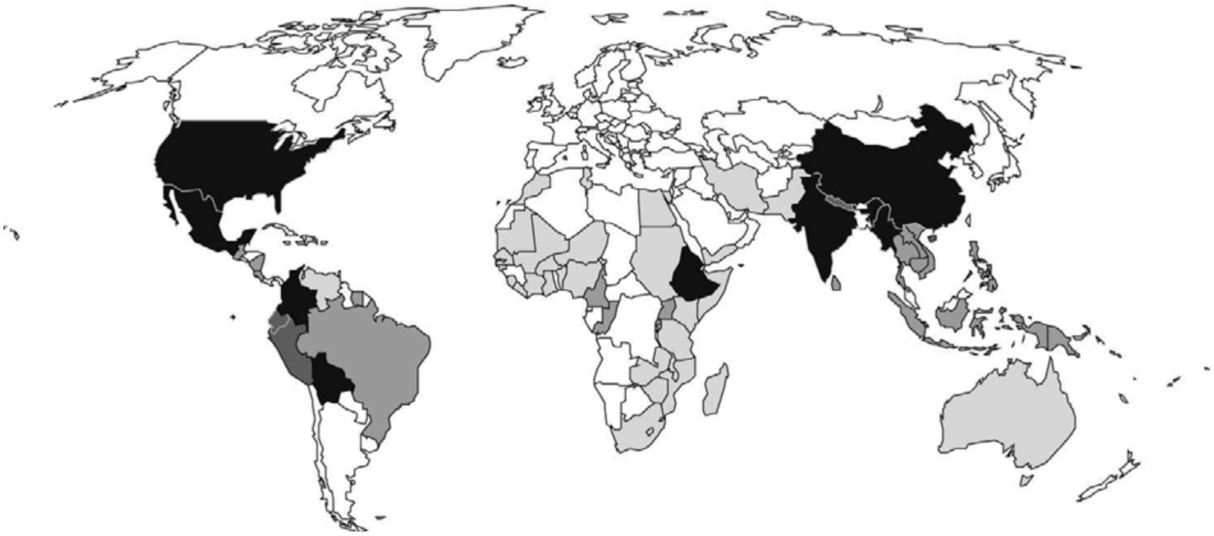


Figure 2.8 Worldwide distribution of ethnopedological studies per agro-ecological zones (Adopted from Barrera-Bassols and Zinck, 2003). Light grey = warm and dry lowlands, intermediate grey = warm and moist lowlands, dark grey = cold and dry highlands, black = complex agro-ecological areas

Most ethnopedological research is performed in developing countries in (sub)tropical regions. Barrera-Bassols and Zinck (2003) looked at 432 ethnopedological publications and found 75 studies in North America, and only five in Europe (Figure 2.8). In North America these studies were focused at Native American interactions with soil and in Europe the emphasis was on Mediterranean farming. Ethnopedological research papers specifically on the interactions between SOM and the food production function in developed countries in a maritime climate, are rare and focus on 'alternative farming'. Studies on conventional farming were not encountered in the literature.

Winklerprins (1999) noted about utilitarian ethnopedology: "This type of local soil knowledge is very useful and illustrates how local soil knowledge can be used as a tool. However, research needs to move further in linking what locals know about and do with the soil and the utility of this knowledge and practice to the development of sustainable land management."

From this review of the literature it is concluded that ethnopedological studies in England and Wales, and similar regions in other parts of the world, are in their infancy. I found no specific knowledge regarding the critical question of this project was not found in the literature. However, methods used for ethnopedological work in developing countries could also be applied to the English/Welsh situation.

The link between social science and soil science, or more specifically the integration of experiential and experimental science systems, is mentioned and emphasized in the literature (Bouma, 1993; Pawluk et al., 1992, Bentley 1989, DeQueiroz, 1992), but mostly not implemented. Oudwater and Martin (2003) focused on methodological issues concerning ethnopedology using case studies in Uganda and Tanzania, where they found scientifically biased interview techniques, and interviewee confusion by use of technical language. They highlighted the need for a more critical integrated approach, which uses continuous cross-checking of information to enhance understanding of experiential science (see section 2.4.1). In addition they noted that rather than dismissing complexity in experiential science, it is crucial to identify the cause of differences and (apparent) contradictions, to enhance understanding of farmers' perceptions.

2.3.1 Creation of theory – basics of qualitative data analysis

The method for analysis of data generated by the semi-structured interview (SSI) survey was based on a process called “grounded theory building” as developed by Glaser and Strauss (1967). They suggested the term ‘constant comparative method’ for this process, whereby ‘underlying patterns’ are discovered through careful and intensive data comparison. The central prerequisite for this is ‘coding’, i.e. relating text passages to categories that the researcher either had developed previously, or develops ad hoc (Kelle, 2000).

The basic elements of grounded theory are concepts, categories and propositions.

1. Concepts are derived by the process of ‘open coding’. *Open coding* refers to that part of the analysis that deals with the labelling and categorising of phenomena, as indicated by the data. The product from labelling and categorising is a set of *concepts* – the basic building blocks of grounded theory construction. Open coding relies on the *constant comparative method.* Data generated by asking questions (semi-structured interviewing) are compared and similar incidents are grouped together and given the same conceptual label (Pandit, 1996).
2. Categories are generated by making comparisons between concepts to highlight similarities and differences. The process of grouping concepts together at a higher, more abstract level is termed *categorising.* Where the *concepts* are the ‘basic building bocks’, *categories* are the ‘cornerstones’ of developing theory.
3. Propositions are generalised relationships between a category and its concepts and between discrete categories. Glaser and Strauss (1967) originally termed these ‘hypotheses’. A recent convention is to use the term ‘proposition’, which is more appropriate because it suggests

conceptual relationships, whereas hypotheses relate to measurable relationships (Pandit 1996; Whetten, 1989).

2.4 SUMMARY

This chapter has described knowledge of SOM genesis and dynamics in general, how the dynamics may result in different SOC ranges, how SOM content and management may provide on-farm benefits, and how farmers' experiential science may be used to provide further insights into actual benefits. Salient points relevant to the research aim (see Chapter 1) are:

- ✓ There is no apparent consensus on a definition of SOM in the scientific literature. A functional definition was suggested as: "the sum total of all organic-carbon containing substances in soil that are not Black Carbon".
- ✓ 'Active' SOC is measured by a growing number of chemical, physical, and biological SOC fractionation methods, which have not been standardised and have not been proven to be robust and consistent for a wide range of soils. It is suggested that different (physical) SOM fractions may be important for different agro-production sub-functions.
- ✓ Several methodologies have been used to quantify SOC ranges. For lower SOC content limits there appears to be a burgeoning consensus regarding the magnitude of its relationship to fine earth measurements. Upper SOC limits have been researched remarkably little, and SOC ranges differentiated for other environmental factors than clay and silt contents (e.g. soil hydrology) have not been reported.
- ✓ SOMFIEs were introduced as indicators of **S**oil **O**rganic **M**atter on-**F**arm **I**mpact on **E**conomics, which may have positive or negative impacts on the agro-production sub-functions

- ✓ Impacts of SOM on the agro-production function were grouped by mode of impact into: i) direct impacts on yield; ii) crop-related impacts; iii) non-crop-related on-farm impacts; and iv) external impacts.
- ✓ A review of the literature found direct impacts of SOM on yield to be mainly associated with increased water availability in water limited agro-ecosystems. In the crop-related impacts group, fertiliser reductions were the most straightforward benefit; disease and chemical use showed both benefits and disbenefits and large variation caused by environmental factors (requiring more research before a consensus may be reached); the soil water regime appeared to provide benefits by increased water retention on the one hand and decreased water logging on the other hand. In the non-crop-related on-farm impacts group, the strongest evidence for benefits was found for ease of tillage (by actual on-farm experimental research). A formal SOMFIE description is proposed in Table 2.7.
- ✓ A review of ethnopedological work showed that studies in contemporary arable farming in developed nations are in their infancy, but a critical integrated approach using 'the creation of theory' concept may be used to investigate farmers' experiential science concerning benefits from SOM.

Table 2.7 SOMFIE list

<table>
<tr><th colspan="2">Agro-production sub-function</th><th colspan="2">SOMFIE indicator</th><th>Units</th><th>Source</th></tr>
<tr><td colspan="2" rowspan="2">Yield</td><td colspan="2">Quantity</td><td>$t\ ha^{-1}\ y^{-1}$</td><td>Farmer</td></tr>
<tr><td colspan="2">Quality (protein content)</td><td>% (dry weight)</td><td>Farmer</td></tr>
<tr><td rowspan="3">Work-ability</td><td>Flexibility</td><td colspan="2">Farmers' perception</td><td>Flexibility index (classification)</td><td rowspan="3">Farmer</td></tr>
<tr><td rowspan="2">Sub-soiling</td><td rowspan="2">Yes-no</td><td>Time spent (man-hours)</td><td>$h\ ha^{-1}\ y^{-1}$</td></tr>
<tr><td>Fuel spent</td><td>$L\ ha^{-1}\ y^{-1}$</td></tr>
</table>

	Passes for seedbed (excluding sub-soiling)	Number of passes	-	
		Time spent in total	h $ha^{-1} y^{-1}$	
		Fuel spent in total	L $ha^{-1} y^{-1}$	
Crop establishment		Seed rate (per variety)	Kg $ha^{-1}y^{-1}$ or number of seeds/m^2	Farmer
		Visual crop uniformity measurement (by scientist)	e.g. chlorophyll index	Scientist
		Visual crop uniformity classification (by farmer)	classification	Farmer
Fertiliser	**Inorganic fertiliser use**	Amounts applied	Kg $ha^{-1} y^{-1}$	Farmer
	Organic fertiliser use	FYM		
		Straw		
		FYM/straw		
		Sewage Sludge		
Irrigation		Yes-no Amount applied	mm y^{-1}	
Disease		Proneness to pests (stability over long period), farmer's perception	classification	Farmer
		Applied amounts of pesticides/herbicides	Kg $ha^{-1} y^{-1}$	
		Loss of crop, measured as farmers' perception/estimate	%	
Erosion	**Soil crustability**	as perceived by farmers' perception of proneness to crusting	classification	Farmer
		as measured by aggregate stability	classification	Scientist
	Sediment transport	Estimation of frequency of sediment transport by farmer	Times per year	Farmer
	Thickness of deposition layer at bottom field	Soil profile by scientist	cm	Scientist

CHAPTER 3

OBJECTIVES AND CONCEPTUAL FRAMEWORK

"Hoe ruimer zou onze opvatting van het leven zijn,
indien het ons gegeven ware dit eens
te bestuderen met verkleinglazen."
"How much broader our notion of life would be,
if we could study it with reducing glasses."
Prof. Louis Bolk (1866 – 1930)

This chapter develops the appropriate methodology to achieve the research aim, considering current knowledge and available resources.

3.1 INTRODUCTION

Chapter 1 set out the need to increase scientific understanding of how, and to what extent, SOM impacts on-farm economics. This gave rise to the critical question: Does SOM, or its management, provide on-farm benefit? Chapter 2 proposed an initial list of these impacts, which were termed "SOMFIEs" (see Table 2.7). It also highlighted potential for gaining more understanding by using farmers' experiential science. In addition it was concluded that there is a knowledge gap regarding the ranges of SOC contents that can be attained for arable fields. This elementary knowledge determined the conditional framework and was essential for reaching an answer to the critical question. Finally, Chapter 2 concluded how different fractions of SOM are important to different agro-production sub-functions, and associated SOMFIEs.

In the light of these findings and recommendations, an integrated methodology was required to determine appropriate SOC ranges, to explore and value SOMFIEs by using farmers' experiential science, and to compare these to SOMFIE measurements along the SOC range.

According to Stuart and Jenny (1984), Bellamy first postulated the term 'the living soil', after which Jenny proposed viewing soil as a 'living system'. He noted that soil has no reproductive capability which is a fundamental property of living organisms. Soil is a living system that exists at the interface of the lithosphere, atmosphere, hydrosphere, and biosphere. Figure 3.1 shows this as a Venn-diagram (often used in pedology), here placed within a pervious Anthroposphere.

Human activity influences the four natural spheres in a fundamentally different way to all other species, in terms of mechanisms, scale and magnitudes. Functionally, therefore, humanity extends beyond the biosphere, and humanity's influence can be represented by an Anthroposphere.

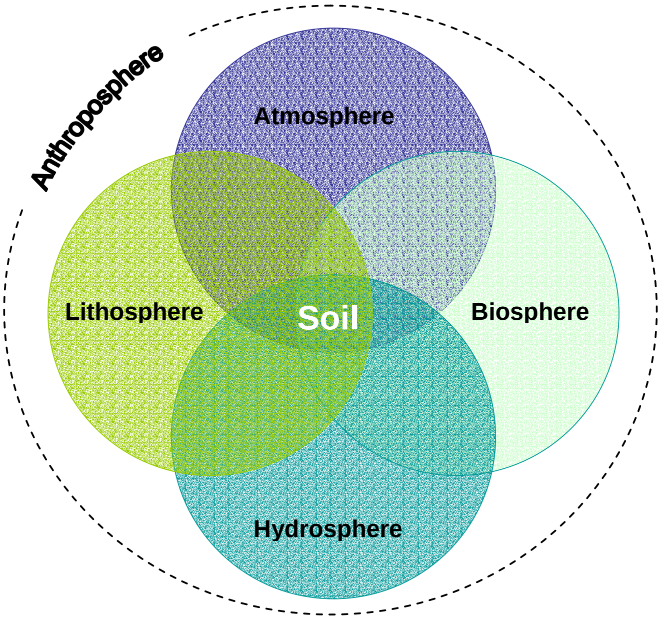


Figure 3.1 Multi-sphere character of soil

The dashed line of the Anthroposphere symbolises its partial, or diffuse, influence (i.e. not 'control') over the natural spheres. The anthropogenic influence on arable soils is relatively large, and makes research, e.g. into on-farm benefit from SOM, particularly complex. Holistic approaches are appropriate when dealing with the complexity encountered when researching the management (or 'stewardship') of soil as a living system. Bouma (1997) acknowledged the need for holistic approaches, but argued the inclusion of a reductionistic phase as well "in which specific and, if necessary, basic or fundamental research is performed based on questions raised in an initial, holistic analysis" (Bouma, 1997). These results can then be fed back into an iteration of the holistic part of the research, or they can be combined with the holistically derived results for discussion in the synthesis.

3.1.1 Thesis flowchart

The research described in this thesis aims to look at the impact of SOM on farming using the Holistic-Reductionistic-Holistic approach. The research methodology combines physical science with social science. By using a bottom-up approach, which integrates the experiential knowledge of the farming community with scientific perspectives, a more comprehensive picture of how SOM might benefit arable farming will be built up. This generates knowledge which is then combined with a framework that determines attainable SOC ranges for sets of environmental conditions, and is tested at field scale on commercial farms. The sample selection in this integration forms the crucial element of this research. To test SOM's impacts on farming it is essential to sample fields along the entire attainable SOC range:

- If field selection was based on SOM management, the sample would be centred around the median SOC contents, and would therefore only cover a part of the SOC range.
- If field selection was confined to research farms, the sample might be limited in the combinations of environmental factors and often substantially greater OM additions are used than encountered on commercial farms (see Section 2.3).
- Commercial farmers are a more appropriate sample group than research farmers to investigate on-farm economic benefit, because of the latter's commercial bias.

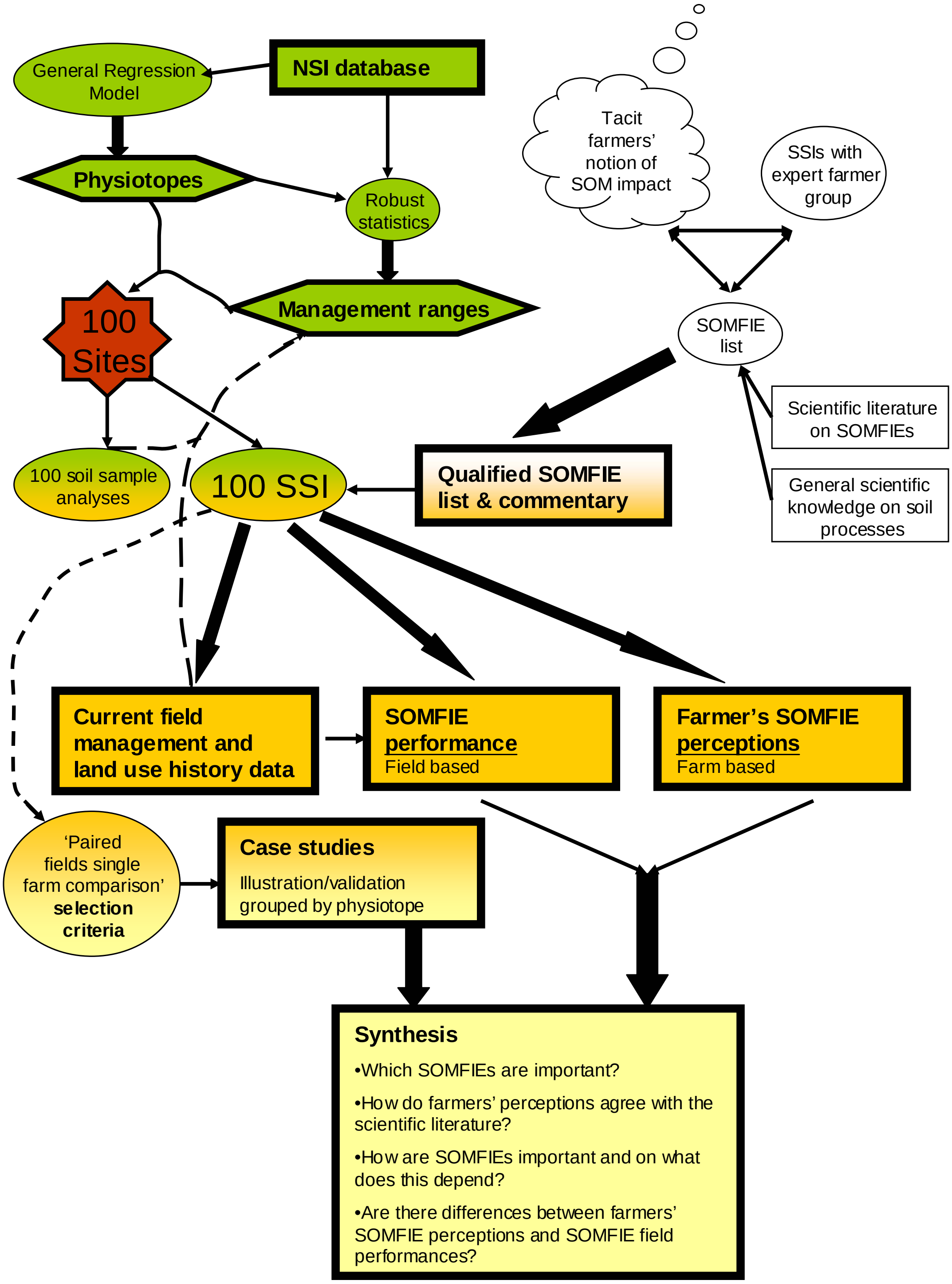


Figure 3.2 Thesis flow chart (see Section 3.1.1). For more detailed methodology flow charts see the methodology sections of Chapters 4-6. For a conceptual framework diagram see Figure 3.3.

Figure 3.2 shows the flowchart for the work investigated in this thesis. The green section concerns the SOC ranges work of Chapter 4. The section in white relates to the SOMFIE list generation via the literature review and the pilot study, described in Chapters 2 and 5. A random stratified sample of commercial farmers (with one field on their farm selected along the SOC range) feeds into the 100 semi-structured interviews (SSIs, in brown). From the experiential science work, a qualified SOMFIE list with measurement recommendations also feeds into the SSIs. In orange are the main data outputs. Melding from orange into yellow are the case studies, which are selected from the 100 SSIs (dashed arrow). Finally, the yellow section addresses the discussions of the individual results (Chapter 4-6) and their synthesis (Chapter 7).

The "Conceptual Framework and Methodology" is described after the objectives. The research plan to meet the research aim and the individual objectives are then discussed. Limitations and expected difficulties are discussed throughout. The synthesis draws the methodology together and can be read as a summary.

3.2 RESEARCH AIM AND OBJECTIVES

The overall aim of this research is to investigate, determine and describe SOC management ranges for agricultural fields in England and Wales, to develop and establish indicators of on-farm economic benefit from SOM, and to qualify and quantify their relative benefits. There were three main objectives:

1. To investigate the environmental variables that govern SOC variation, and to define 'SOC Indicative Management Ranges (SOCIMRs)' for arable ecosystems in England and Wales.

Research questions:

- What are the environmental variables that govern SOM variation in arable ecosystems in England and Wales?
- Is it possible to determine differential SOCIMRs for these variables?
- What causes fields to fall outside the identified SOCIMR?

2. To develop indicators of on-farm economic impact from SOM (SOMFIE indicators) and investigate farmers' perceptions and valuations of these relative to environmental conditions and SOM management.

Research questions:

- Which SOMFIE indicators do the primary and secondary stakeholders put forward?
- How do the stakeholders value the SOMFIEs?
- How can SOMFIE indicators be measured most efficiently and consistently?

3. To qualify and quantify the SOMFIE indicators for fields along the SOC management range, and/or under different SOM management.

Research questions:

- Which SOMFIE indicators perform better or worse along the SOCIMRs, and by what magnitude?
- Is it possible to give an indication of the benefits or disbenefits to a farmer if a field is 'moved' to a different position in the SOCIMRs?
- Is there a relationship between the relative and absolute importance of SOMFIE indicators and physiotopes (see Box 3.1)?

It is hoped that this study will provide sound scientific evidence about under which circumstances SOM has sufficient value in contemporary arable farming to justify policy measures to conserve SOM.

Box 3.1 Physiotope

The term 'physiotope' originated in 1965 in the field of landscape ecology (Lausch and Thulke, 2001), where it is ordered between a 'soil body' and a 'terrain unit' (Zonneveld, 1989). Physiotopes include the atmosphere above and rock and hydrosphere below the soil (unlike a soil body), and a terrain unit is often a mosaic of physiotopes (Zonneveld, 1989). In contrast to 'ecotopes', physiotopes do not consider biotic factors.

3.2.1 Omni-hypothesis

The overall hypothesis for this work is:

Greater SOC contents and more intensive SOM management of arable fields in England and Wales provide on-farm benefit.

3.3 CONCEPTUAL FRAMEWORK AND METHODOLOGY

This chapter describes the 'how' and 'why', i.e. how the objectives can be reached by different methodologies, and why a certain methodology was chosen. The selected methods are described in detail in Chapters 4, 5, and 6. The methodology has been divided into four phases (Figure 3.3), which are described individually. A synthesis is presented after Phase IV.

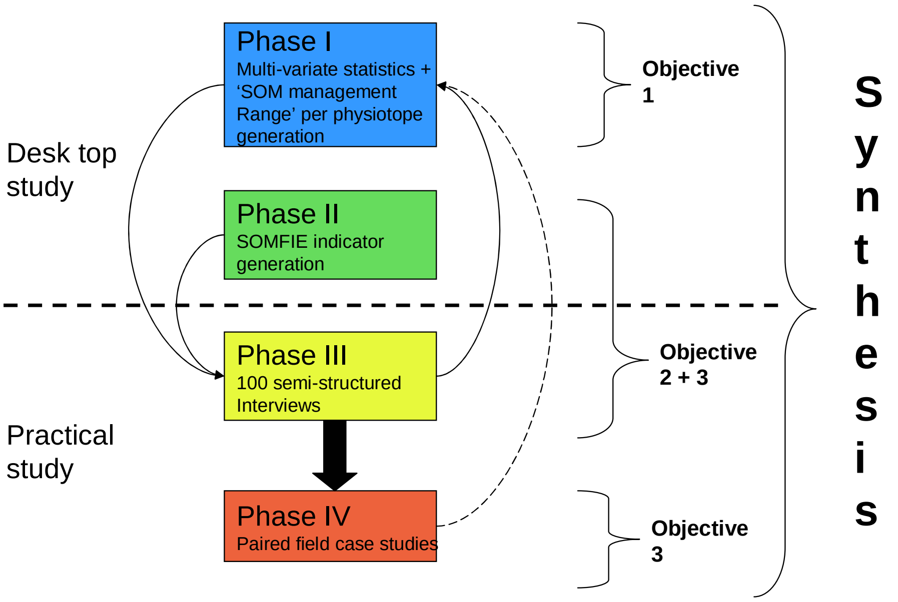


Figure 3.3 Conceptual framework diagram showing information input feedbacks (black connection arrows), information analysis (dashed arrows) and direct input (block arrow). The dashed line indicates the division between desk top and practical work. On the right the objectives are listed.

The synthesis, as depicted in Figure 3.3, will integrate the achieved research objectives, and draw conclusions between objectives where possible. It is expected the synthesis format will be in descriptive ranges rather than absolute numbers. It is hoped that this will provide a sound basis for assessing policy options regarding SOM management.

3.3.1 Conditional framework for SOC levels (Phase I)

The methodology for this phase is designed to provide an answer to the first objective: *"To investigate the environmental variables that govern SOC variation, and to define 'SOC Indicative Management Ranges (SOCIMRs)' for arable ecosystems in England and Wales"*.

The first part of this objective – identification of the environmental variables that govern SOC variation in arable ecosystems in England and Wales – is a basis for defining SOC physiotopes (see Box 3.1). In this work, the term physiotope is used in the context of SOC and is defined as "a unit in the landscape where environmental conditions, that govern SOC, are similar". The number of physiotopes defined depends on the number of governing variables. For each physiotope a SOCIMR can be determined – which is the second part of the objective. The National Soil Inventory (NSI) dataset provides a basis for meeting this objective (see Box 3.2).

The relatively high number of observations in the NSI makes robust multi-variate statistical analysis possible. Multi-variate analysis requires input variables in a directional and numerical format. Therefore, variables that do not meet these requirements need reformatting, and variables which cannot be reformatted need analysis using uni-variate statistics.

Box 3.2 The National Soil Inventory

The 1980 NSI dataset consists of 2448 arable, and ley-arable, soil samples, with accompanying (measured or determined) environmental variables. Samples were taken on every 5 km grid point (Ordnance Survey) offset by 1 km, in England and Wales. See also Section4.3.1.

A separate SOCIMR can be developed for each physiotope, as long as there is a sufficient number of observations to support statistical analysis. A robust statistical approach has been proposed by Rousseeuw (1993), for data that are not distributed normally nor skewed, and this makes it possible to determine SOCIMRs for all physiotopes.

Possible causes for the existence of a range in SOC contents per physiotope include unmeasured environmental variables and management variation (e.g. drainage, organic matter amendments, tillage practice, rotation, land use history, etc.). The semi-structured interviews (carried out in Phase III, see Figure 3.2 and Section 3.3.3) need to be designed to capture relevant land use history and field management information, so that observed positions in the SOCIMR can be investigated.

LIMITATIONS AND EXPECTED DIFFICULTIES

The NSI database is extensive but not comprehensive, i.e. not all environmental variables are listed. Furthermore, some of the listed variables are modelled rather than measured values. Complementary management and landuse information is gathered by the integration with Phase III, but only a relatively small subset of the NSI data can be investigated (see Phase III, 3.3.3).

3.3.2 Qualified SOMFIE list and perceptions (Phase II)

The methodology for this phase is designed to provide an answer to the second objective: *"To develop indicators of on-farm economic impact from SOM (SOMFIE indicators) and to investigate farmers' perceptions relative to environmental conditions and SOM management"*. It seeks to establish a first set of indicators and then to extend and validate this by gathering expert opinion.

The resulting qualified SOMFIE list can subsequently be used to test farmers' valuation and awareness of the established SOMFIEs, on a random stratified sample of commercial farmers in England and Wales. Phase III provides such a sample (see 3.3.3.).

Sources of information for SOMFIE indicator development include: first, scientific literature; second, professional (farming) literature; and third, primary and secondary stakeholder information. For a list of SOMFIEs to be as complete as possible, all of these need to be considered. Indicator development should be a dynamic, iterative process between the available information sources.

The primary stakeholders (farmers) form a special group that require a distinct methodological approach. Their knowledge is derived in part from experiential science (Baars, 2002; see also Section 2.4). This means that they solve operational problems using locally-developed knowledge. An important limitation of experiential science is described by Bouma: "Some existing expertise is not based on verifiable facts but on ideologically based assumptions". This limitation may be expected to be particularly apparent in agricultural systems that have developed within an ecological/environmental ideology, e.g. organic farming or minimum tillage.

Scientists who investigate experiential science methodologies may be described as cultural ecologists or ecological anthropologists (Baars, 2002). The recognition of farmers as experiential scientists is critical for the acquisition of a complete SOMFIE indicator list. Farmers' experiential knowledge, about how SOM interacts with farming and impacts on on-farm economics, is often in a tacit or semi-conscious format. Semi-structured interviews between a soil scientist and farmer are a tool for investigating this tacit knowledge and for formulating new SOMFIE indicators. A semi-structured interview is an interview using a flexible checklist rather than a formal questionnaire, allowing the interviewee to continue useful trains of thought, and allowing the interviewer to explore emerging themes (see Section 5.3.1). In conclusion, a methodology, which integrates social science with soil science, is needed to achieve the research aim. This requires a broad understanding of farm system management and farmer behaviours, as well as soil and SOM processes. Bouma (1997) refers to these types of soil scientists as 'knowledge brokers' with 'T-shaped skills', who have both broad and deep appreciation of different aspects of soil management.

METHODOLOGY SELECTION AND MOTIVATION

The first step for this phase is compilation of an initial SOMFIE indicator list from the scientific literature, supported by discussion with scientists within the project and beyond it (see Chapter 2). The second step tests the initial SOMFIE list on a group of primary and secondary stakeholders, i.e. research farmers, commercial farmers, agronomists and representatives of farming organisations. The farms should be representative of the main types of environment in England and Wales, as this affects SOM dynamics (input from Phase I, see Section 3.3.1). This step involves validation of the initial SOMFIE list, evaluation and development by rephrasing of SOMFIE questions (including definition/choice of different units of – qualitative or quantitative – measurement). The process of SOMFIE development is iterative (see Figure 3.4), leading to a 'qualified' SOMFIE list. The term 'qualified' refers to the outcome of this SOMFIE development, which also allows the expert knowledge of primary and secondary stakeholders to inform question phrasing and answer categorisation.

LIMITATIONS AND EXPECTED DIFFICULTIES

As already identified, ideologically based assumptions can create bias in experiential science. Care is needed to limit the qualification of SOMFIE indicators based on ideology rather than tacit, experiential knowledge. It was decided to exclude organic farms from the study because it was anticipated that this group would at least interpret experiential science differently, and may arguably impose an ideologically-based bias when identifying and assessing SOMFIEs. A second limitation is the number of observations in the second step. A larger sample might provide more SOMFIE information. Due to resource constraints, the number of semi-structured farmer interviews was limited to thirteen when compiling an initial SOMFIE indicator list. However, the selection of farms/farmers was done with some account being taken of environmental variables and of the 'progressiveness' of farmers.

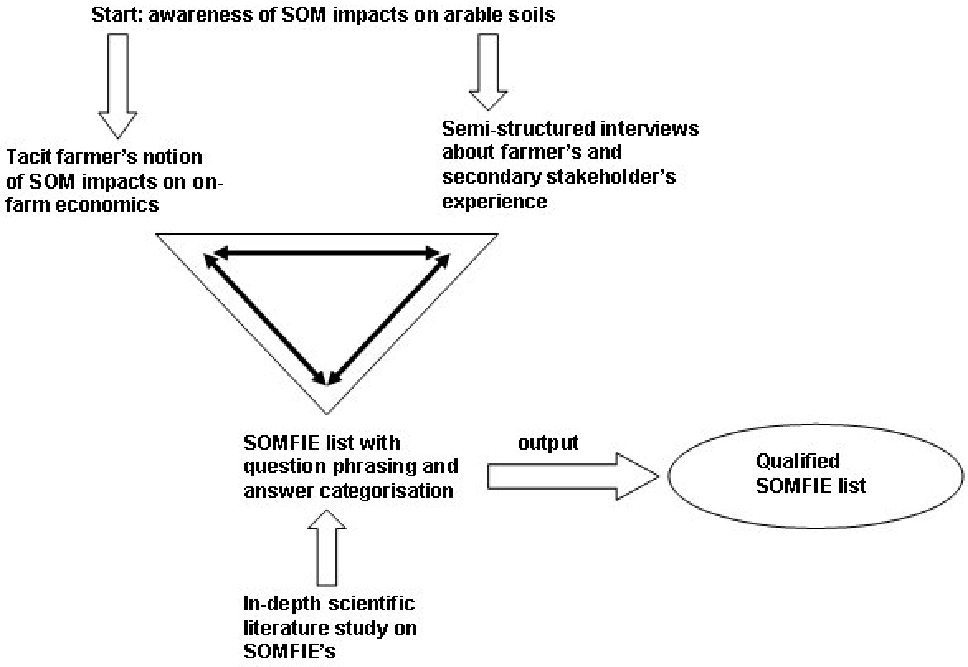


Figure 3.4 SOMFIE list generation diagram

3.3.3 SOMFIE performance (Phase III)

This project focuses on the question: *"Whether SOM provides on-farm economic benefit"*. The literature review provided indications of SOM benefit (see Chapter 2), but these rely mainly on reports from research and demonstration sites which are not truly representative of farms in general. For example, research farms commonly have more intense management. It is useful, as an illustration, to know that a 13 to 18% fuel decrease was measured on a research plot with a particular set of environmental variables (in Canada) and 50, or 100 t ha^{-1} y^{-1} of FYM additions (McLaughlin *et al.*, 2001). However, the fuel benefit for sites with different sets of environmental variables and lower (more realistic) FYM additions can not be extrapolated from these results. Furthermore, the result may not necessarily be applicable to the English and Welsh climatic situation.

An alternative to the research plots approach is the use of fields on commercial farms. Pulleman *et al.* (2000) reviewed the different methodological approaches and concluded about the use of fields on commercial farms:

"…use of soil survey information offers an alternative. A wide variety of 'field experiments' is already there, waiting to be sampled and analysed."

Although this is probably true, a disadvantage of using fields on commercial farms is the difficulty of controlling the environmental variables, i.e. whereas it may be possible to choose fields high and low in SOM on three different soil types on research farms, it is more difficult to do so on commercial farms, since data to inform choices are not readily available. Another important disadvantage is the wide variation in soil and crop management on different farms.

The critical research question of this project however, makes commercial farms suitable for analysis. It is considered that on-farm economic benefit is often masked on research farms because research and non-commercial objectives are overarching. It is anticipated that commercial farmers are more likely to observe on-farm economic benefits.

To explore the relationship between SOM content and SOMFIEs (for fields, or parts of fields, with similar environmental variables), several SOM levels are required. Two main comparison approaches can be used: a temporal and a spatial comparison. An advantage of the temporal comparison approach is that it is based on a 'single information source'. A farmer who has changed the SOM management of a field at some point in the past can compare the pre-change situation with the current situation, so both the farmer and the field provide continuing sources of information. A disadvantage of temporal comparison was realised early on in Phase II when conducting pilot studies with research and commercial farmers. In the recent past – especially since the second world war – the farming community has undergone considerable changes. The main changes are a shift to larger-scale systems, capital intensification and advances in farming knowledge and technology. Small fields have been amalgamated into larger ones. Tractors have become more powerful and are therefore able to work with wider implements that cover more ground, or work quicker. More effective biocides and crop varieties have been introduced, and knowledge on soil and crop management has increased through workshops, agronomist contacts and training sessions by farmer organisations.

When the farmer is asked to compare, for example, the situation before the ban on stubble burning with the present one, these changes mask the effect of SOM on on-farm economics. As a result, a risk is induced of promoting false, exaggerated, or understated SOMFIEs. Therefore, to obtain a clearer picture of the effect of SOM alone, a spatial comparison may provide an alternative. Several types of spatial comparison methods exist:

1. **Intra-field comparison, on single non-precision agriculture farm**

2. **Intra-field comparison, on single precision agriculture farm**
3. **Inter-field comparison, on multiple farms**
4. **Inter-field comparison, on single farm**
5. **Comparison of agricultural experimental sites**

Each type of spatial comparison has advantages and disadvantages, determined by the context of the research, the research aim and the available resources. Table 3.1 compares relevant features of the five types of comparisons.

Intra-field comparison on non-precision agriculture farms was impossible for the majority of the pilot study farms in phase II, where a common soil and crop management is applied regardless of intra-field differences. This makes on-farm economic data gathering impossible.

For the intra-field comparison on precision agriculture farms the soil and crop management is different for the different zones in a field, which provides the potential for on-farm economic data analysis. However, from a Home-Grown Cereals Authority (HGCA) report (no.296, 2003), where Electro Magnetic Induction (EMI) maps were overlayed with yield maps to identify the intra-field causes of yield differences, it is clear that there are many different contributing factors, with texture playing a dominant role. The role of SOM was not researched. An ideal situation would be one where different land use history has created different SOM levels on a field that is otherwise environmentally homogeneous, e.g. where a part of a field used to be in permanent grassland. It can take decades for a soil to reach its new SOC equilibrium after it is taken out of permanent grassland. However, such situations are thought to be relatively uncommon and are certainly difficult to locate.

Table 3.1 Spatial comparison methods

Type of spatial comparison	Advantage	Disadvantage	Note
1. **Intra-field comparison, on non-precision agriculture farm**	- Single 'SOMFIE information' source - Single field	- SOM differences often related to textural differences - Management not adapted to different zones in field	
2. **Intra-field comparison, on precision agriculture farm**	- Single 'SOMFIE information' source - Single field - Management adapted to zones in field	- SOM differences often related to textural differences	
3. **Inter-field comparison, on multiple farms**	- A priori selection of fields similar in environmental variables, contrasting in SOM	- SOMFIE information multiple source - Management different on every farm	Dependence on available resources
4. **Inter-field comparison, on single farm**	- Single 'SOMFIE information' source	- SOM differences between fields often related to different environmental variables	Scarcity of valid cases
5. **Comparison of agricultural experimental sites**	- Single 'SOMFIE information' source - environmental variables controlled	- Farmer is not commercial	

<u>Inter-field comparison on a single farm</u> offers good conditions to determine the impact of SOM on on-farm economics. Single source information is combined with whole fields with different SOM levels, providing units large enough to justify adaptation of soil and crop management. The pilot study showed, however, that different environmental variables often mask the effect of SOM,

and make an inter-field comparison on one farm impossible. It appears rare to locate two fields with similar environmental conditions, but contrasting SOM contents. Therefore, this type of comparison opportunity holds great potential, but it is difficult to obtain.

Inter-field comparison on multiple farms is less powerful because it has multiple information sources and different soil and crop managements. The obvious advantage is the potential to acquire many cases, but the extensive variability arising from many, varying factors offsets this accessibility.

Agricultural experimental sites have been described above as having the disadvantage of reduced commercial awareness.

METHODOLOGY SELECTION AND MOTIVATION

The criteria for methodology selection are: consideration of the research aim and objectives; methodological integration; statistical robustness; and available resources.

For Phase III, temporal comparison and spatial comparison on agricultural experimental sites have been discarded on account of data masking. The intra-field comparison on single non-precision agriculture farms (Type 1) is prevented by data gathering difficulties. This leaves: intra-field comparison on precision agriculture farms (Type 2); inter-field comparison on multiple farms (Type 3); and inter-field comparison on single farms (Type 4). Type 2 is acknowledged as a valuable method, but not easily accessed. A combination of Types 3 and 4 are the most appropriate for this project, taking account of the need for methodological integration and statistical robustness.

A further consideration is that the NSI database (see Box 3.1; and Section 4.3.1) makes it possible to control environmental variables, while selecting fields that cover the SOC management range. The first two objectives – the differential description of a SOC management range and the impact of SOC on SOMFIEs - can thus be integrated. A relatively large number of cases can be selected from the database supporting statistical interpretation, although methods need to be developed to deal with the multiple information sources. Type 4 comparisons can not be selected from the NSI database, and two fields with similar environmental conditions and contrasting SOM contents or management on a single farm are relatively uncommon. It was found that roughly one in 10-20 farms have such fields. However, the Type 3 comparison approach is a tool for locating Type 4 comparison case studies.

The selected methodology was to perform a Type 3 comparison on a large number of fields (approximately 100) selected from the NSI database and representing the SOCIMR (see Section 3.3.1), while controlling for other environmental variables. Semi-structured interviews were carried out to gather SOMFIE information from the farmers of these fields. Each SOMFIE indicator is treated as a hypothesis. In general the hypothesis for an individual SOMFIE indicator is:

The position in the SOCIMR of physiotope X has an impact on SOMFIE indicator Y.

Methodological integration was supported by gathering of landuse history and the investigation of current land use information. These data were used to explain outlying values in the SOCIMR (feedback to Phase I).

LIMITATIONS AND EXPECTED DIFFICULTIES

The Type 3 comparison is weakened by multiple source information and different soil and crop managements. These difficulties can be overcome in part by standardised question-answer formats and maximising the number of observations. However, time and resources constraints limited the total number of observations to approximately 100. Inevitably, some data for individual SOMFIE indicators are unavailable, for example because the farmer is not willing or able to answer a relevant question.

Further data loss arises where the field is too environmentally heterogeneous, e.g. several texture classes occur in the field. If four physiotopes are identified, each with three classes of SOC contents, the maximum number of observations per class is eight, assuming 100 observations in total. With three observations per class as a minimum for statistical analysis, and five observations as statistically ‘desirable’, the maximum data loss allowable is 50 to 70%.

The use of standardised question-answer formats limits the analysis to non-parametric statistics for qualitative SOMFIEs. The outcome of quantitative SOMFIEs can be analysed with parametric statistics, providing a numerical indication. If an ideologically biased SOMFIE entered the qualified SOMFIE list in Phase II (Section 3.3.2), no relationship with the position in the SOCIMR will be found. Overall, the number and mix of samples, in relation to physiotopes, is crucial.

3.3.4 Paired field case studies (Phase IV)

The methodology in this phase is designed to provide a verifiable illustration of the third objective: “*To qualify and quantify the SOMFIE indicators for fields along the SOCIMR, and/or under different SOM management.*” The number of Type 4 comparisons is limited by their availability, and because they are selected from and during Phase III, the data gathering and analysis of the case studies occurs after all the SSIs in Phase III have been completed.

The aim is to make a Type 4 comparisons for each physiotope. The first step is to verify that the environmental conditions are similar for the two fields. Where this is true, the fields are monitored over a growing season. In cooperation with the farmers more detailed SOMFIE information is gathered.

LIMITATIONS AND EXPECTED DIFFICULTIES

Paired-field case study selection depends on the available instances encountered in Phase III. It is possible that case studies are not found for all selected physiotopes. Furthermore, considerable resources are required for testing of environmental similarity of the two fields.

3.4 SYNTHESIS

All four phases were needed – with feedbacks between phases – to arrive at a balanced answer to the overall research question: "*Does SOM, or its management, provide on-farm benefit to farmers?*". The output from Phase I provided information about the environmental conditions governing SOC variation, which were needed to create physiotopes and their SOCIMRs.

The creation of physiotopes was a vital step. Different environmental conditions provide different dynamics for soil processes involving SOM. These different dynamics lead to different SOC management ranges per physiotope. In the literature, other attempts at finding SOC management ranges have been reported. Körschens *et al*. (1998) provided a SOC management range for arable soils in Germany depending on one environmental variable – clay content. However, SOC management ranges for physiotopes constructed from multiple environmental variables have not been reported in the literature up to the present. Looking at just the minimum SOM level, Nortcliff (2002) notes: "*There has been no consensus on what the critical level of soil organic matter should be in agricultural soils and how this level will vary between soils of different textural classes under different environmental conditions*". Therefore, the output of differential SOCIMRs was a result in itself.

Physiotopes were needed in Phase III, where fields in different physiotopes and SOC contents were selected. This selection procedure controlled important environmental variables, and allowed fields to be selected from the lower to the upper limit of the SOCIMR. The latter is important, because when selecting fields on the basis of SOM management as opposed to actual SOC contents, the sample will be centred around the median and therefore not represent the whole of the SOCIMR.

The process of SOMFIE indicator generation and consistent question-answer phrasing in Phase II (questionnaire) were both needed in the SSIs of Phase III. At the same time the SSIs of a random stratified sample of commercial farmers, provided by Phase III, were integrated with Phase II for SOMFIE valuation and awareness assessment. The physiotopes play a vital role, since SOMFIE indicators are likely to be 'sensitive' (respond with varying magnitudes) to different physiotopes. In the case of easier tillage for example, when comparing fields high and low in SOC contents, different clay content will be an extra variable in measuring the SOMFIE 'ease of tillage', distorting the effect of SOM alone. Physiotopes are a tool for preventing SOMFIE distortion. In-depth case studies in Phase IV were needed to provide more detailed, monitored examples to check against the larger sample group.

Chapter 4

ORGANIC CARBON MANAGEMENT RANGES IN ARABLE SOILS

> ***"Statistics can be made to prove anything - even the truth"***
>
> Author Unknown

This chapter investigates the environmental variables that govern variation in SOC contents, and it defines 'SOC Indicative Management Ranges' (SOCIMRs) for arable ecosystems in England and Wales.

4.1 INTRODUCTION AND OBJECTIVES

Chapter 1 stated the knowledge gap regarding attainable SOC contents in arable fields, the interest in OC sequestration in arable soils, and the need for future policy to be based on sound scientific evidence. Chapter 2 reviewed the research on SOC contents which showed a consensus on a positive relationship with clay contents. A limited number of studies have determined a lower limit for SOC contents relative to clay contents. The identification of upper SOC limits, for a given clay content, is more difficult because the upper boundary of SOC contents values is less distinct, with many outliers (Figure 2.3). Körschens *et al*. (1998) calculated upper limit SOC contents by adding 'active' SOC values derived from field experimentation to an estimated lower limit, but this approach relies on an extrapolation of results from field-scale experimentation to whole landscapes. For other environmental factors (than clay), the scientific evidence of their importance is not clear (see Section 2.2).

Chapter 3 explained that detailed knowledge regarding attainable SOC ranges for different locations in England and Wales is essential as fundamental knowledge to find an answer to the over-arching research question:
Does SOC, or its management, provide arable on-farm benefit in England and Wales?
Therefore, this chapter aims to reduce the knowledge gap by investigating environmental factors and by determining SOC ranges relative to the most important environmental factors.

OBJECTIVES

Specific objectives were defined as follows:

1. To determine which environmental factors control variation in SOC contents in England and Wales
2. To derive a range of attainable SOC contents relative to governing environmental factors in England and Wales

HYPOTHESIS

The hypothesis tested in this chapter is that there are physiotope-specific SOC ranges in arable fields in England and Wales.

4.2 METHODOLOGY

This chapter determines the environmental factors that control most strongly the variation in SOC contents. Subsequently, 'SOC indicative management ranges' (SOCIMRs) for SOC contents are determined by using 'robust' statistics (to overcome the problems arising from outliers when estimating an upper boundary as well as a lower one for soils under arable and ley-arable management). For a detailed methodology critique see Section 3.3.1. Figure 4.1 shows the methodology flow chart for this chapter to be divided into two phases.

In Phase A the NSI database was analysed statistically (General Regression Model) to establish which environmental factors explain variation in SOC contents. The most important factors were selected and grouped into physiotopes. In Phase B the NSI database was divided into the selected physiotopes and for each physiotope a SOCIMR was established by determining a robust confidence interval.

In this context an indicative management range is defined as the range of SOC contents potentially attained in soils under arable landuse, with different types of management under particular environmental conditions.

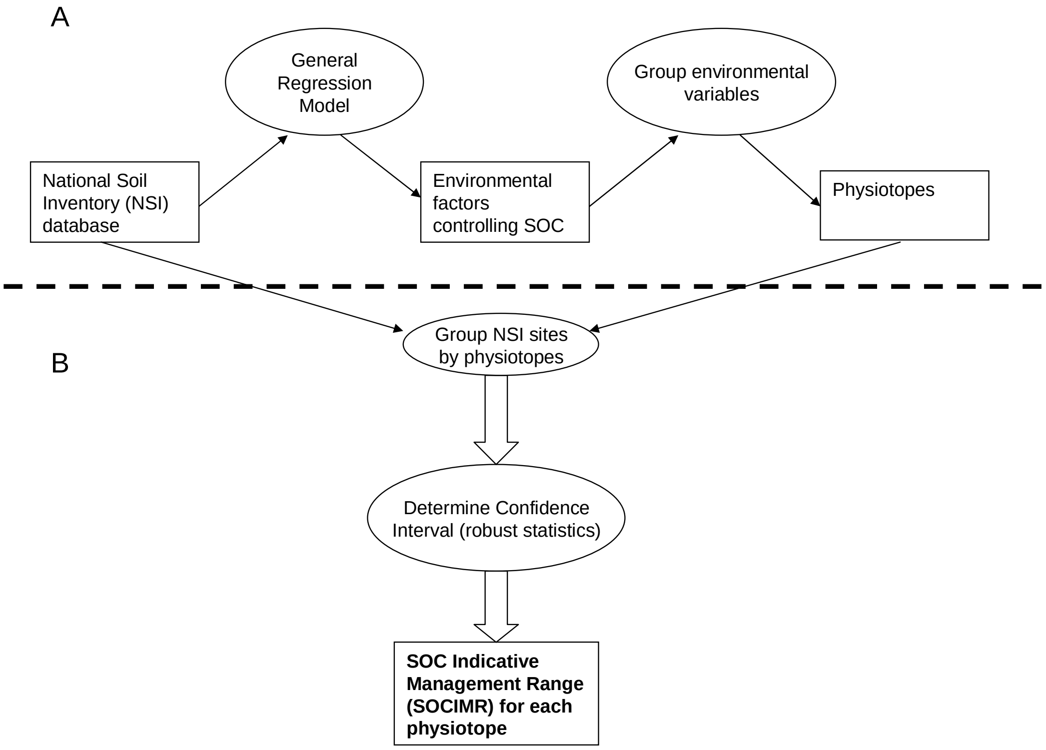


Figure 4.1 Flowchart of Chapter 4 methodology (see Thesis Flowchart, Figure 3.2, for integration in thesis methodology). The dashed line divides the flowchart in two parts. In part A environmental factors that explain variation in SOC are determined, on which physiotopes are based. In part B a SOCIMR is determined for each physiotope.

4.3 METHODS

4.3.1 National Soil Inventory database

Between 1978 and 1983 the topsoil (0-15 cm) was sampled at every 5 km National Grid point, offset by 1 km, in England and Wales, and analysed for a number of parameters (Loveland, 1989). Gravimetric SOC concentrations were measured by a modified Walkley-Black method (Kalembasa and Jenkinson, 1973). From a total of 5870 sites, 2448 were classified as arable or ley-arable. Since a short term (2-5 years) grass ley is part of an arable rotation it is not possible to discriminate between ley and arable in the NSI database. The spatial distribution of the arable and ley-arable site data can be seen in Figure 4.2.

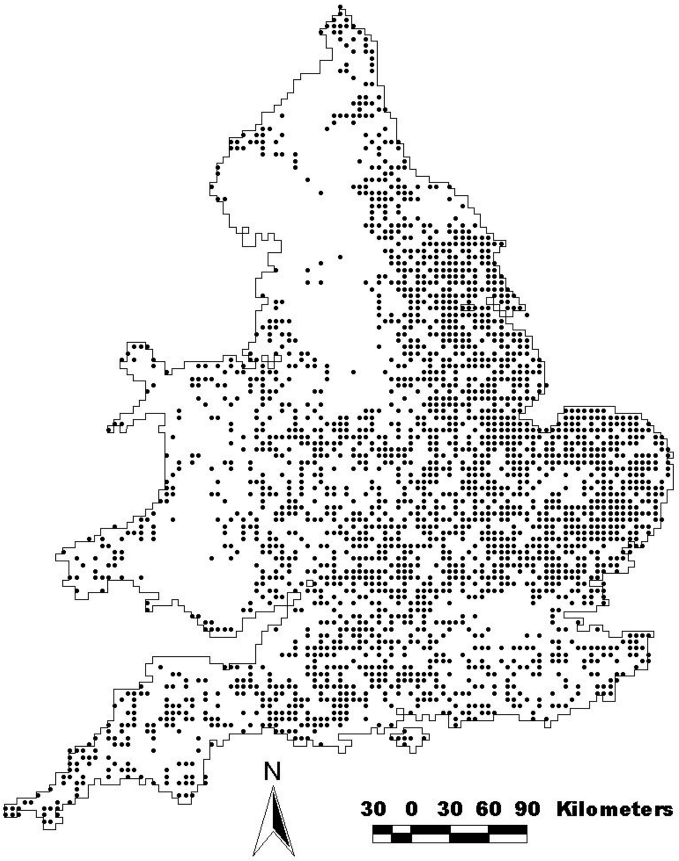


Figure 4.2 Map of spatial distribution of arable and ley-arable sites in the National Soil Inventory sampled between 1978 and 1983 (n = 2448)

4.3.2 Stepwise General Regression Model (GRM)

The parameters used in the analysis to try to explain the variation in the SOC are shown in Table 4.1; there are 12 environmental and two anthropogenic parameters.

Table 4.1 Characteristics of the independent variables

	(In)direct measurement	Coverage	Units	Description	Type
Clay & silt content	Direct	High	%	Gravimetric	Environmental
Clay mineralogy	Direct	Low/ moderate	Class	20% threshold[a]	Environmental
Depth of surface horizon	Direct	High	cm	Depth of A_p	Anthropogenic
Calcareous topsoil	Direct	High	Y/N	Acid test	Environmental
pH	Direct	High		Lab test	Environmental/ Management
Depth to gleyic properties	Direct	High	cm	[b]	Environmental/ Management
Precipitation	Indirect. Interpolated from MET office data	Moderate	mm yr^{-1}	Average annual precipitation	Environmental
Temperature	Indirect Interpolated from MET office data	Moderate	ºC	Accumulated annual temperature above 0 ºC	Environmental
Flooding susceptibility	Direct	Moderate /high	Y/N[c]	Field observation by surveyor	Environmental
Slope angle	Direct	High	°	Measured/ estimated by surveyor	Environmental
Aspect	Direct	Moderate	Class	Measured by surveyor into 16 classes	Environmental
Altitude	Indirect	High	m	Interpreted from OS 1:25.000 map	Environmental
Sampling personnel	Direct	High		Initials of surveyor	Anthropogenic
Day of sampling	Direct	High	Julian day	Day soil sample was taken	Environmental

[a] Dominance threshold (20%) of clay mineral class, [b] Depth at which fluctuating water table causes redox reactions, [c] Y/N : Yes/No, OS = Ordnance Survey

The statistical distributions of all these parameters were examined to identify those that could be included in a multiple regression analysis (i.e. continuous, normally distributed and independent) and those that could be considered effects in terms of a General Linear Model (categorical). Overall, the *F* test (used in General Linear Models) is robust to deviations from normality (Lindman, 1974).

It was found that by removing extreme values (>8 % SOC; NB arable soils), the distribution of SOC was approximately normal (with a skew and kurtosis of 1.16). Clay content, silt content, depth of surface horizon, altitude, pH, annual average precipitation and annual accumulated temperature above °C were plotted in histograms, and all were distributed normally. Depth of surface horizon was measured, in the field, as the depth of the Ap horizon. Depth to gleying was not a continuous variable; it was recorded to 118 cm, but for depths greater than this was given a value of 999. This parameter was divided into four categories. The distribution of slope angles was not normal and could not be transformed to normality so values were put into one of two categories (<5° and >5°). Date of sampling was categorised into the common four seasons. Calcareous topsoil and susceptibility to flooding were categorical parameters (Yes/No).

For aspect, sampling personnel and clay mineralogy there were insufficient data in each class to allow inclusion in the General Regression Model. These parameters were analysed using analysis of variance to test for any significant differences between different classes. Sites were assigned to a clay mineralogy class (smectite, kaolinite, illite, vermiculite) on the basis of >20% of total clay content being a clay mineral type. The small number of sites with peat soils was eliminated from the data set as being atypical of the bulk of soils under arable and arable-ley management in England and Wales. A forward stepwise General Regression Model was performed using STATISTICA version 6.1 (StatSoft, 2003); see 4.4.2.2 for results.

4.3.3 'Robust' statistical methods

Once the most important parameters explaining the variation in SOC had been identified, using the GRM analysis, the data set (including the extreme values) was divided into *physiotopes*, i.e. landscape units with similar values for factors governing SOC. Each physiotope contains a relatively small number of observations, so it was not desirable to remove outliers. Hence *robust* statistics were used to describe each physiotope. Robust statistics have been developed to reduce the sensitivity of statistical analysis to outliers. The *median* was used as an alternative to the mean as an estimator of the central tendency of the data within each physiotope, and Rousseeuw and Croux's (1992, 1993) estimator *Qn* was used as an alternative to the standard deviation (Equation 4.1). The estimator *Qn,* based on a linear combination of order statistics, was found to be both consistent and efficient. For a set of values of a variable X_i, $i = 1, 2, \ldots, n$

$$Q_n = 2.219\left\{\left|X_i - X_j\right|; i < j\right\}_{\binom{H}{2}}, \qquad [4.1]$$

where H is the integer part of (n/2) + 1 and the term $\{\cdot\}_{\binom{H}{2}}$ denotes the value of the $\binom{H}{2}$th ordered term in the braces.

The constant is a consistency correction, so that *Qn* estimates the standard deviation as if the data were drawn from a normal distribution. Q_n was calculated using software (Rousseeuw & Croux, 1992) and it and the median were used to determine confidence intervals (see Section 4.3.4) for values of SOC contents for each physiotope.

4.3.4 Categorisation and interpolation of data

To determine SOCIMRs, five primary clay content categories and three secondary precipitation categories were defined to provide similar numbers of observations between categories. For each category, the median of the SOC contents value was computed and Q_n calculated. The lower and upper limits for each category were estimated as the 80% confidence intervals of the Q_n statistic around the median. The choice of 80% confidence intervals was arbitrary and reflected a judgement on the extent to which the tail of especially larger SOC contents values should be included in generic indicative ranges.

4.4 RESULTS

For all results, gravimetric SOC content is used. SOC stocks (t ha^{-1}) were also considered. However, measured bulk density data were not available for the NSI sites, and bulk density pedo-transfer function performance was poor. Also, stone content data were only available as a rough estimate. Therefore, only SOC contents were used as the dependent variable.

4.4.1 Controls on SOC variation

4.4.1.1 Analysis of variance

There were no significant differences in SOC contents for different classes of aspect, clay mineralogy and sampling personnel.

4.4.1.2 General Regression Model

Clay content, average annual precipitation and depth of surface horizon were the main factors controlling SOC content variation (Table 4.2a). Clay content and precipitation were correlated positively with SOC contents, whereas depth of surface horizon showed a negative correlation. A second group of significant but less important factors was formed by 'sites susceptible to flooding', 'calcareous topsoil' and pH. The latter was correlated negatively with SOC contents, the former two factors positively. The remaining factors – depth to gleying, accumulated annual temperature (above 0°C), day of sampling, silt content, slope angle, and altitude – were either not correlated significantly with SOC contents or explained a negligible part of SOC contents variation.

Table 4.2a Stepwise General Regression Model (GRM) results for non-peaty sites (n= 2448) under arable, and ley-arable land use in England and Wales, with SOC as the dependent variable.

	Step	F stat	P level
Clay content	1*	263.0	0.000
Precipitation	2*	175.1	0.000
Depth of surface horizon	3*	34.5	0.000
Susceptibility to flooding	4*	17.1	0.000
Calcareous topsoil	5*	13.0	0.000
pH	6*	32.7	0.000
Depth to gley	7*	5.9	0.000
Temperature	8*	9.6	0.002
Day of sampling (Julian)	9*	2.9	0.036
Silt content	10	0.3	0.580
Slope angle	11	2.2	0.140
Altitude	12	0.8	0.375

*** = significant at $p<0.05$.**

When sites susceptible to flooding, and those with calcareous surface horizons – representing respectively 8 and 23% of total sites - were omitted from the GRM, the total assignable SOC variation increased to 25.5% based on the factors clay content (16.5%), average annual precipitation (7.9%), and depth of surface horizon (1.2%) (see Table 4.2b). This omission of sites did not alter the normal distribution of SOC contents, which may be explained in part by noting that the surface horizons of many soils on calcareous parent material have been decalcified.

Table 4.2b Stepwise General Regression Model (GRM) results for non-peaty, non-calcareous topsoil and non-flooding sites (n=1511) under arable, ley-arable land use in England and Wales, with SOC as the dependent variable

	Step	F stat	Cumulative R^2	R^2 change	P level
Clay content	1*	297.1	0.165	0.165	0.000
Precipitation	2*	156.8	0.243	0.079	0.000
Depth of surface horizon	3*	23.7	0.255	0.012	0.000

*** = significant at $p<0.05$.**

4.4.2 Physiotopes

Clay and precipitation ranges were used to define 15 physiotopes, i.e. landscape units with similar values for these SOC governing factors. Although the same soil processes occur in different physiotopes, differences in their magnitudes and interactions result in different SOC contents between physiotopes. Data for each physiotope were then analysed using 'robust' statistics to estimate lower and upper limits for SOC contents (Sections 4.3.3 and 4.3.4).

Soils were assigned to classes on the basis of five clay content ranges and three precipitation ranges, as presented in Table 4.3. As far as possible, ranges were chosen to provide similar numbers of observations in the categories. Physiotope boundaries are arbitrary and depend on their intended application. In this case, the main criterion was having sufficient observations within each physiotope for 'robust' statistics to be applied. Also, clay content, as the most important factor in the GRM, was allocated more classes than precipitation.

Table 4.3 'Robust' median SOC values per physiotope (Q_n in parentheses)

Clay (%)	< 650 mm yr^{-1} AAP[a]	650 – 800 mm yr^{-1} AAP	800 – 1100 mm yr^{-1} AAP	Permanent Grassland
0 - 10	1.1 (0.41)	1.2 (0.61)	2.1 (1.06)	2.6 (1.23)
10 – 20	1.5 (0.65)	1.9 (0.88)	2.4 (1.10)	3.3 (1.31)
20 – 30	1.9 (0.66)	2.5 (0.88)	2.7 (1.08)	3.8 (1.33)
30 – 40	2.4 (0.88)	2.5 (0.88)	3.4 (1.29)	3.8 (1.29)
40 – 50	2.8 (1.08)	3.4 (1.30)	4.0 (1.14)	4.8 (1.31)

[a] AAP = Average Annual Precipitation. Permanent Grassland data serve as a comparison and could not be differentiated for precipitation (limited data points). Q_n is a robust alternative to the standard deviation. All SOC values are gravimetric percentages for the top 0-15 cm.

4.4.3 SOC indicative management ranges (SOCIMRs)

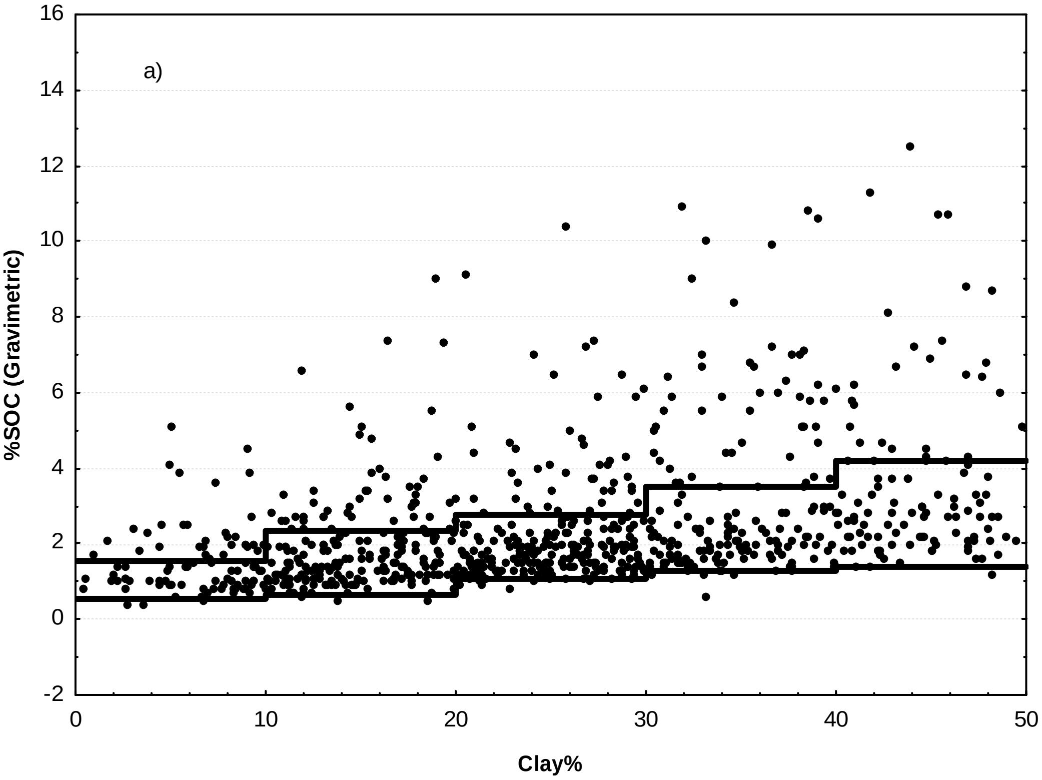


Figure 4.3a SOCIMRs for dry soils (< 650 mm yr^{-1} of average annual precipitation) under arable and ley-arable farming (n=500). See Appendix 6 for results of intermediate and wet soils.

SOCIMRs were estimated by categorisation and interpolation (4.3.3 and 4.3.4). Figure 4.3 shows the result of applying 'robust' statistics to calculate 80% confidence intervals (the heavy lines) for SOC values per clay category within one precipitation class (< 650 mm yr^{-1}). The same procedure was followed for the other two precipitation classes, 650-800 mm yr^{-1} and 800-1100 mm yr^{-1} (individual data not shown). Figure 4.4 shows the 80% confidence intervals for all precipitation categories. Permanent grassland data have been added for comparison, as have other SOC guideline values from the literature.

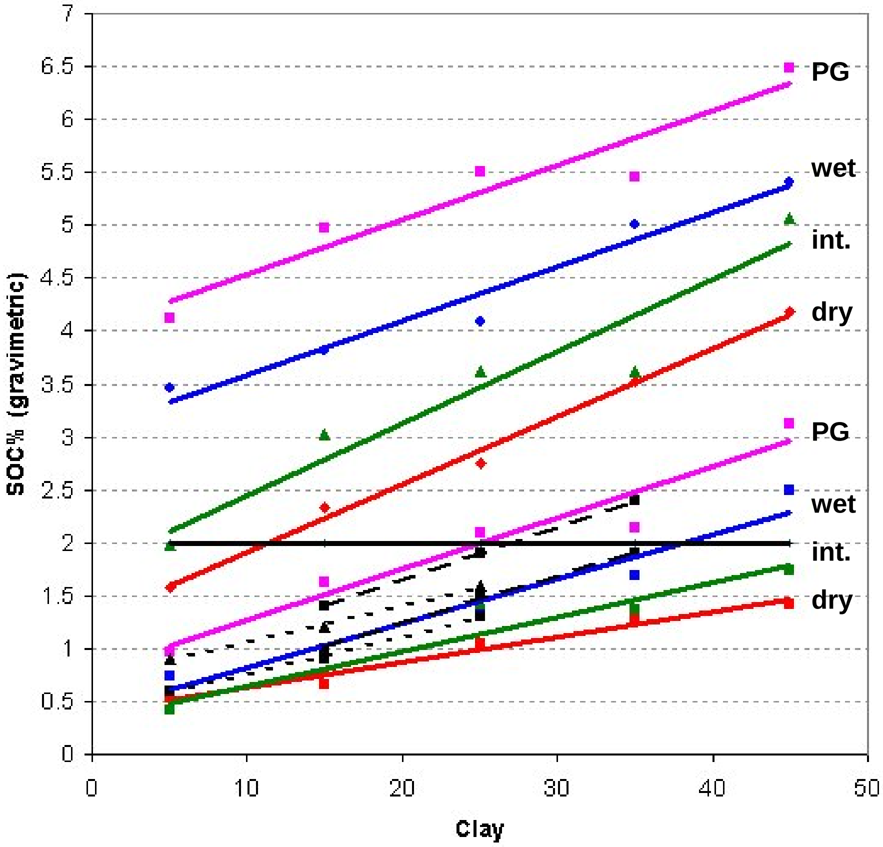


Figure 4.4 SOCIMRs for dry (red), wet (blue) and intermediate (green) soils under arable and ley-arable farming, plus soils under permanent grass (pink), which were not differentiated for precipitation due to lack of data. The precipitation classes and corresponding mean SOC values are defined in Table 4.3. Both types of dashed lines in are based on data of Körschens *et al.* (1998), and the heavy horizontal line at 2% SOC is taken from Greenland *et al*. (1975). See Table 4.4 in Appendix 7 for data values.

4.5 DISCUSSION

4.5.1 Governing controls on SOC variation

4.5.1.1 Analysis of variance

In a one-way ANOVA, clay mineralogy was not identified as a controlling factor on SOC contents, although it has been identified as a factor influencing rates of SOC turnover (Powers & Schlesinger, 2002; Wattel-Koekkoek *et al.*, 2003). Soils in England and Wales generally have a relatively high degree of mixed clay mineralogies. Sites were assigned to a clay mineralogy class on the basis of >20% of total clay content being a clay mineral type and this may have limited the observed correlation to SOC contents.

Although Net Primary Production (NPP) is lower on north facing slopes, higher SOC contents might be anticipated in these soils, because of decreased turnover rates, as north facing slopes are generally wetter and cooler in England and Wales. This effect was not observed, probably because 95% of the sites have < 5° slope angles.

4.5.1.2 General Regression Model

From the General Regression Model, this study confirmed the strong positive correlation between SOC contents and clay content, which has been reported previously (Russel & McRuer, 1927; Freitag, 1980; Spain *et al.*, 1983; Nichols, 1984; Parton *et al.*, 1987; Burke *et al.*, 1989; Jenny, 1994; Loveland *et al.*, 1997; Körschens *et al.*, 1998; Rühlmann, 1999; Lettens *et al.*, 2004). It also confirmed the presence of a minimum SOC content for arable soils which rises with increasing clay content (Körschens *et al.*, 1980; Hassink, 1997; Loveland et al., 1997;

Körschens *et al*., 1998) possibly due to increases in the absorption of SOC to clay surfaces and its occlusion within clay particles and more stable aggregates (Skjemstad *et al*., 1996; Christensen, 2001; Eusterhues *et al*., 2003;).

Precipitation has been identified as a factor controlling both total SOC contents (Russel & McRuer, 1927; Jenny & Leonard, 1934; Amelung *et al*., 1997; 1998; Alvarez & Lavado, 1998) and 'active' components of SOC (Franzluebbers *et al*., 2001). In this study, annual average precipitation was correlated positively with SOC contents, explaining 8% of the variation in the latter. Greater equilibrium SOC contents could arise from both increased Net Primary Production (NPP), caused by higher precipitation, and/or decreased aerobic decomposition of organic matter in wetter soils. The precipitation values were interpolated data from permanent weather stations. A stronger correlation might exist between actual precipitation at sampling locations and SOC contents, but these data do not exist. Precipitation is also only a proxy for soil wetness, which also depends on factors for which data were not available, including position in the landscape (water supply) and soil hydraulic properties. Some support for the possibility that soil wetness is an important controlling factor on SOC contents in non-peat soils is afforded however, by the significantly higher average SOC contents for the 8% of sites susceptible to flooding (3.5% compared to 2.62% for non-flooding sites, $P<<0.05$). A further consideration is that the wetter parts of England and Wales have more and longer term grass leys in arable rotations and these increase SOC contents, leading to an indirect effect on SOC contents from precipitation.

Temperature was relatively weakly correlated with SOC variation in this study. This is most likely caused by the use of air temperature rather than soil temperature, a small temperature range (compared to precipitation range), and interpolated temperature data from permanent weather stations.

The third factor controlling SOC contents is the depth of the surface horizon, which in the arable sites studied equates to ploughing depth. The observed negative correlation with SOC contents is possibly explained by a dilution of OC input into different volumes of soil depending on the depth of the plough layer.

The remaining approximately 75% of SOC variation is attributable to other and unrecorded environmental factors, or management factors. These could include: position in the landscape; excessively free draining subsoil; organic matter additions to the soil; crop residue management; ploughing intensity; crop rotations; landuse history; etcetera (see Sections 6.4.2 and 6.5.4).

4.5.2 SOC indicative management ranges

The SOC indicative management ranges (SOCIMRs; Figure 4.4) illustrate a strong influence of two environmental variables – clay and precipitation – on SOC contents. In a drier-sandy physiotope, indicated SOC contents are 0.5 to 1.6 % while in a wetter-clay physiotope, the indicated range is 2.0 to 5.4 %. The divergence of the lower limits for different physiotopes, with increasing clay content, suggests that the impact of precipitation on the lower SOC limit is greater in 'heavier' soils, as the divergence of the envelopes increases with higher clay contents. The divergence of the SOCIMRs decreases with increasing precipitation. Data for permanent grassland sites (Figure 4.4) have been included for comparison and show no marked divergence in SOC envelope limits, suggesting that the divergence for arable soils may result from the influence of precipitation on the extent to which SOC contents are affected by soil management activities, e.g. tillage, irrigation, drainage, liming and organic matter additions.

The omission of sites susceptible to flooding and those with calcareous surface horizons was justified on the grounds that such sites are relatively atypical under arable landuse. However, the consequence of this is that the proposed SOCIMRs cannot be applied to such sites.

4.5.2.1 Comparison of SOC contents and ranges

Körschens *et al*. (1998) related the lower SOC limit to clay plus fine silt (< 6.3 μm), while Webb *et al*. (2003) related it to clay (< 2 μm). Körschens *et al*. (1998) base their 'minimum line' of SOC for arable (no ley) soils without groundwater influence on a combination of experimental and survey data. The 'minimum line' was interpreted to reflect increasing inert SOC with increasing clay content. The 'maximum line' was calculated by adding 0.5 to 0.9% %SOC to the minimum line, again based on long-term experiments, whereas in this research the upper limit was based on a robust statistical analysis of populations of SOC values. Comparison of the Körschens *et al*. 'SOC guideline values' with the SOCIMRs (Figure 4.4), indicates that the lower limits are similar but the upper limits proposed by this work are much greater, with the majority of samples from sites in England and Wales above the upper limit proposed by Körschens *et al*. (1998). An additional mechanism behind this narrower SOC range can be the lower precipitation of the study area used by Körschens *et al*. (Bad Lauchstädt, Germany), i.e. 484 mm yr^{-1} annual average precipitation, and free draining soils.

These lower and upper limits should not be confused with critical or threshold SOC levels, which refer to a particular SOC content at which the performance of a soil function changes significantly. Lower and upper limits merely give a robust estimate of the SOCIMR for a physiotope. Greenland *et al*. (1975) proposed that as a 'rule of thumb', surface arable soils in the UK with less than 2% SOC content are expected to be very liable to structural deterioration. Differential SOC ranges suggest that Greenland's lower threshold is potentially an oversimplification. A critical SOC threshold for soil structure is likely to be different for different physiotopes. Soil structure related impacts of SOC are analysed and discussed in Sections 6.4.3 and 6.5.3, respectively.

4.5.2.2 Implications for soil management

This work suggests that SOC target values should only be set after taking account of the management ranges for different physiotopes. Specifically, target levels may not be achievable if they are set above or below the relevant management range.

If there is a threshold SOC content below which some dysfunction occurs (for example, the 2% level below which Greenland postulated that there is a higher risk of structural damage), sandy soils in drier areas may always be "at risk" if the upper limit of the manageable range is below such a threshold value. Fine sandy and silty soils are more structurally sensitive to SOC and would thus need to be looked at separately. A careful choice of tillage method and other measures will then be required to reduce the risk of damage, regardless of SOM management. Conversely, if the lower range limit is above the threshold value then the risk of dysfunction will be small however the SOC content is managed, and a wider range of tillage methods and other soil management options may be adopted safely. In intermediate cases, proactive SOM management may be needed to ensure that the SOC contents is maintained above a threshold, if one can be identified, that is appropriate to soil use and management practices.

The SOCIMRs concept has potential to be developed into a practical tool through more knowledge (and research) of environmental variables (discussed here and others) and land use/management variables (e.g. recent management, past conversion from permanent grass or forest, and anthropogenic inputs close to urban areas).

Climatic change can alter the environmental conditions for the physiotopes and thereby lower and upper limit estimates. Higher annual average precipitation in the future would lead to higher potential levels of SOC, although this will depend on the temporal distribution of the rainfall, i.e. if precipitation increase coincides with a more bimodal precipitation distribution, i.e. high in winter and low in summer (Moberg and Jones, 2005), effects on SOC are uncertain. Furthermore, if the precipitation increase coincides with a rise in temperature, the concomitant enhanced turnover rates of SOM might offset the increased precipitation effect. At present there is no consensus on the relative importance of precipitation and temperature (Giardina & Ryan, 2000a; 2000b; Powlson, 2005).

4.5.2.3 Implications for active SOC

The lower limits for SOC in soils with similar clay contents are raised where precipitation is higher. Wetter conditions may result in longer mean residence times for more ‘active’ SOC fractions because aerobic decomposition is decreased. More research is needed into the interaction between physiotopes –

or sets of environmental variables – and the proportion of 'active' SOC for varying positions in the SOCIMRs.

4.6 CONCLUSIONS AND RECOMMENDATIONS

Clay content and precipitation explain 25% of the variation in the SOC contents of arable and ley-arable soils in England and Wales. They have been used to define SOC indicative management ranges (SOCIMRs), which show large differences. This is illustrated by viewing two opposing physiotopes: the SOC contents in a dry-sandy physiotope range from approximately 0.5 to 1.6%, while those in a wet-clayey physiotope range from about 2.0 to about 5.4%. These results demonstrate a need to take account of both clay and precipitation in SOC management and when investigating the effects of management on SOC contents. More research on additional environmental conditions is needed to further develop and differentiate the 'SOC management range' concept (see Section 6.5.4). Once a consistent method of measuring Black Carbon has been established (see Section 2.1), potential further differentiation may be achieved by including Black Carbon in analyses. Climatic change can alter the environmental conditions for the physiotopes and thereby lower and upper limit estimates. SOCIMRs provide a tool for estimating the potential range of SOC levels for arable soils with a known clay content and average annual precipitation.

CHAPTER 5

FARMERS' PERCEIVED VALUE OF SOIL ORGANIC MATTER IN ARABLE FIELDS

> ***"Well…..it must be good.***
> ***That's what you guys have been telling us for years!"***
> Participating farmer's reply when asked about SOM

This chapter describes the development of a qualified SOMFIE indicator list. It also investigates which indicators farmers perceive to be more important, depending on environmental conditions.

5.1 INTRODUCTION

The aims of the research described in this chapter are to develop indicators of on-farm economic impact of SOM (SOMFIE indicators), to assess farmer awareness of these, to qualify and quantify their value and to relate these values to farmer experience and to physiotopes.

Technological innovation has reduced the dependency of arable farming on SOM, with for example, conventional farming systems supplementing nutrients supplied by SOM with inorganic fertilisers. A large body of literature exists on SOM processes and interactions with environmental and biological factors, but this provides limited insight into the extent and distribution of SOM impacts on arable farming. Studies on research farms or in laboratories often use a limited number of soil types, and often with no apparent consensus (see 2.2.2). Very few studies have reported on farmers' experiential knowledge about how SOM impacts on farming, although this is a rich source of potential information (see 2.3).

5.1.1 Objectives

Specific objectives were defined as follows:

1. To develop a comprehensive, qualified SOMFIE indicator list and commentary.

2. To assess farmers' awareness of SOMFIEs.

3. To assess the perceived value of SOMFIEs relative to each other, in different physiotopes and with varying SOM management.

5.1.2 Proposition

The proposition tested in this chapter is that arable farmers in England and Wales perceive SOM as providing a beneficial on-farm economic impact.

5.2 METHODOLOGY

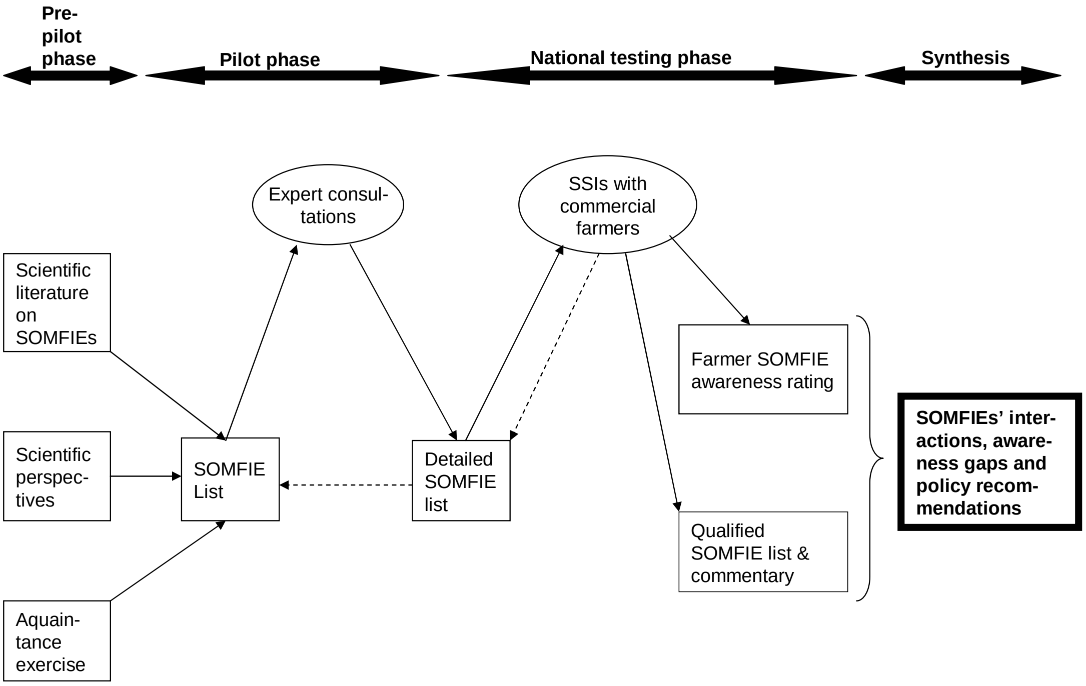


Figure 5.1 Flowchart of Chapter 5 methodology (see the Thesis Flowchart, Figure 3.2, for integration in thesis methodology). SSI = semi-structured interview.

This chapter explores the experiential science of primary and secondary stakeholders within the context of scientific perspectives. For a detailed methodology critique see Section 3.3.2. Figure 5.1 shows the methodology used which is divided into four phases:

1. A pre-pilot phase to acquaint the investigator with arable farming in general and its interaction with SOM and SOM management in particular.
2. A pilot phase to generate a comprehensive, qualified SOMFIE indicator list (including commentary), by using an iterative process involving exploration of the scientific literature, experimental or research farmers' knowledge, and opinions of a group of expert commercial farmers (see Figure 3.4).
3. A national testing phase to further develop the SOMFIE list, and rank it by assessing perceptions of commercial farmers, within four contrasting physiotopes. Investigation of contrasting physiotopes is required for testing if and how the relative importance of SOMFIEs is influenced by environmental factors related to SOM. A range of SOM management types and intensities was intended to be represented by the stratified random sample, with a wide geographic coverage. Farmers' awareness of SOMFIEs was tested by open questioning versus prompting. This provided information to rank the values that farmers perceive for different SOMFIEs. Rankings were assessed in relation to physiotopes and farmer experience. This leads to a discussion of the range of SOMFIE values – economic and otherwise.
4. A synthesis to integrate contrasting SOMFIEs and their interactions in arable production. In Chapters 6 and 7, conclusions about SOMFIE perceptions are validated by reference to their measured impacts.

5.3 METHODS AND MATERIAL

The NSI database was used to select a stratified random sample of arable farmers in England and Wales. Environmental selection criteria were set as discussed in Chapter 6 (see Section 6.2), i.e. four physiotopes based on two clay contents classes (10 – 20 and 30 – 40 % clay) and two precipitation classes (< 650 and 800 – 1200 mm yr^{-1}). Therefore, at least one field (or part of a field) on each farm was in one of the physiotopes. Farmer contact information was compiled by use of facilities on the World Wide Web (i.e. yell.co.uk, bt.co.uk, and google.com), and, in case no information was found, by 'cold visits'. Appointments were made by phone, email, or fax with every farmer. After conducting a SSI with each farmer, interview data were stored in an Excel database for subsequent qualitative data analysis.

5.3.1 Semi-structured interview survey

Semi-structured interviews (SSIs) use flexible checklists rather than formal questionnaires, allowing useful trains of thought to develop and the exploration of emerging themes (see Section 3.3.2). The following sequence was followed:

1. The interviewers (normally two scientists) introduced themselves and the institutes involved in the project and Defra as the project sponsor.
2. The need for the research was explained.
3. The interview itself was then opened with one of the interviewers asking for general information about the farm (e.g. size, rotations).
4. This led to an exploration of the farmer's experience with OM management, including a discussion about different ways to manage SOM. To establish consensus on the topic of discussion, the farmer was asked (unprompted) about his/her perceptions of how SOM impacts on their farming. Care was taken to ensure only open questions were asked.
5. After giving the interviewee ample time to mention SOMFIEs, s/he was prompted for the remaining SOMFIEs. The farmer was then asked to value all the SOMFIEs that had been recognised. The SSI ranged from one to two hours duration.

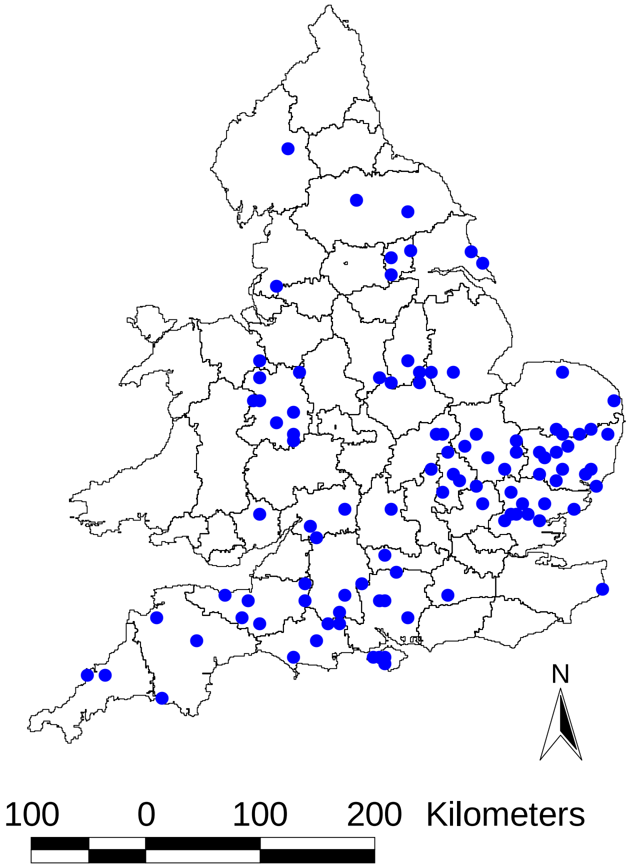


Figure 5.2 Locations of participating farmers in SSI survey (n = 101).

The collection and analysis of semi-structured interview data are particularly sensitive to investigator bias. The 'correctness' of the findings may be assessed by corroboration and repetition. Internal validity (credibility of findings), and external validity (establishing the domain to which the results can be generalised) may be supported by corroboration with results described in the literature. Repeatability, known in the social sciences as reliability (the extent to which the results of the study can be repeated with the same results), is impractical for the resources available here. A separate research group deploying a similar study may be the only way of demonstrating reliability.

5.3.2 Database

All SSI data were recorded on paper during the interview. On returning from the field, data on farmers’ perception were entered into an Excel datasheet. Land use history and farm management data were entered into the online project database SOMATIC (for accessibility to all project colleagues) and subsequently downloaded into an Excel datasheet, before being merged with the data on farmer perceptions.

5.3.3 Creation of theory – basics of qualitative data analysis

Environmental conditions important to SOM (see Chapter 4) combined with scientific perspectives (see Chapter 2), were used to build theory via an iterative, participative process drawing on the experiential science of stakeholders. The method of ‘grounded theory building’ is described in Section 2.3.1.

In a naïve inductivist model of the research process, it is assumed that theoretical categories will simply emerge from the empirical material if the researchers free their minds of theoretical preconceptions. However, one of the most crucial insights into modern philosophy of science and cognitive psychology is the fact that ‘there are and can be no sensations unimpregnated by expectation’ (Udo, 2000). The overall expectation of this research is expressed by the proposition in Section 5.2.1. The SOMFIE list makes expectations explicit, by expressing the assumed existence of a link (a positive or negative correlation) between individual SOMFIEs and SOM.

5.4 RESULTS AND INTERPRETATION

Of the pre-pilot phase only results for the 'acquaintance exercise' are described. See Chapter 2 for results on scientific literature and perspectives of SOMFIEs.

5.4.1 Acquaintance exercise

The initial 'acquaintance exercise' was aimed at familiarising the investigator with the relevant farming systems and agriculture in general, and specifically with SOM interactions within arable production. This was achieved by a literature study and discussion with secondary and 'expert' primary stakeholders. Secondary stakeholders are defined as researchers, professional experts and representatives of organisations involved in agriculture. They are considered to be 'secondary' stakeholders because they operate in a support role to primary stakeholders (farmers).

Table 5.1 Research farms visited in the acquaintance exercise.

Research farm	Soil type	Precipitation class	Farming system	Topography
Rothamsted	loamy	dry	arable	flat/lightly undulating
Gleadthorpe	sandy to clayey	intermediate	arable	hilly
Broom's Barn	sandy to clayey	dry	arable	flat/lightly undulating
Rosemaund	clayey	wet	mixed	undulating

The expert primary stakeholders consulted in the acquaintance exercise were operational managers of research farms belonging to ADAS and Rothamsted Research, with different soils, precipitation levels, topographies, and farming systems (see Table 5.1). The consultation method chosen was one of 'open interview' between the research farmer and a project group, which included soil scientists, a social scientist, an economist, and a 'practical agricultural expert'. The project group was kept to a maximum of four members during the interview to avoid overwhelming the interviewee, and to reduce any potential for an unbalanced discussion.

Facts and opinions were sought to corroborate (or otherwise) and complement information gathered in the literature review (see Section 2.2 and Table 2.7). At the same time, initial ideas were developed and evaluated about the formatting of a structured questionnaire for use in the next phase of the research, which needed to be comprehensible and that could be applied universally and consistently (see Chapter 6).

The acquaintance exercise revealed a need for attention to semantics. Research farmers and academic soil researchers do not share the same jargon, acronyms and colloquialisms. It was clearly of paramount importance to assure that the language being used by interviewee (farmer) and interviewer (academic researcher) was compatible and consistent enough to ensure a meaningful discussion that would generate good quality data. This problem was expected to be more pronounced between *commercial* farmers and academic soil researchers, because their environment and cultural backgrounds are even more distant.

An important additional output from the acquaintance exercise was the conclusion that commercial farmers, rather than research farmers, are the appropriate group for questions targeting 'on-farm economic impacts'. Research farmers appear to have detailed ideas about the processes by which SOM impacts on aspects of agronomy, and they are able and willing to make rough quantifications of these impacts. Their awareness of the financial impacts of SOM however, which were critical to this research, was less developed than that anticipated of commercial farmers.

5.4.2 SOMFIE indicator list (pilot phase)

The starting point for the pilot phase was a candidate list of SOMFIEs generated from literature and scientific perspectives (see Table 2.7). Individual SSIs were conducted with a group of 20 commercial farmers, some of whom were identified by the research farmers and others by random selection from the NSI database. The pilot phase resulted in additional SOMFIEs, including: yield stability; workability window; lodging; water logging; and drought stress. It also informed the design of an appropriate question-answer format (see Chapter 6).

The SOMFIEs that were identified can be grouped by their mode of impact, as devised in Chapter 2, namely: 1) direct impacts on yield, 2) crop-related impacts, and 3) non-crop-related impacts. Each group is composed of a number of functional categories, and, where necessary, sub-categories (a sub-category can be represented by one or more SOMFIEs).

5.4.3 SOMFIE description and measurement evaluation

The SOMFIEs are discussed by category. Firstly, the category is described in general, and then the SOMFIE background is dealt with in terms of functional sub-categories, possibilities and limitations of measurement in space and time, and applicability to England and Wales. Finally, the relevant SOMFIEs are defined and discussed. SOMFIE quantifications and qualifications are examined in Sections 5.4.4 and 5.5.5.

5.4.3.1 Direct impacts on yield

Tables 5.2 and 5.3 give the SOMFIE categories in this group, i.e. ‘yield’ and ‘seed rate’.

- YIELD

Table 5.2 SOMFIE definitions in the 'yield' category

Category	Sub-category	SOMFIE	Definition
Yield	Production	Quantity	Quantity of crop
		Quality	Quality of crop
	Stability	Stability Classification	A measure of the variation in yield over a number of years with varying weather conditions

SOMFIE description. Yield can be divided into two sub-categories 'yield production' and 'yield stability'. The former is composed of 'yield quantity', which is conventionally expressed as t ha^{-1}, and 'yield quality', for which there are several measures.

Yield quantity is measured routinely every growing season. Combinable crops are measured during harvest, and root crops are weighed after lifting.

Yield quality is also measured, but not for every crop harvested, and not every season. Root crop quality is measured more intensively than the quality of combinable crops. Examples are the sugar content of sugar beet, the size and skin quality of potatoes, etc. Cereals are often tested for moisture content and for nitrogen (as a proxy for protein content). Grain density/hardness (bushel weight or 'thousand grain weight') is measured on milling wheat and malting barley. Within the scope of this study it was not possible to collect quantitative information on yield quality.

Annual variation in weather complicates farmers' perceptions of SOM impact on yield. This became clear early in the pilot phase, when every farmer replied to "How much does field A yield?" with words like: "Well, that depends on the kind of year". There does not appear to be a simple way to classify the weather in different years in terms of its impact on yields. A wet autumn can result in late drilling, lower seedbed quality (and therefore worse seedling emergence and establishment), or even the necessity to change winter seed to spring seed. A dry spring can result in drought stress and slow crop growth, and a wet spring can result in waterlogging stress and crop loss. Dry summers can reduce yield quality (shrivelled grains), as well as yield quantity. Wet summers can increase canopy diseases (fungal diseases particularly) although these do not generally affect yield substantially, and high intensity/short duration rainfall events (e.g. thunderstorms) shortly before harvest can cause lodging of large areas.

The difficulties of drawing conclusions are illustrated by the apparently positive correlation between autumn rainfall quantity and yield (McDonald, 1995) and the potentially negative impact of the same rainfall on subsoil compaction from operations on wet soil (which might continue to affect yields for several growing seasons).

- SEED RATE

Table 5.3 SOMFIE definitions in the 'seed rate' category

Category	Sub-category	SOMFIE	Definition
Seed rate	-	Seed rate	Quantity of seed perceived to be required to attain desired yield

SOMFIE description. Seed rate is expressed either as number of seeds per surface area (seeds m^{-2}) or as weight of seed per surface area (kg ha^{-1}). Seed rates are dependent on crops and varieties. Because of the variation in both the application units, drilling date and variety dependence, this SOMFIE does not appear appropriate for survey based comparative analysis. Research using experimental plots would be able to keep these variables consistent and provide a more substantive comparison.

SOMFIE MEASUREMENT RECOMMENDATIONS

- ✓ Yield quality of combinable crops is inappropriate for comparative analysis based on surveys, because of its infrequent measurement and the variety of measurement methods. However, for root crops a survey could provide a sound method of comparison, given a sufficient number of observations. Seed rate is unsuitable as it depends on crop type and variety, both of which are highly variable. Moreover, different units of measurement are employed widely.
- ✓ Yield quantity is nearly always measured, although silage and straw yields are generally estimated. Yield quantity is appropriate for surveys if a robust approach is used to deal with inter-annual weather variation. Many farmers only perceived an impact of SOM on yield in extreme weather years, so a SOMFIE measuring yield stability over a number of years, or yield quantity targeted at known extreme weather years, could prove valuable.

5.4.3.2 Crop-related impact

Tables 5.4 to 5.6 give the SOMFIE categories in this group, i.e. 'fertilisers', 'crop establishment', and 'disease'.

- FERTILISERS

Table 5.4 SOMFIE definitions in the 'fertiliser' category

Category	Sub-category	SOMFIE	Definition
Fertiliser	Quantity	Nitrogen (N)	Quantity of fertilising nutrient perceived to be required to attain target yield
		Phosphorus (P)	
		Potassium (K)	
		Sulphur (S)	
		Micro-nutrients	

SOMFIE description. This category is represented by the different nutrients used as fertiliser. Nitrogen is applied both on its own and as a compound fertiliser (normally as different ratios of P and K). Many different forms of fertiliser exist, e.g. ammonium phosphate, superphosphate, urea, etc. Measurement of a single nutrient requires information on the quantity and type of fertiliser used (including nutrient ratios). Information on N fertiliser was mainly given in metric units (kg ha^{-1}), although also often as a combination of metric and imperial units (kg acre^{-1}), and sometimes as 'units of nitrogen'. A 'unit' in this context equals 1/100 of one hundredweight, or approximately 0.5 kg. As different crops have substantially different nutrient requirements, an effective survey is only possible for a single target crop. For nutrients other than N, application frequencies were found to be low or erratic, providing no useful data.

- CROP ESTABLISHMENT

Table 5.5 SOMFIE definitions in the 'crop establishment' category

Category	Sub-category	SOMFIE	Definition
Crop Establishment	Seedling emergence	Classification	How well seedlings emerge (visual estimate, relative to seed rate)
	Crop levelness	Classification	Extent of taller and shorter crop areas (visual estimate)
	Lodging	Classification	Percentage of field area that lodges (visual estimate)

SOMFIE description. Crop establishment is a broad term that describes how well a crop grows in a field. It is 'measured' in several qualitative, and visual, ways (sub-categories). Seedling emergence is important for crops that germinate weakly (e.g. root crops) and on soils that are prone to soil capping. Farmers assess all the SOMFIEs in this category via a qualitative visual assessment. Farmers reported this to be an useful measure when using a robust classification format.

- DISEASE AND WEEDS

Table 5.6 SOMFIE definitions in the 'disease and weeds' category

Category	Sub-category	SOMFIE	Definition
Disease & weeds	Soil borne	Biocide application	Number of biocide passes perceived to be required to keep crop disease from affecting yield
	Air borne	Biocide application	Number of biocide passes perceived to be required to keep crop disease from affecting yield
	Pests	Slug pellets	Number of pellet application passes

SOMFIE description. Disease is crop sensitive and requires a target crop for survey comparison. The variety of diseases is large. Normally, disease assessment is done by the farmer walking the fields together with an agronomist, although insect traps are also used. Farmers found it very difficult to differentiate between soil-borne and air-borne diseases. Estimating disease using the amounts of biocide applied to a field as a proxy, was not familiar to most farmers. Furthermore, this poses difficulties for interpretation because of the variety of biocides used. A more robust measure of disease was found to be the number of biocide passes made on a target crop.

SOMFIE MEASUREMENT RECOMMENDATIONS

- ✓ The crop related SOMFIEs were mainly qualitative. Nitrogen application was the only truly quantitative SOMFIE. When a target crop is used, and both units and fertiliser type are carefully noted, this is a valuable measure. Useful supplementary data would include the number of N application passes (and even their dates), but this level of detail is beyond that of the interviews.
- ✓ Disease was found to only be a quantitatively robust SOMFIE when expressed as the number of biocide passes required on a target crop. Crop establishment was found to be a difficult category to measure.

Robust descriptive classifications were reported to be a potentially useful measure.

✓ The SOMFIEs in the disease and crop establishment categories should also be averaged over several years (e.g. 10 years) to account for weather variation.

5.4.3.3 Non-crop-related impacts

Tables 5.7 to 5.9 give the SOMFIE categories in this group, i.e. 'workability', 'hydrology', and 'soil degradation'. 'Non-crop-related' in this context means that the impact of SOM on the categories is derived, more or less, independently of the crop type. Although this differentiation is not arbitrary, some overlap between categories belonging to different groups does occur.

- WORKABILITY

Table 5.7 SOMFIE definitions in the 'workability' category

Category	Sub-category	SOMFIE	Definition
Workability	Tillage effort (ease of tillage)	Number of passes	Number of passes required to make a seedbed
		Labour	Number of man hours required to make a seedbed
		Fuel use	Number of litres of fuel required to make a seedbed
		Implement wear	Rate of tillage implement wear
	Subsoiling	Frequency	Number of years between subsoiling operations
	Window	Workability window	Number of days required before tillage operations after sustained rainfall (as a proxy for field capacity)
		Trafficability window	Number of days required before non-tillage operations after sustained rainfall
	Flexibility	Classification	Ease of using the field in planning operations

SOMFIE description. Workability can be divided into four sub-categories, namely 'tillage effort', 'subsoiling', 'workability window', and 'workability flexibility'. Tillage effort is the direct energy and time required to establish a seedbed, and breaks down as shown in Table 5.7. The number of passes to create a seedbed is a crude SOMFIE. It does not differentiate between non-powered and powered tillage implements, nor does it take into account the many different types of tillage implements used, e.g. discs, harrows, spring tines, etc. However, when confined to a single tillage type (either conventional/inversion tillage, or minimum/non-inversion tillage), and with a correction factor for powered tillage implements, this SOMFIE was perceived by the interviewees to be robust. An additional complication, identified in the interviews, is the deliberate practice of 'weathering tillage', when the weather (wetting and drying cycles) breaks down large soil clods over a period of several weeks. Although this practice may not be widespread, as it complicates cultivation planning and delays early drilling, it needs to be taken into account.

Most farmers thought that SOM reduces implement wear. Measurement of implement wear, however, is complicated, both in time and space. Changes in machinery over the last decade make temporal comparison impossible and, since plough points are not changed or monitored between fields, links between SOM levels in fields and implement wear are obscured.

Farmers recognised the 'labour' and 'fuel use' aspects of tillage effort. They reported that fields higher in SOM can be ploughed in a higher gear, reducing labour and fuel costs. However, these SOMFIEs proved to be inappropriate for survey based comparison, as both were not monitored on a regular basis by farmers. They hold potential for research farm comparison. Similarly, for subsoiling it proved difficult to find a suitable format. Measuring benefits to subsoiling operations from reduced fuel use or labour presented the same difficulties as for tillage, but subsoiling frequency (measured as the number of years between subsoiling operations) could be a useful measure. It should be noted, however, that root crops in the rotation distort this SOMFIE, as harvesting root crops is a process that can cause considerable compaction. Many farmers always subsoil after a root crop. Therefore, subsoiling frequency could only be used to assess SOM impacts for rotations that do not include root crops.

The category 'workability window' can be extended to 'trafficability window'. The former refers to periods when tillage operations have a positive effect on soil structure, and the latter to those when soil traffic does not cause damage to soil structure (Droogers *et al.*, 1996). However, the farmers interviewed did not perceive these categories separately. Farmers also found it difficult to identify the length of either window. Normally, tillage operations are simply carried out as quickly as possible after harvest. A more useful measure of the workability window was found to be the time after sustained rainfall before it was possible to get onto the field. Therefore, in using the definition of Droogers *et al.* (1996) it is the trafficability window that is suitable for survey comparison.

From the interviews, it was found that farmers also perceive a benefit from SOM that relates to how flexible the field is when scheduling operations on the farm. This links directly to the workability window, as fields that are perceived to be 'flexible' are those that are thought to have a larger window. A robust classification can be used to measure this 'workability flexibility', although the farmer's perception will naturally depend on the farming system and the number of fields.

- SOIL HYDROLOGY

SOMFIE description. This category can be divided into 'drought stress' and 'waterlogging stress'. These SOMFIEs are sensitive to annual weather variations, so that perceptions need to either represent an average over a multi-year time period, or be targeted at specific (extreme) years, preferably with a dry growing season or a wet cultivation period.

Table 5.8 SOMFIE definitions in the 'hydrology' category

Category	Sub-category	SOMFIE	Definition
Hydrology	Drought stress	Occurrence	Number of years in the last 10 when drought stress was percieved to affect the crop
	Water logging stress	Occurrence	Number of years in the last 10 when water logging stress was observed to affect the crop

A direct economic impact from fewer irrigation applications is confined to irrigated agriculture. For rainfed agriculture, both drought and waterlogging stress may have indirect economic impacts by affecting yield (quantity, quality, or stability) or disease.

- SOIL DEGRADATION

Table 5.9 SOMFIE definitions in the 'soil degradation' category

Category	Sub-category	SOMFIE	Definition
Soil Degradation	Soil capping	Occurrence	Number of years in the past 10 when soil capping was observed to affect the crop
	Soil erodibility	Occurrence	Number of years in the past 10 when soil erosion was observed

Two specific types of soil degradation that were found useful to describe separately were 'soil capping' and 'soil erodibility'. Both can have economic impacts. Soil capping can impede crop establishment leading to yield loss. Soil erosion can cause direct crop loss. It may also incur costs if remediation, such as earth moving, is required. Soil degradation and soil hydrology are inherently linked, e.g. soil capping can lead to ponding (level areas) and waterlogging stress, or to runoff (sloping areas) and erosion.

SOMFIE MEASUREMENT RECOMMENDATIONS

- ✓ The large variation in machinery used (e.g. tractor power, cultivation implement types, etcetera) means that labour and fuel use have to be discarded for survey comparison for consistency reasons.

- ✓ The number of passes to create a seedbed is of possible use for survey comparison, although a correction factor may be required to take account of powered tillage implements.
- ✓ Account also needs to be taken of 'weathering tillage'. Subsoiling frequency is acceptable for survey comparison, when rotations including root crops are omitted.
- ✓ The workability/trafficability window is, in practice, only reportable as the time period between sustained rainfall and when a field can accept traffic (trafficability). Workability flexibility, measured by a robust classification, was perceived by the farmers to be a useful indicator.

5.4.4 Farmer SOMFIE awareness

Awareness of SOM and its benefits is important because it is likely to influence the acceptance and implementation by the farming community of policy or advice on SOM and its management. In this study, farmer awareness is assessed by the number of SOMFIEs that were recognised, prompted and unprompted, and whether the impacts were regarded as negative or positive. This measure of awareness is described as 'SOMFIE recognition'.

5.4.4.1 SOMFIE recognition

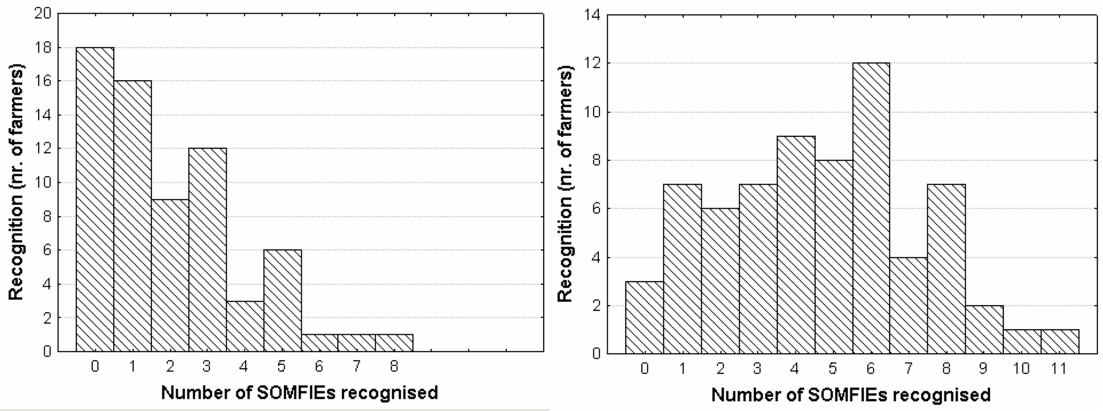


Figure 5.3 SOMFIE recognition histograms; unprompted only on the left, unprompted + prompted on the right.

Sufficient SOMFIE data for analysis were obtained from 67 of the 101 farmers included in the national testing phase. Data loss was due to logistical and time constraints and incomplete data recording by the interviewers. On average, for the 67 farmers, 4.6 out of a possible 15 SOMFIEs, were recognised, based on responses from both unprompted and prompted questioning, as shown in Figure 5.3.

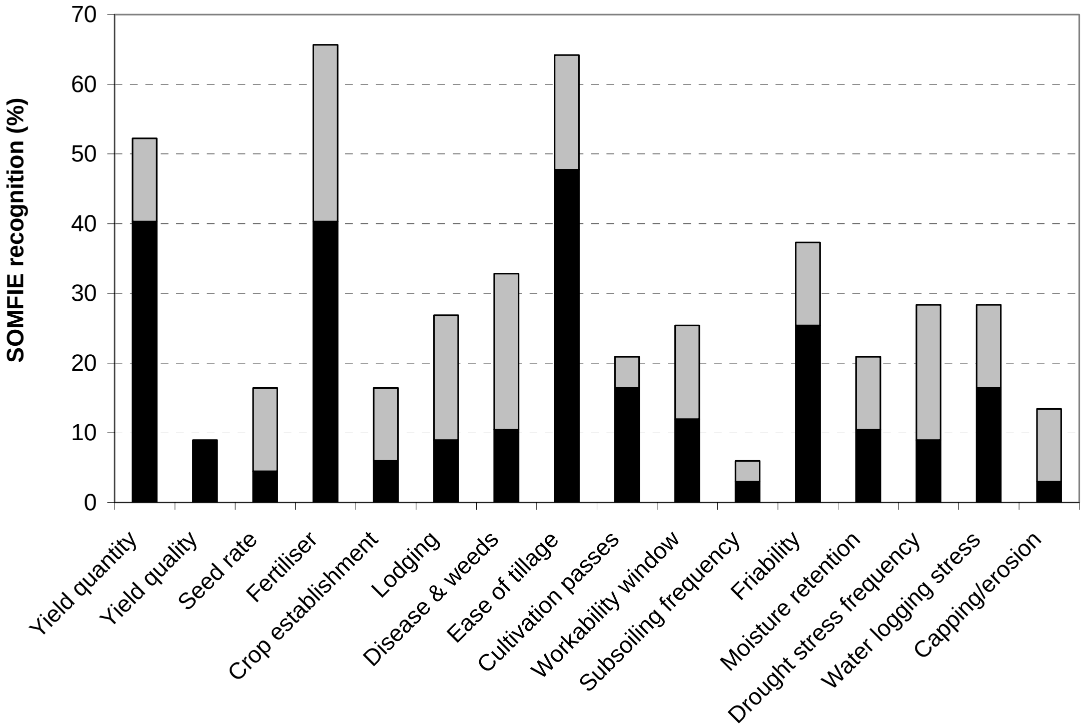


Figure 5.4 (Un)prompted farmers' SOMFIE recognition. Recognition is expressed as the % of participating farmers who recognised that SOMFIE (unprompted + prompted). The black part of the bars represents the unprompted and the grey part the prompted recognition.

Without prompting, an average of only two SOMFIEs were perceived by an individual farmer. Figure 5.4 shows that two SOMFIEs were recognised by nearly two thirds of interviewees, namely 'ease of tillage' and 'fertiliser', with just over half recognising impacts on 'yield quantity'. Despite their general agreement that SOM benefits the ease of tillage and with 38% of farmers reporting ‘friability’ benefits, only 21% of the interviewees reported a consequent reduction in the number of cultivation passes. Other SOMFIEs were recognised by 15 to 33% of participating farmers. The least recognised were ‘yield quality’ and ‘subsoiling frequency’ (less than 10% of interviewees).

5.4.4.2 Prompted vs unprompted

After exploring farmers’ perceptions in an open discussion, the interviewees were prompted for all remaining SOMFIEs. Figure 5.4 also shows to what degree farmers needed to be prompted before recognising a SOMFIE impact. The general trend is that prompting did elicit more recognition of SOMFIEs. Of the average of 4.6 impacts recognised by farmers, more than half (2.9 impacts) were only perceived after prompting. But the three most recognised SOMFIEs (yield quantity, fertiliser, and ease of tillage) were mainly reported unprompted, as were the number of cultivation passes, friability, and yield quality. However, all remaining SOMFIEs mainly required prompting for recognition. The SOMFIEs seed rate and capping/erosion needed most prompting.

Table 5.10a Unprompted farmer SOMFIE perceptions

	Direct impact on yield			Crop-related impact				Non-crop-related impact								
	Yield quantity	*Yield quality*	*Seed rate*	*Fertiliser*	*Crop establishment*	*Lodging*	*Disease & weeds*	*Ease of tillage*	*Cultivation passes*	*Workability window*	*Subsoiling frequency*	*Friability*	*Drought stress*	*Water logging stress*	*Capping/erosion*	*Flexibility (stress)*
% mentioned	45	9	4	40	6	9	21	39	18	13	4	25	10	9	10	4
Positive impact	90	100	100	96	50	0	29	97	83	89	67	100	100	100	100	67
No impact	7	0	0	0	0	0	7	3	8	11	33	0	0	0	0	0
Negative impact	0	0	0	4	50	100	50	0	8	0	0	0	0	0	0	33
Unknown impact	3	0	0	0	0	0	14	0	0	0	0	0	0	0	0	0

Table 5.10b Prompted farmer SOMFIE perceptions

	Direct impact on yield			Crop-related impact				Non-crop-related impact								
	Yield quantity	*Yield quality*	*Seed rate*	*Fertiliser*	*Crop establishment*	*Lodging*	*Disease & weeds*	*Ease of tillage*	*Cultivation passes*	*Workability window*	*Subsoiling frequency*	*Friability*	*Drought stress*	*Water logging stress*	*Capping/erosion*	*Flexibility (stress)*
% mentioned	24	2	30	36	13	24	33	37	8	48	6	15	15	60	58	0
Positive impact	50	0	40	71	78	0	27	44	60	28	50	80	80	33	8	0
No impact	31	0	60	25	11	19	50	56	40	56	50	20	20	63	54	0
Negative impact	0	0	0	0	0	75	9	0	0	0	0	0	0	0	31	0
Unknown impact	19	100	0	4	1	6	14	0	0	16	0	0	0	5	8	0

5.4.4.3 Positive vs negative impact

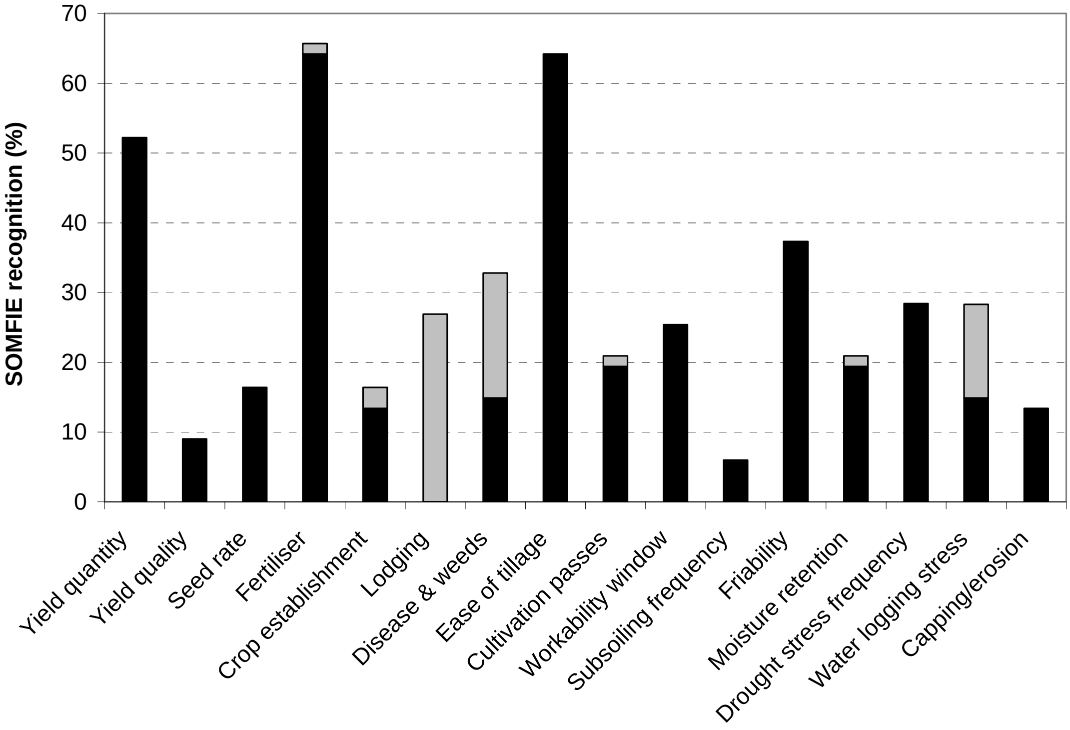


Figure 5.5 SOMFIE (dis)benefit recognition. Recognition is expressed as the % of participating farmers who recognised that SOMFIE (unprompted + prompted). The black part of the bars represents a positive and the grey part a negative perceived impact.

The majority of SOMFIEs were perceived to have a positive on-farm impact. Exceptions were lodging, diseases and weeds and waterlogging stress. Lodging was perceived to impact entirely negatively, whereas the latter three were perceived to impact both negatively and positively (by roughly equal numbers of interviewees).

Opinions on disease and weeds were the most divided of all. Less than a third of the interviewees recognised that SOM has an impact. Of these, 50% claimed a negative impact, 29% a positive impact, 7% no impact (Table 5.10 a, b). The remaining two thirds was unable to identify any impact.

Without prompting, workability flexibility, implement wear, and crop levelness were not mentioned at all.

5.4.5 Farmers' SOMFIE valuations

After the initial part of the SSI where SOMFIE awareness was tested, more detailed information was asked of the interviewees to quantify or qualify the SOMFIEs which they had recognised. Farmers were not always willing or able to provide this elaboration. The SOMFIE valuations, described in Sections 5.4.5.1 to 5.4.5.3 and summarised in Section 5.4.6 and Table 5.11, are based on a sub-set of the 67 farmers who are judged to have provided sufficient information. Valuations are presented and interpreted by category.

Table 5.11 **Summary of SOMFIE valuations and key associations. FYM = Farm Yard Manure, SS = Sewage Sludge, PG = Permanent Grassland. Strength of benefits and disbenefits valuation are indicated by "+" or "-". See Section 5.4.3 for full descriptions of each category.**

SOMFIE category	**SOMFIE**	**+ or -**	**Key associations**
Yield	**Quantity**	++++	FYM + SS on light soil (most for root crops)
	Quality	+	Weak
	Seed rate	+	Reluctance to adjust
Crop establishment	**Lodging**	--	Light soils + poultry manure/ploughed up PG
	Seedling emergence	++	Root crops (weak germinators) on silty soil prone to capping
Fertiliser	**N**	+++	Dependent on type + intensity of OM
	S, micro-nutrients	0	No perceptions
Disease & weeds	**Slugs & fungal disease**	-/+	Straw incorporation
	Weeds	-	Heavy soils with large seed bank
Workability	**Ease of tillage**	+++++	Heavier soils. Nothing for light soils ("Boys' Land")
	Cultivation passes	++	Power harrow pass on heavier soils
	Subsoiling	0	No perceptions
	Implement wear	0	No perceptions
	window	++	Heavy soils in high precipitation areas
	stress	+	Very valuable
Soil degradation	**Capping**	+/-	Silty soils (yield effect on root crops)
	Gullying	+	Silty sloping soils
Soil hydrology	**Water logging**	+	Heavy soils in wet areas
	Drought stress	+	Root crops on light soils in dry areas

5.4.5.1 Direct impacts on yield

- YIELD

Thirty-two farmers are included in this evaluation (91% of those recognising the SOMFIE 'yield'). A clear perception existed in the interview group that SOM benefits crop growth and vigour. The effect of SOM was often described as "a thicker, taller, and darker green crop", yielding more straw. This benefit was not always accompanied by a perception of grain yield increase with 28% perceiving only crop growth and vigour benefits.

The most spectacular yield benefit perceptions were recorded by three farmers growing sugar beet, who quoted 10 t ha^{-1} increases, one of whom claimed a doubling of yield. These yield increases may arise from straw incorporation (in the year before growing sugar beet) which reduces soil-capping, leading to better seedling emergence, especially on soils that are silty and prone to capping.

For combinable crops, the perceived benefits were less, but still substantial. For cereals, the perceived yield benefit ranged from 5 to 30%. The lower end of the range was mainly associated with straw incorporation (after 10 years) and the higher end with heavy FYM or slurry additions. Most perceptions were of yield increases of between 10 and 20%. The benefit of FYM was considered to be greatest in the first year after application, and then seen to drop off in subsequent years. Three farmers with arable fields in a grass ley rotation pointed to a large impact on silage yields, particularly in dry years (20-50% increases quoted).

- SEED RATE

Ten farmers were able to elaborate on this SOMFIE (91% of those recognising seed rate). The most revealing aspect in the interviews was the apparent reluctance of farmers to lower their seed rates, even when they perceived this to be possible. This general point is summed up by one farmer saying: "*You need to have the guts to do it!*". This particular interviewee added that he had only started changing his seed rates after attending a canopy management course. The reason farmers are reluctant to lower seed rates seems to be their concern that unforeseen adverse conditions later in the growing season could result in less yield if seed rates are lowered. Most farmers followed manufacturer's advice at all times.

The farmers in the 'aware group' connected seed rate benefits from SOM to better seed to soil contact due to the soil being more friable. Average reductions in seed rates of 10 to 20% were reported. One farmer reported a specific reduction of 30% in required seed rates after grass leys.

5.4.5.2 Crop-related impacts

- CROP ESTABLISHMENT

There was a general perception that SOM enhances soil structure which benefits crop establishment. Commercial farmers, however, use as much tillage as is needed to achieve a satisfactory seedbed. So, if soil structure is poor, with soil of low friability, farmers will overcome this by increased tillage. In this way crop establishment benefits overlap with 'tillage effort' and 'seed rate'.

SOM was perceived to have a negative impact by increasing lodging (14 farmers, 78% of those recognising crop establishment). Specifically, lodging was perceived to be a substantial hazard on ploughed up permanent grassland, or when using large amounts of sewage sludge, or poultry manure. The risk from this hazard was reported to have been reduced with the introduction of growth regulators and more efficient use of fertiliser. A single growth regulator application was considered sufficient to control lodging (and can be included in a biocide application pass). A typical cost would be £8 – 12 ha^{-1} (2003/2004 growth regulator prices), offset by reduced fertiliser costs. However, increased farmer stress caused by the necessity for lodging control was valued negatively.

- FERTILISER

Eleven farmers expanded upon this SOMFIE (25% of those recognising fertiliser). Reductions in fertiliser requirements were perceived from SOM management, but not explicitly linked to SOM levels. Generally, and specifically in Nitrate Vulnerable Zones (NVZs), guidelines for inorganic nitrogen reduction in conjunction with OM additions to soil are used (MAFF, 2000). This provides a clear cost reduction benefit of SOM. FYM, poultry manure, and sewage sludge were perceived as N sources. Straw incorporation and ley grassland were not perceived to have a beneficial nutrient impact, with straw incorporation sometimes leading to perceived N lock-up and higher inorganic N requirements. This disbenefit, however, was only reported for ephemeral straw incorporation practice. Consistent straw incorporation was perceived to enable reductions in K applications. Oil seed rape straw was perceived to have more benefit than wheat or barley straw. Sewage sludge was also perceived to be high in potash, allowing additional reductions in fertiliser reductions in K.

The duration of reduced inorganic N requirements with OM amendments was perceived to be only one year after OM application. For heavy FYM additions on clayey soil this was extended to two years. No impact was perceived on the supply of sulphur and micro-nutrients.

- DISEASE AND WEEDS

Twenty-two farmers detailed this SOMFIE further (100% of those who recognised disease and weeds). Experience of the impact of SOM on disease was mixed, with observations that disease was more controllable, but also occurred more often. However, two clear trends could be discerned. Firstly, farmers who incorporated straw perceived a higher incidence of slug outbreaks, typically requiring one or two more passes with slug pellets. Other farmers reported increased slugs when straw was left on the field, i.e. not incorporated. The second clear trend was that of ley grass diminishing both slug outbreaks and fungal crop diseases. This benefit was perceived to last several years (up to three years) and longer with multiple year leys (two to four years). One farmer perceived the benefits to occur mainly in the second and third year.

FYM, sewage sludge, and permanent grassland were perceived to result in more weeds (“higher weed burden”), but farmers found it difficult to quantify this possible impact (five farmers, 23% of those recognising disease and weeds).

5.4.5.3 Non-crop related impacts

- WORKABILITY

Of all the SOMFIEs in this category ‘ease of tillage’ (tillage effort) was perceived to be the most important, with a relatively consistent valuation (44 farmers, 93% of aware group). Typical quantifications of benefits were reductions of 10 and 15% in fuel and labour requirements. Variations were also evident depending on SOM management type and physiotopes. Benefits following straw incorporation were generally perceived to be lower (5-10% reductions) than from heavy FYM additions and particularly sewage sludge additions were higher. A clear difference was reported between the impact of SOM on the tillage effort for different soil types, with greater benefits perceived for heavier soils. Very light soils were often referred to as “Boys’ Land” (only boys – not men – were needed to work them in past times), and no workability benefit from SOM was perceived for these soils.

Five farmers (12% of aware group) translated the structural benefits of SOM into an opportunity to drop out a seedbed preparation pass. The remaining farmers highlighted fuel and labour benefits only. If a pass could be dropped it was mostly a press or power harrow pass, and again only on heavier soils.

Interestingly, one farmer experienced a need for a 30% increase in rolling operations to consolidate a "more fluffy" soil (greater SOM content) into a seedbed. On a broader level it was frequently commented that soils with greater SOM contents were easier to switch from conventional to minimum tillage. Implement wear, subsoiling frequency, and flexibility were generally believed (although not experienced) to benefit from higher SOM levels.

A benefit from SOM on the workability window was described in terms of early access to the soil one or two days sooner after rainfall, and similarly one or two days later after rainfall started (12 farmers, 71% of aware group). In all cases, this benefit was regarded as valuable because it reduces farmer stress. Economic benefits were not reported, except in extreme weather years when wet autumn conditions might require a field low in SOM (small window) to change from winter to spring seed. No benefits were perceived for very light fields or heavier fields with excessively free draining subsoil, as was the case for other workability SOMFIEs.

- SOIL HYDROLOGY

Less drought stress and waterlogging stress with higher SOM levels were perceived by 14 (74% of aware group) and six (67% of aware group) farmers, respectively. It was, however, qualified as a relatively small impact. Only in extremely dry and wet growing seasons was the impact reported as substantial.

- SOIL DEGRADATION

SOM was perceived to have both a positive and negative impact on the risk of aeolian (wind) erosion. On very light soil ("blowing sands") SOM was thought to hold the soil together and prevent erosion (three farmers). In one case it was perceived that on heavy soil a higher SOM content resulted in more 'fluffy' topsoil that was more prone to aeolian erosion.

The only comments relating to SOM lowering water erosion were made regarding soil structural benefits on a very silty soil, and for a clayey soil on a relatively steep slope. In both cases, gully erosion was perceived to be reduced by greater SOM contents.

5.4.6 Summary of farmers' SOMFIE valuations

The most negatively-rated SOMFIEs were lodging and disease and weeds (crop-related-impacts group). Although the increase in lodging was reported to be potentially severe, it was not regarded as having a large economic impact. Possibly this is because it is confined to combinable crops after less common SOM management practices, such as ploughing in permanent grassland, or applying sewage sludge or poultry manure. Furthermore, technological developments, in the form of growth regulators, have made lodging more controllable with relatively low costs.

For disease and weeds, the negative impact was firstly an increase in biocide applications (for slugs from straw incorporation), and secondly, increased herbicide application costs (more weeds with FYM, sewage sludge, and after ploughing in permanent grassland). Thirdly, in the start-up phase of straw incorporation (approximately 1-5 years) N lock-up was perceived, and hence higher N application costs were incurred.

The non-crop-related-impacts group showed some relatively minor, and less common, disbenefits from SOM in the form of increased rolling requirements (more 'springy soils' from straw incorporation; higher relaxation ratio, see Section 2.2.3) and more aeolian erosion ('fluffier topsoils' on heavy soils; dilution effect, reduced inter-particle binding force and reduced filament effect, see Section 2.2.3).

The majority of SOMFIE categories were regarded as having a positive impact on farming operations. Workability was regarded as the most beneficial category, particularly for heavier soils, with widely perceived cost reductions in fuel and labour (tillage effort). Where FYM or sewage sludge applications had been made, it was reported that, sometimes, fewer cultivation passes were needed. SOM benefits on heavy soils (specifically in higher precipitation regions) were linked to a larger workability window leading to less stress for farmers, and in extreme weather years (wet autumn) to substantial economic savings.

After workability, fertiliser reductions (following application of FYM, poultry manure or sewage sludge) and yield increases (especially for root crops on light soils) were reported to deliver the greatest economic benefit

On balance, perceived benefits from SOM appear to considerably outweigh the possible disbenefits. However, variation of impacts by i) physiotopes (clay content and soil wetness), ii) SOM management type (straw incorporation, ley grassland, FYM application), and iii) crop type (root crops or combinable crops) were reported to strongly influence relative and individual SOMFIE importance.

At the end of the interviews farmers were asked if they would burn the stubble on the field if the ban on stubble burning was ended. Thirty-six percent said they would burn stubble again, mainly quoting benefits for weed and slug control, especially for heavy soils. Forty-seven percent said they would not resume burning on grounds of perceived dangers, stress, and the availability of desiccators offering the same weed and slug benefits as burning, while releasing additional benefits from OM incorporation. The remaining 17% of interviewees said they would burn only in fields that either particularly needed it (e.g. heavy soils with large weed or volunteer seed bank), and/or fields that were a safe distance from any buildings or infra-structure.

5.5 DISCUSSION

5.5.1 Observations on interviewing farmers

It is essential for interviewers to be flexible when visiting and interviewing farmers. Generally, the interviewer would be invited around the kitchen table, and given ample time, not to mention coffee or tea. However, conducting interviews was also done standing outside, in a field, in a barn, or looking up to the tractor (in all possible weather conditions). The interviewer needs to be prepared for any situation, and be flexible to adapt to the farmer's time constraints (making friends with the farmer's dog is also advisable). Furthermore, in many cases a rapport needed to be built-up before starting, and during, the interview, to enable the flow of the interview and reduce the interviewee's inhibitions, thereby stimulating loquacity.

Apart from the need to acquire topic consensus, it was found vital to establish a consensus in language and terminology at the beginning of the interview, to avoid skewed or incomplete data collection. For example, it was decided, after the acquaintance exercise, to consistently use the term 'soil organic matter' rather than 'soil organic carbon'. In many cases, the term SOC was found to be confusing to interviewees.

The process of probing the farmer to qualify or quantify impacts was valuable (particularly for taciturn interviewees), but had to be handled carefully to avoid influencing the interviewee. Probing by asking open questions was preferred (*"What is your experience of the benefit or disbenefit of A on B?"*), although in many cases closed questions were found to be necessary (*"So, considering X and Y, did you in fact observe Z impact of A on B?"*). In general, it was found that farmers are circumspect; they avoid making statements about which they are not comfortable. A common reply from farmers was (after having taken time to think about the question): "*I'm not sure about that one, I wouldn't want to say*", at which point the prompting would be ceased. A well established rapport helps the prompting process.

From discussing SOM management in the interviews, it became clear that there is a general misconception in the farming community that 'natural regeneration set-aside' is a form of SOM management, and that it increases SOM contents. However, this is not borne out by scientific assessment. Several workers have shown that natural regeneration set-aside does not increase SOM contents (Paustian *et al*., 2000; Karbozova-Saljnikov *et al*., 2004).

5.5.2 SOMFIE bias

It was anticipated that there might be a danger of idealistically – rather than experientially - based SOMFIEs entering the SOMFIE list (see Chapter 3). The interview process revealed that there is also a risk of environmentally - or technologically - biased SOMFIEs being promoted without a basis in experience, as summarised in Table 5.12.

In the semi-structured interview the farmer would often require some degree of 'pressing and probing' to express perceptions. This process of probing helped to develop the hypothesis that farmers base their experientially derived perceptions of SOM impacts either on the apparent consequences of a change or difference in SOM management, or on those arising from a SOM management practice that is temporally variable. The latter refers to cyclic OM additions, e.g. slurry or FYM applied once every 4 years. The former consists of four types of possible comparison, two temporal and two spatial. The temporal were either historic (e.g. the farmer recollected how difficult the field was to work as a boy 30 years ago, compared to now), or related to a relatively recent change in SOM management (e.g. straw used to be burnt until the 1992 ban on burning, since when straw has been incorporated into the soil). The spatial comparison was either between two fields on the farm or between a field on the interviewee's farm and a neighbouring farm. In these cases the SOM was perceived to differ, on account of the history of land use (e.g. it was previously long-term grass leys) or current SOM management (e.g. it is a field close to stables that receives more manure than a field further away).

Table 5.12 Risk of SOMFIE bias relative to perception basis

		Perception basis (experiential SOM impacts)				
		Temporally variable SOM management	**Change or difference in SOM management**			
		Cyclic	**Temporal**		**Spatial**	
		Recent/ historical	**Recent**	**Historical**	**Single farm**	**Multiple farm**
SOMFIE bias type	**Technological**	*Weak*	*Moderate*	*Extreme*	*Weak*	*Moderate*
	Environmental	*Weak*	*Weak*	*Weak/ moderate*	*Strong*	*Strong*
	Other	*Perception truncation in time*	-	-	-	*Pride factor*

Perceived changes-based temporal comparisons have other possible causes than SOM impacts. For example, substantial changes in agricultural technology (tractor power, new varieties, etc.) and knowledge (drill dates etcetera). Often, the farmer would comment on this after having formulated his/her perceptions, noting that these were confounded by changes in technology, which he could not quantify. Temporal comparisons can only be reliable if the farmer used the same machinery, rotation, varieties, fertilisers, biocides, etc.

over the period of comparison. As substantial changes in SOM occur over long periods following altered management (from a few to 10 or 15 years, depending on type of management and physiotope) the period of comparison is normally too long for technological factors to remain constant. Therefore, caution needs to be taken when farmers base their perceptions, and the quantification and qualification of those perceptions, on temporal comparison. It was found that certain farmers were able to revise their SOMFIE valuation for changes in technology. However, these farmers were a minority, and the accuracy of their revisions is unknown.

The temporally variable SOM management-based comparison is normally free of technological bias. However, in the case of short cycles (e.g. OM additions every other year), longer lasting effects will not be perceived (perception truncation).

Spatial comparison between a field of the interviewee and a field on a neighbouring farm also presents problems due to differences in management systems on the two farms (e.g. drill dates, seed rates, tillage equipment, etc.), as well as environmental differences not realised by the interviewee (e.g. texture, soil wetness, soil depth). In addition, the human factor ‘pride’ might influence perceptions.

The uncertainties and potential dangers of SOMFIE perception bias are least for spatial comparisons between two fields on the interviewee’s farm. When a farmer was asked and probed to identify two fields similar in soil but with different SOM levels on the farm, these were often identified by the interviewee who then listed many perceived differences in SOMFIEs. However, on further questioning environmental differences were revealed between the two fields. Commonly, their textures would be different and sometimes the soil depth, or wetness did not match. Unless the two fields have synchronous rotations, weather variation might complicate perceptions for weather dependent SOMFIEs (e.g. waterlogging or drought stress).

Only about one in 20 farmers were able to identify a paired field comparison, i.e. two fields with similar environmental conditions but contrasting levels of SOM.

As these types of SOMFIE bias were discovered during the interviews in the pilot phase it is possible that SOMFIE valuation (see Section 5.4.3) is tainted to some extent. Since it was realised early on, and from then on mitigated by establishing the interviewee's basis of comparison in the beginning of the interview, it is not believed to have affected the valuation substantially.

5.5.3 SOMFIE costs

This research focused on SOM impacts in arable fields. SOM management incurs costs, which vary depending on management type. Straw incorporation, for example, has relatively low costs, whereas FYM application has substantially higher costs. The cost of SOM management was frequently commented on by farmers but was often diffuse in definition. It appears to be highly dependent on farming system, location and regional factors. Proximity to OM buyers (e.g. straw burning facilities) and sellers (water companies, intensive poultry units) was identified as important. Socio-economic studies on this topic are recommended to complement results from this research.

When evaluating agriculture's historical dependence on SOM against current reported benefits (see Section 5.4), it appears that the arable SOM functionality has shifted from a primary function to a buffer function. This is illustrated by the fact that many SOMFIEs were only perceived to have a quantifiable economic impact in extreme weather years (one in 10-30 year events).

5.5.4 SOMFIE awareness

The majority of the SOMFIEs generated by the iterative 'expert' process were subsequently mentioned by the group of commercial farmers without prompting. However, workability flexibility, implement wear and crop levelness were not mentioned at all and seed rate, crop establishment, subsoiling frequency and capping/erosion by < 5%. No clear reason for this is apparent. Possibly, these SOMFIEs are too indirect to be recognised, or perhaps they overlap with other SOMFIEs that were mentioned. The absence of reported 'implement wear' impacts was surprising as it was a strong candidate SOMFIE in the 'expert' process, and related SOMFIEs (e.g. ease of tillage and friability) were important perceived impacts. Implement wear seems to be something most farmers simply do not monitor. The low perceived impact of SOM on seed rate can probably be explained by fear of unforeseen weather conditions later in the growing season, which causes farmers to follow manufacturer guidelines on seed rates, regardless of SOM levels or indeed other factors.

It appears that farmers' awareness of how SOM impacts on farming is relatively limited. Only 4.6 out of a potential 15 SOMFIEs were recognised on average. But this could be due partly to the fact that a SOMFIE which is important in one physiotope, might be irrelevant in another physiotope (e.g. 'Boys' Land' simply always having a maximum 'ease of tillage').

The three main SOMFIEs represent the groups devised in Chapter 2:

- Direct impacts on yield (yield quantity)
- Crop-related impacts (fertiliser)
- Non-crop-related impacts (ease of tillage)

However, when considering all SOMFIEs it seems yield impacts are uppermost in farmers' perceptions, although seed rate is an important exception. Crop-related impacts were perceived to be the most uncertain and variable (dependent on SOM management type), including negative impacts (i.e. lodging and 'disease and weeds'). Non-crop-related impacts are mainly perceived as primary soil structural impacts; expressed by 'ease of tillage', friability, and 'cultivation passes', and these scored relatively well without prompting. Secondary (or indirect) soil structural impacts are perceived less, and required more prompting. Most secondary impacts are related to the soil's hydrological function. Apart from the SOMFIEs in the hydrological category (moisture retention; drought stress frequency; water logging stress), 'workability window' and 'capping/erosion' are influenced by the hydrological function (tertiary soil structural impacts).

In the crop-related impacts group, the nutrition function is perceived to be the main SOM impact, both as a benefit (fertiliser reduction) and disbenefit (lodging). SOMFIEs that integrate several primary functions are perceived less frequently, e.g. 'crop establishment' and 'disease & weeds' can be considered to integrate structural, hydrological, and nutrition functions.

From the above, it appears that those direct impacts on SOMFIEs that represent a single SOM function are perceived most frequently and strongly, while indirect impacts on SOMFIEs representing multiple SOM functions are perceived substantially less. This may be simply because more complex relationships are more difficult to discern. For similar reasons, lower perceptions for indicators sensitive to variation in weather might be expected.
From the difference in perceptions between 'ease of tillage' and 'number of cultivation passes', it might be hypothesised that there is a threshold level of SOM, below which the SOM leads to savings in labour and fuel costs, and above which an entire cultivation pass could be foregone, without losing

seedbed quality. If it exists, this threshold is likely to be different for different soil types.

Potentially, the relatively low perception of crop establishment (and possibly seed rates) occurs because its impact is offset by farmers putting in extra tillage effort to create a good seedbed.

A final important interpretation of the unprompted vs prompted exercise, is that the lack of readily-available SOMFIE knowledge or awareness is the main contributing factor to farmers' general SOMFIE unawareness. This may imply that the SOM benefits have not been communicated successfully by advisors and experts. Alternatively, it may imply that the message has reached most farmers, but their focus is on other aspects of farming (e.g. new technologies), and therefore the SOMFIE knowledge is not readily assimilated.

5.5.5 SOMFIEs holistically

In creating categories and sub-categories and assigning SOMFIEs to these, the impact of SOM on arable farming was disassembled. In this way, tacit or unexplored benefits of SOM have been made clearer or more tangible, which can be qualified and quantified for different environmental factors and SOM management types. However, in reality the individual parts and processes interact with each other to create a complex, total or holistic impact. Although this was recognised generally and commented upon by most farmers, only a select number of interviewees were able to express the holistic impact beyond two interactions. An example is given below:

"SOM improves soil structure which allows faster ploughing and timeliness of operations – this allows me to take advantage of good weather conditions to establish the crop. Without this, time and money would be wasted by, for example, having to

establish the crop on waterlogged ground – using more seed and increasing soil compaction."

Furthermore, it must be noted that farmers were asked specifically for impacts that they had experienced, rather than impacts that they either believed should occur or had been taught to occur. The case studies, described and discussed in Sections 6.4.5 and 6.5.5, attempt to explore this holistic impact.

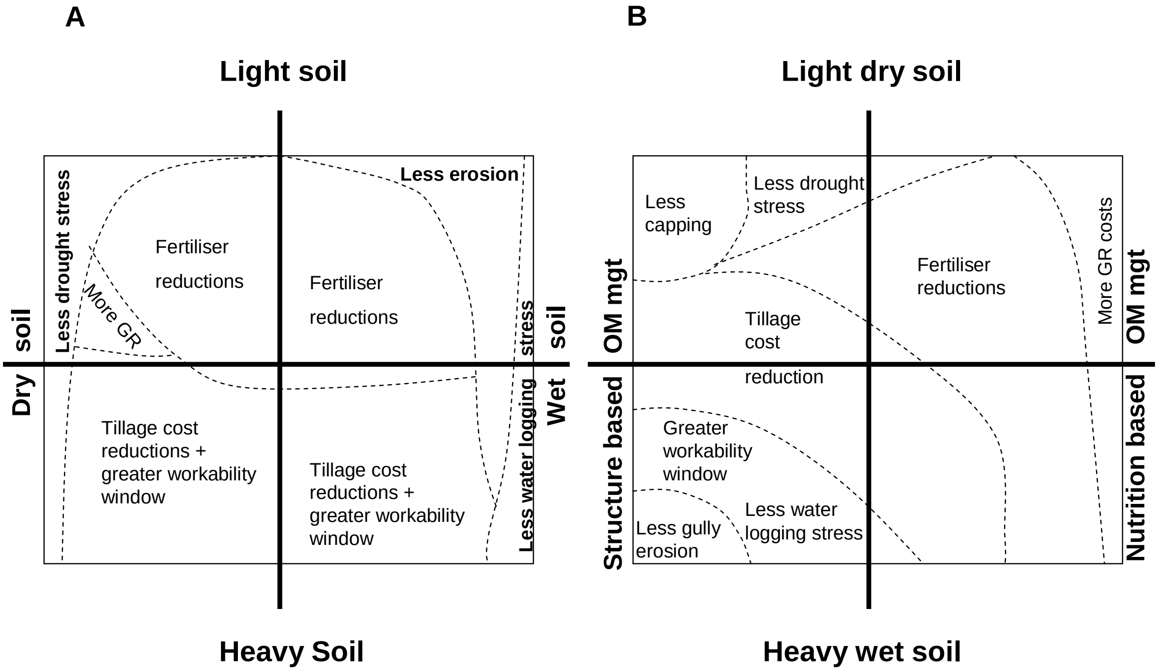


Figure 5.6 Relative SOMFIE domain sketches (dashed lines) for environmental (A) and SOM management factors (B). See text for description. The heavy lines are dimension axes. Mgt = management; GR = growth regulator.

To summarise the findings in this chapter, SOMFIE domains, relative to environmental and SOM management factors, were sketched. The domains are scientific interpretations of farmers' valuations and aim to show relative occurrence only. In reality, domains overlap and might have thresholds or intensity gradients. Figure 5.6A depicts how SOM impacts on farming between physiotopes. The vertical axis is a 'soil heaviness' dimension, and the horizontal axis is a soil wetness dimension. Figure 5.6B depicts how SOM management impacts on farming between physiotopes. The vertical axis is a 'physiotope gradient', and the horizontal axis is a gradient from structure based OM management (ley grassland, straw incorporation) to nutrition based OM management (poultry manure, slurry). FYM is somewhere in between the two, depending on its straw content.

5.6 CONCLUSIONS AND RECOMMENDATIONS

Exploring the 'experiential science' of primary and secondary stakeholders, in iterative conjunction with scientific literature and perspectives, proved to be a useful method to generate a qualified list of SOMFIE indicators. It is recommended that SOMFIE indicators are researched further, individually and together, both on experimental or research farms and in socio-economic studies.

From the commercial farmer interviews, it is concluded that understanding of 'SOM management' appears to be limited in the arable farming community of England and Wales. The causes of this are not known. Possibly, farmers' and the agro-industry's greater focus on crops rather than soil is an explanation. Furthermore, the levels of 'SOMFIE recognition' that were observed, indicate limited knowledge and awareness of SOMFIEs.

It is recommended that information on SOM impacts on arable farming is made available to the farming community (including the agro-industry), in a semantically compatible and integrated way.

From the SOMFIE qualifications and quantifications made by farmers, it appears that clear and substantial differences in perceived SOMFIE importance exist for different physiotopes. It follows that it is not possible to award a single SOMFIE the title 'most important SOMFIE in England and Wales'. Rather, it is essential to evaluate SOMFIE importance taking account of physiotope and SOM management types.

It is recommended that more research is conducted on the costs of SOM management to complement the results of this study. For policy development, more research into OM amendment availability and socio-economic scenarios of farming system change are needed, to establish feasibility.

The above leads to acceptance of the research proposition (see Section 5.1.2). Overall, farmers in England and Wales perceive SOM to have a positive on-farm economic impact. Relatively few modes of impacts are recognised by farmers and their readily available knowledge is limited. The magnitudes of impacts are perceived as small to moderate, and vary considerably between both physiotopes and SOM management practices.

A general recommendation, for both further research and policy development, is to always determine the important environmental variables (physiotopes) for a factor before investigating the factor (and related impacts and interactions) itself. This work has focused on the factor 'SOM' in the English and Welsh situation, and has shown the requirement for policy to be based on appropriate physiotopes.

It needs to be noted that physiotopes based on SOM will inevitably be different for different regions, as climatological, geological, geomorphological, hydrological, pedological, and anthropogenic (land use) factors vary. Naturally, environmental variables important to SOM, for any region, change on a geological timescale (10^3 – 10^9 years). Potentially, this could also occur on the timescale of (several) human generations, possibly even within a generation, and subsequently policy might have to be adjusted accordingly. Climate change is of particular importance in this context as it is likely to change substantially within generations (Fowler and Kilsby, 2003). Anthropogenic factors influencing physiotopes are mainly related to land use change and can have impacts (shifting physiotopes) nearly instantly. Particularly land use changes involving changes to soil hydrology, i.e. draining and (temporary) flooding of agricultural land, will have important impacts on SOCIMRs.

CHAPTER 6

ARABLE FIELD PERFORMANCE FOR DIFFERENT SOIL ORGANIC CARBON LEVELS, MEASURES, AND MANAGEMENT

> ***"Measure what can be measured,***
> ***and make measurable what cannot be measured"***
> Galileo Galilei (1564 – 1642)

This chapter develops a robust SOMFIE questionnaire, which is then used to measure how well arable fields perform. Analysis of the results reveals to what extent SOC content and SOM management benefits field performance. Finally, five case studies are described.

6.1 INTRODUCTION AND OBJECTIVES

The aims of the research described in this chapter are to develop a consistent measure of the performance of each SOMFIE, and to analyse arable SOMFIE performance against measures of SOC and sets of environmental factors (i.e. physiotopes). The methodology to achieve these aims was developed by linking social science and soil science. Whereas the link in the previous chapter focussed on farmers' perceptions and SOM management, in this chapter the link is made between farmers' 'field performance observations' and various scientific SOC measures, for different sets of environmental variables.

Chapter 4 demonstrated that SOC variation is explained most by clay content and precipitation. SOCIMRs were developed for 15 physiotopes constructed by different combinations of clay contents and precipitation. These SOCIMRs were shown to differ substantially. For example, the SOC content in a dry-sandy physiotope ranged from approximately 0.5 to 1.6%, while those in a wet-heavy physiotope ranged from about 2.0 to about 5.4%.

Chapter 5 extended current knowledge (described in Section 2.2) of the mechanisms and magnitudes of SOM impacts on arable farming by investigating farmers' perceptions using experiential science. It also showed that both the mechanisms and magnitudes were perceived to vary considerably between physiotopes and SOM management.

Farmers' perceptions were validated in part by corroboration with the literature review (Chapter 2). However, validation for the mechanisms and magnitudes of new SOMFIEs was not possible, because of the absence or inadequacy of information in the literature. Furthermore, the introduction of SOMFIE bias was discussed (including technological, environmental and ideologically based SOMFIEs, 'saying what the scientist wants to hear', and experiential science being contaminated with educational or commercial information, e.g. agricultural college text books, agricultural equipment manufacturer's brochures, workshops, etcetera). Although mitigation of SOMFIE bias was integrated in the methodology, it remained uncertain to what degree SOMFIE bias occurred.

Therefore, this chapter aims to validate SOMFIE perceptions (Chapter 5) and SOMFIE literature (Chapter 2) by an independent analysis of SOMFIE performance of arable fields with similar sets of environmental factors (i.e. physiotopes; see Chapter 4).

6.1.1 Objectives

1. Develop and test a robust, standardised 'question and answer' format for each SOMFIE in the qualified SOMFIE list.
2. a) Analyse arable SOMFIE performance along a SOC gradient.
   b) Analyse arable SOMFIE performance in relation to SOM management
3. Analyse arable SOMFIE performance within and between sets of environmental variables.

Research questions for this chapter are:

- Can a robust questionnaire be developed to test arable field performance in relation to SOM via semi-structured interviews with farmers?
- Do individual SOMFIEs perform better according to their position in SOCIMRs (Sections 4.4.4 and 4.5.2)?
- Does SOMFIE field performance differ between physiotopes?

- What is the relationship between SOC management and SOMFIE field performance?

6.1.2 Hypothesis

The hypothesis tested in this chapter is that arable field performance increases with higher positions in the SOCIMR, and with more intensive SOM management.

6.2 METHODOLOGY

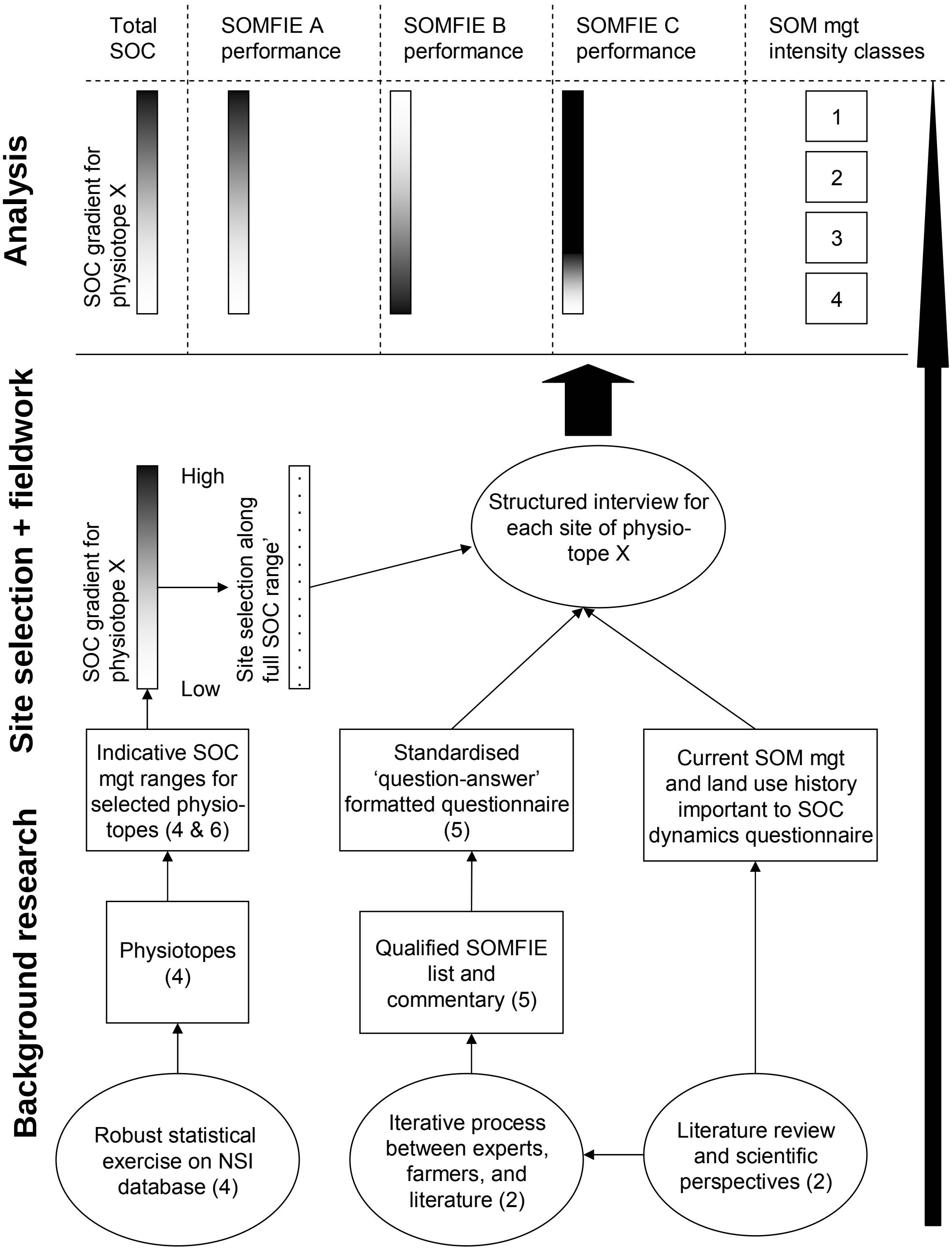


Figure 6.1 Methodology flowchart for Chapter 6 (for integration in thesis methodology, see the Thesis Flowchart, Figure 3.2). The numbers 1-6 in parentheses in the 'background research' section refer to corresponding thesis chapters. SOMFIE A is an example of a positive response to increasing SOC, SOMFIE B of a negative response, and SOMFIE C of a response characterised by a critical threshold. The target number of sites to be selected from physiotope X is 25. In total, four contrasting physiotopes are selected. Mgt = management.

This chapter explores the experiential science of primary stakeholders within the context of scientific perspectives. For a detailed methodology critique see Section 3.3.3. Figure 6.1 shows the flowchart of this chapter.

The methodology is divided into three phases.

- In Phase 1 the SSI data are checked and where necessary units are converted from imperial to metric. Sites with incomplete SSI data are omitted.
- In Phase 2 current field management and land use history data are classified to create an alternative indicator to total SOC for use as a variable in statistical analyses. This classification is based on both cultivation practice and type and intensity of OM amendments to the soil.
- In Phase 3, a statistical analysis is performed. Each individual SOMFIE's performance is checked for correlations with the 'position in the SOCIMR', topsoil OC stocks (0-15 cm), OC stocks for cultivation layer and the field management classification (Phase 2). This is performed on the whole data set, for each physiotope, and for the dry vs the wet sites. Finally, categories of SOMFIEs are established and compared to the SOMFIE categories from the farmers' perceptions (Chapter 5).

Five paired-field case studies were made to illustrate SOMFIEs holistically and to investigate environmental SOMFIE bias. The case studies required a separate methodology. Identification of case studies occurred during the SSIs described in Chapter 5. Subsequently, for each case study the paired fields were sampled and analysed to test significant environmental similarity and significant SOC difference. An additional SSI was performed at the end of the next growing season (summer 2005), allowing farmers to monitor the discussed SOMFIEs in more detail.

6.3 METHODS AND MATERIALS

6.3.1 Soil sampling methods

NSI sampling locations were found by combining topographical map (1:25,000) and GPS readings. Composite soil samples for all sites were taken during two field campaigns (2003/2004) according to the NSI topsoil sampling method (Loveland, 1989), i.e. 25 sub-samples (5 metres interspaced) in a 20 by 20 metres grid (see Section 4.3.1). For each field in the case studies (see Section 6.4.4), five such (roughly equally interspaced) grids were randomly chosen and sampled, and differential GPS location were noted.

6.3.2 Physical and chemical soil analyses

All analyses were performed on the composite samples. For the case studies the five composite samples were analysed separately. All standard analyses were performed by the same methods used in the original NSI sampling (Loveland, 1989). SOC was determined using a modified Walkley Black method (Kalembasa and Jenkinson, 1973). Nitrogen was analysed using a CN analyser (Vario EL III Elementor, by Calibre). Bulk density samples (82.8 cm^3 ring) were taken at central positions of two depths (0-7.5 and 7.5-15 cm) at three locations (roughly equally interspaced) within the 20 by 20 metre grid. Samples were subsequently dried (48 hours at 105°C) and weighed. For data analyses (see Section 6.3.3), average bulk density values (over the two depths) were used.

6.3.3 Data analysis methods

All SSI information was written down on paper during the interview and inserted into SOMATIC, the online project database (for SSI methods see

Section 5.3.1). Relevant data were subsequently downloaded from SOMATIC into an Excel worksheet. For each site, SOMFIE field performance data (Appendix 3), land use history data and current management data (Appendix 4) were listed. The formats are either qualitative or quantitative. Physical and chemical soil data, and environmental data, were entered for each site in a separate Excel worksheet. This was subsequently uploaded in STATISTICA (Statsoft, 2001) for statistical analysis in the following sequence:

1. Individual SOMFIEs were screened for outlying values by plotting histograms, and by cross-referencing to SOC measures and ancillary variables (Tables 6.1 and 6.2).
2. SOMFIEs (with appropriate omissions) were entered as the dependent variable and appropriate ancillary variables (Table 6.1) were entered as independent variables, including one of the SOC measures (see Table 6.2), into a general regression model (GRM). A separate GRM run was performed for each SOC measure, for each SOMFIE.
3. A multiple regression analysis was run for those variables that entered the model, to establish the direction and strength of any correlation.
4. When a correlation between a SOMFIE and any of the SOC measures could not be established (i.e. no variable entered the GRM), an alternative robust approach was performed: the five highest and lowest values were grouped and tested for significance using a one-way ANOVA.

Table 6.1 Ancillary variables used in the GRM runs

Ancillary variable	units
Drill date	classification
Depth of A horizon	cm
Depth of tillage	cm

6.4 RESULTS

The results are given first as the standardised SOMFIE question/answer questionnaire with comments and limitations. Secondly, the arable field performance (measured by the questionnaire) is presented for different SOC measures and SOM management. Thirdly, four case studies are described. An additional result from the semi-structured interviews is a tentative picture of current and historic SOM amendments to soil (Appendix 5).

6.4.1 SOMFIE variables

Those SOMFIEs that were appropriate for survey comparison (see Section 5.4.3) were assembled in a questionnaire and carefully phrased, according to the SOMFIE recommendations (see Section 5.4.3). A clear output of the pilot phase, described in the previous chapter, was the need for a target crop for a survey-based comparison. As the field selection was already conditional to several environmental variables (see Chapters 3 and 4), a crop with a wide geographic distribution was needed. The most common crop in England and Wales is winter wheat, which can be grown successively in rotation, i.e. several years in a row before a break crop is used. It was also perceived that several SOMFIEs would be dependent on the year in the succession (most strongly for yield and disease). Therefore, SOMFIE performance indicators were targeted at a 1st winter wheat crop.

The second clear output of the pilot phase (see Section 5.4.2) was the dependence of SOMFIE performance on weather, with dry growing seasons perceived to have the most substantial SOMFIE impact (see Section 5.4.6). Targeting a particularly dry growing season was investigated. This approach was, however, discarded due to farmers having difficulty recognising a specific year, of rotations in which the target crop was not grown in the target year, and of apparently different drought years being reported for different parts of the country. Alternatively, weather dependence was considered by designing SOMFIE performance indicators to target a 10-year average (i.e. farmers were asked to provide their answers averaged over the last 10 years). The choice for this time period reflects a balance between the time increase demand (because weather-based SOMFIE distortion decreases with time), and the time decrease demand (because technological SOMFIE distortion increases with time, see Section 5.5.2).

The indicator units were noted as the farmer expressed them (i.e. there was no forced conversion by the interviewee to standard units), and subsequently converted to metric units if necessary. Descriptive classifications were developed where recommended (see the SOMFIE performance questionnaire, Appendix 3). In addition, a number of ancillary variables were recorded (Table 6.1).

6.4.2 Environmental variables

PHYSIOTOPES

The first stage of the methodology (data evaluation) reduced the number of sites by 51% (from 101 to 49). In 24 cases, the farmer classified the field as heterogeneous in texture. These cases were regarded as unsuitable for SOMFIE analysis and hence omitted. A further 28 cases were discarded on grounds of there being insufficient collected SOMFIE data. The remaining data set is spread across England, with the highest concentrations in East Anglia and the East Midlands, a more sparse cover in other parts of England and no coverage in Wales (Figure 6.2).

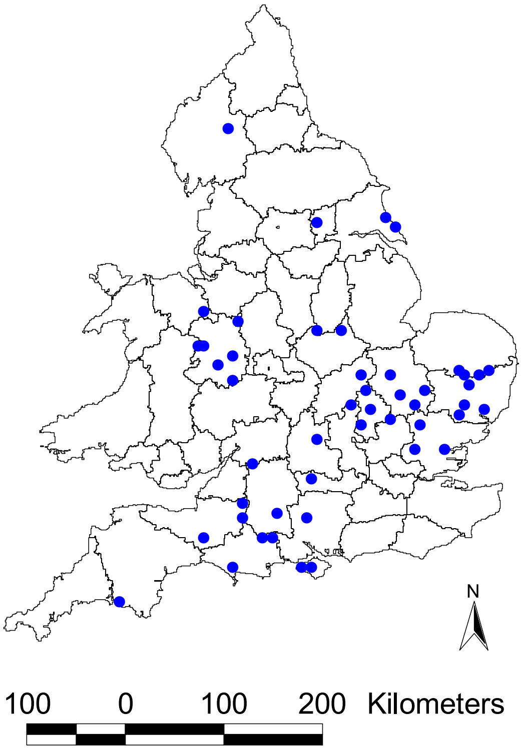


Figure 6.2 Sites with consistent and sufficient data (n=49)

The reduction in sites substantially changed the frequency distribution of clay content of the topsoil (Figure 6.3). The bimodal distribution in Figure 6.3a was constructed using the 1980 data and was made to allow physiotope comparison, i.e. light vs heavy soils. However, the necessary omissions in the 2003 data (Figure 6.3b) reduced the number of observations of these groups and created a modal or 'normal' distribution. This disallowed analysis within contrasting physiotopes, as the number of observations had been reduced to a statistically unacceptable level. Alternatively, clay was considered as a factor influencing SOMFIE performance by being entered in a GRM and multiple regression analysis as an independent variable, or the effect of clay was removed by sampling around the median clay content.

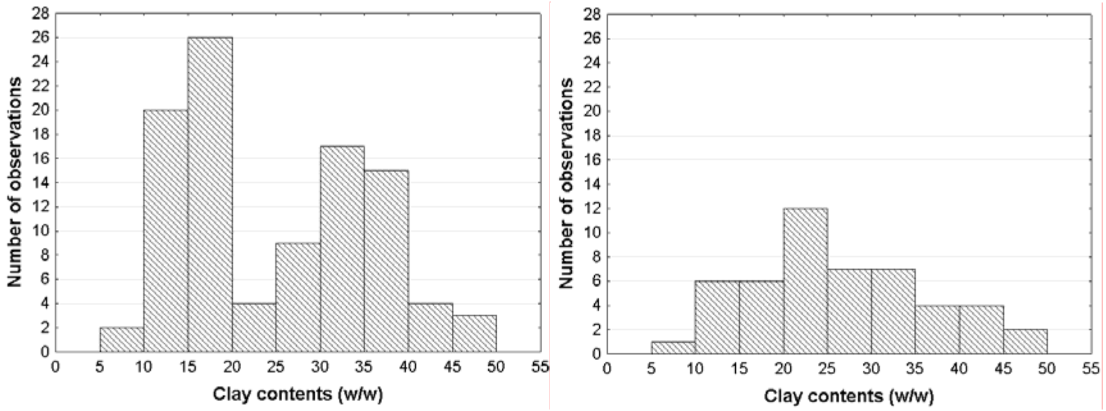


Figure 6.3 **Clay content histograms. Left shows the bimodal distribution of the original data set (n = 101). The right graph shows a nearly normal distribution of the same data after removal of sites with insufficient data (n = 49).**

Precipitation data from 2003 are not included in the NSI, and therefore a potential change in the frequency distribution of wet and dry sites could not be observed. However, the number of observations and the range of precipitation were not equal for both groups. The number of sites for the dry group was higher while its range was smaller than the wet group, which reflected difficulties in finding appropriate sites in the wet group during the field campaign (see Section 6.5.2). Despite the differences, the wet and dry groups qualify to be analysed separately and compared for appropriate SOMFIEs.

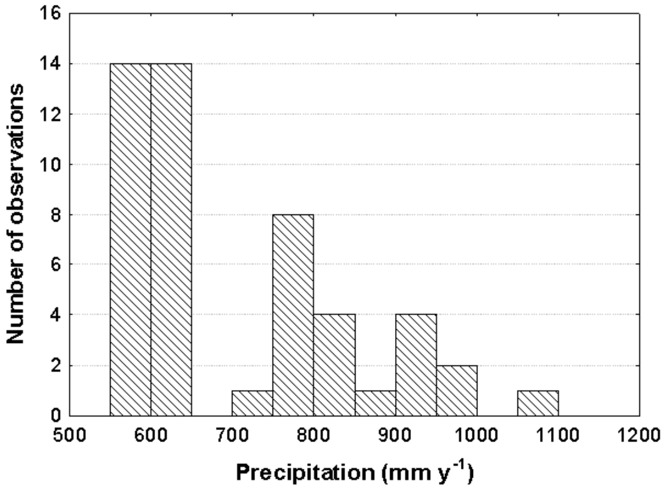


Figure 6.4 **Frequency distribution of average annual precipitation of sites in the qualified data set.**

PREDICTOR VARIABLES (SOC MEASURES)

Several different measures of SOC were calculated and considered for analysis (Table 6.2). At some sites, bulk density measurements were not possible due to the soil being extremely hard at the time of sampling (summer 2003). Therefore, bulk density was measured for 80% of the sites (39 out of 49) and only for the top 15 cm of the soil. To use as many data cases as possible a pedotransfer function (Hollis *et al.*, 1995) was used to compute all 'quantity SOC measures' (Equation 6.1):

$$BD=1.46-0.0254*\ln(clay)+0.0279*\ln(sand)-0.261*\ln(SOC) \qquad [6.1]$$

with BD=bulk density; clay, sand and SOC=w/w.

Table 6.2 Definition of SOC measures

SOC measures		**Description**
Gravimetric content (%)	$\%SOC_{total}$	Weight SOC/weight sample
Quantity (stocks) ($t\ ha^{-1}$)	$SOC\text{-}STOCK_{topsoil}$	Amount of OC in 0-15 cm of soil
	$SOC\text{-}STOCK_{till}$	Amount of OC in the tilled part of the soil
	$SOC\text{-}STOCK_{dtop}$	Amount of OC in the top horizon
Quality	Position in Indicative SOC Management Range	Percentage SOC in the top 15 cm of soil, as a percentage of the determined upper limit
	$\%SOC_{active}$	$\%SOC_{total} - \%SOC_{lower\ limit}$
	SOM management intensity	Combination of OM addition type, quantity, and frequency
	SOM management type	Structural or Nutritional
	C:N	Ratio of OC over N

The %SOC$_{total}$ and C:N ratio were based on measured values. SOM management type was based on farmer information, as was SOM management intensity which also includes an element of scientific interpretation by this investigator (see Table 6.3). The %SOC$_{active}$ and the 'position in the SOC management range' are determined values based on robust statistical analysis (Chapter 4). The rationale of defining 'active SOC' in this way is the idea that the fraction of SOC that is associated with clay is a relatively 'inert' or 'passive' fraction which does not contribute substantially to soil functions (see Section 2.1.1).

Table 6.3 SOM management intensity classification. N=nutrient based OM, S=structure based OM

SOM management class	Intensity description	Practical examples
1	No additions	-
2	Infrequent additions	1 FYM application (< 40 ton ha^{-1}) or 2 crop residue incorporations, in last 10 years
3	Little N + S	Medium crop residue incorporations (4-5 out of 10 years)
4	Medium N + little S (or vice versa)	Frequent crop residue incorporations (8-10 out of 10 years)
5	Heavy N + little S (or vice versa)	Less intensive leys/crop residue (< 3 out of 10 years) with slurry/poultry applications (or vice versa) or 1-2 FYM applications in 10 years
6	Medium N + S	Less intensive FYM or intensive leys (> 3 out of 10 years)
7	Heavy N + S	Frequent FYM or sewage sludge (3 very high rates, or 5 medium rates, in 10 years)

One of the main outcomes of the previous chapter was the difference in farmer perception for structural vs nutritional based SOM management (see Section 5.5). To investigate this perception, the OM management history was used to classify fields as being mainly 'structural' or 'nutritional'. Straw and ley grass were interpreted as structural. Slurry, poultry manure, sewage sludge and FYM were classified as nutritional. FYM, a mixture of animal manure and straw, was regarded as mainly having nutritional benefits (this will depend on the amount of straw mixed in with the manure, but seemed a reasonable assumption from the interview process). When a field received both FYM and either ley grass or straw, it was classified as structural. A field receiving OM additions of both groups (except FYM) was classified nutritional/structural. Fifteen were structural, 20 nutritional, eight structural/nutritional, and six had no OM management.

In the first instance, all SOMFIE analyses were run with $\%SOC_{total}$ as the predictor variable. Where appropriate, or when not showing any relationship, additional analyses were run for 'quantity' or 'quality' predictor variables.

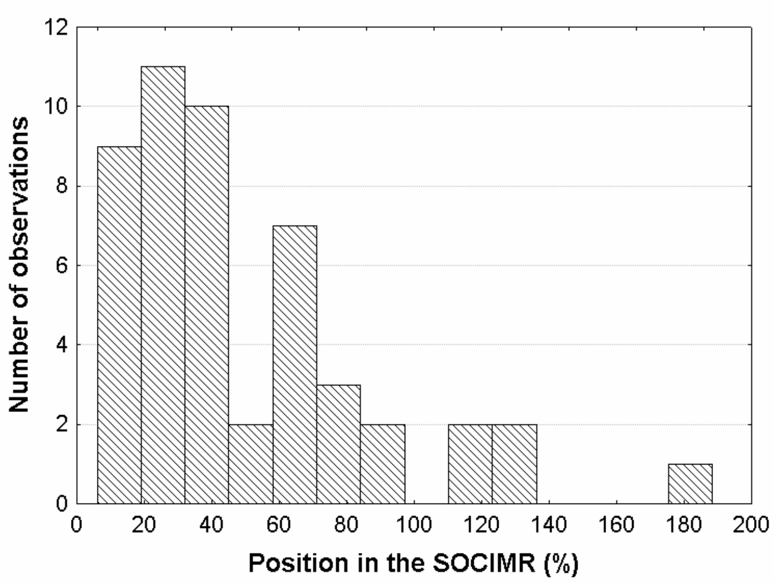


Figure 6.5 Histogram of the 'position in the SOC indicative management range' of the sites in the qualified data set. On the x-axis 0% represents the lower limit and 100% the upper limit.

Figure 6.5 shows five sites to be above the upper limit in the SOCIMR (see Chapter 4). The lower limit in the SOCIMR is set at 0%, and the upper limit at 100%. The three most extreme outliers (> 130%) were explained by environmental factors. The most extreme outlier (188% of range) was explained by degraded material from a rendzina soil mixed into the plough layer. Locally these soils are referred to as 'Black Puff' soils, where the 'black' is likely to refer to the dark colour of the organic matter and the 'puff' could refer to the low bulk density of these soils. It was classified as a 'brown rendzina over chalk'

(Soil Survey Record No. 32), and small and large chunks (up to 20-25 cm) of humified organic material were found throughout the topsoil during sampling. The second outlier (135%) was explained by the sample being located where a hedge had been removed. Its C:N ratio corroborated this explanation (C:N = 21.2, mean = 8.14, S.D. = 1.0). The third extreme value (134%) was reported to be susceptible to flooding and in permanent grassland until 10 years before sampling. It had a relatively high C:N ratio of 11.3 (mean = 8.14, S.D. = 1.0). The fourth most extreme outlier (122%) was explained by SOM management, as the farmer reported applying 150 t ha^{-1} of FYM to the field, every four years. For the least extreme outlier (114%) no obvious environmental, land use, sampling or laboratory factors could be identified to explain its relatively high position in the indicative SOC management range.

As a result of the 'bimodal to modal distribution shift' in clay levels from the original (1980) data to the re-measured (2003) data (see Figure 6.3), and the halving of the number of sites due to field heterogeneity and missing data, the methodology (Chapter 3) had to be modified. Separate analysis for physiotopes could be performed only for wet and dry physiotopes (no differentiation for light and heavy soils). The effect of clay was excluded by selecting around the mean of the distribution (highest number of observations), or included as a predictor variable in a multiple regression analysis (see Section 6.4.2).

6.4.3 SOMFIE performance

YIELD QUANTITY AND STABILITY

General regression model runs on the whole data set did not reveal any factors which explain significantly the variation in yield quantity. Drill date class did show a weak negative trend (more yield for earlier drilling dates), but this was only significant when all cases with minimum yield (7.5 t ha^{-1}), and the case with highest yield (10.6 t ha^{-1}) were omitted (n=28, R^2=0.14, p=0.04). As a measure of the active fraction of SOC (see Section 2.2), the '%active SOC measure' is calculated by subtracting lower limit estimates (determined using %clay and precipitation, Section 4.4.4) from the percentage of total SOC. As is shown in Figure 6.6, no significant correlations were found (possibly due to there being many other confounding factors).

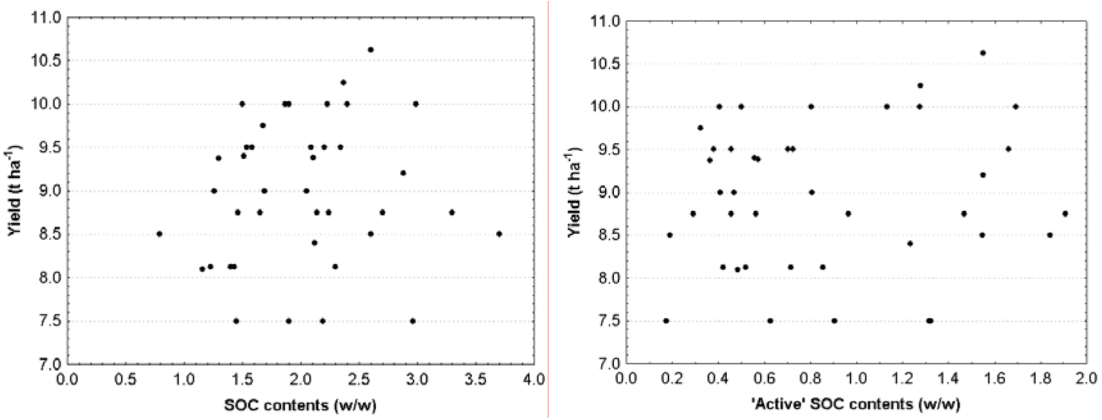


Figure 6.6 Relationship between first winter wheat yield and SOC measures in the top horizon (n = 34). The left graph uses the percentage of total SOC (r^2=0.012, p>0.1). The right graph uses % active SOC calculated by subtracting the lower limit estimate (see 4.4.4) from the percentage of total SOC (r^2=0.010, p>0.1).

Separate analyses of wet and dry sites, revealed no significant difference in yield between the two. Similarly, no difference was observed for nutritional vs structural OM additions, or for the SOM management intensity measure (Figure 6.7).

For yield stability, as well as for 'nutritional vs structural OM management', no relationships were observed.

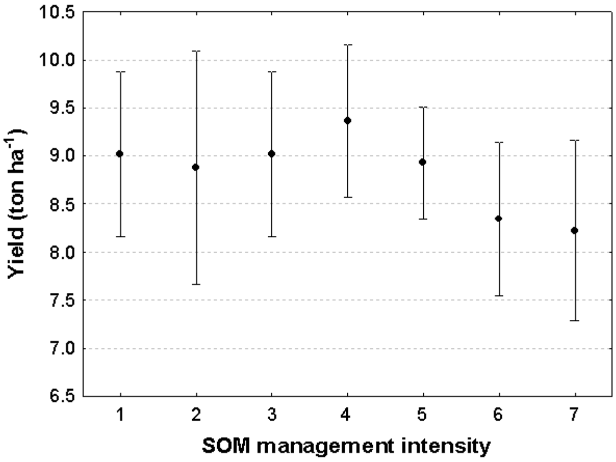


Figure 6.7 **Relationship between first winter wheat yield and the intensity of OM additions to the field (1=lowest intensity); vertical bars indicate the data spread.**

CULTIVATION PASSES AND FLEXIBILITY

The number of passes required to make a seedbed was normally distributed, with a median of five passes. It ranged from one to nine, when a power harrow pass is assigned two passes. It was not significantly related to any of the factors in the GRM, nor were any significant differences observed for OM types, or precipitation group.

For a field's flexibility rating (see Appendix 3), only a texture effect could be discerned. Fields with rating 1 (very inflexible) were predominantly of heavier texture (median=32.5 %clay) than fields with a 4 rating (very flexible) which had a lighter texture (median=20.7 %clay). No effects of SOC predictor variables were observed.

BIOCIDE PASSES

This factor was normally distributed with a median of five biocide passes, ranging from one to nine. In the GRM, only pH and N fertiliser were entered in the model. Multiple regression analysis of these factors revealed a weak positive, but not significant, relationship. None of the SOC predictor variables explained variation in the number of biocide passes.

DROUGHT AND WATERLOGGING STRESS

Drought stress results ranged from 0 (drought stress never observed) to 10 (drought stress observed every year of the last 10 years), with a median of observed drought stress twice in ten years. A GRM revealed that none of the factors explained drought stress variation significantly. No difference was found for wet versus dry sites. Structural OM management had a lower mean (3.7) and median (2) than nutritional OM management (5.3 and 4 respectively). However, the number of observations was too small to allow robust analysis and no significant relationships were found. There was insufficient data on waterlogging stress for analysis.

BIOLOGICAL ACTIVITY

Biological activity Classes 2 and 3 were the only ones with sufficient data for analysis. No relationship between biological activity and predictor variables was found.

GROWTH REGULATOR PASSES

For the wet sites, a GRM and multiple regression analysis with clay%, SOC stock, seed rate, drill date, and N fertiliser showed the number of growth regulator passes to only be significantly correlated with amount of N fertiliser applied ($n=17$, $R^2=0.52$, $p=0.001$). An increase in N fertiliser application of 60 kg ha^{-1} requiered one additional growth regulator pass to be applied. No significant trends were found for the dry sites. No differences were found for SOM quality indicators.

SUMMARY OF SOMFIE PERFORMANCE

SOC levels (gravimetric concentrations and stocks), SOC quality measures (%active SOC, C:N ratio), and SOC management type, or intensity, measures did not show any significant correlation with any SOMFIE, either in a regression or in a robust analysis.

6.4.4 Case studies

Five paired-field case studies were identified on the basis of farmer descriptions in the SSIs and subsequently analysed in more detail. To test the farmers' claims that the fields were texturally similar and contrasting in SOC, five evenly spaced grids were sampled for each field. Each grid consists of 25 sub-samples (over a 400 m² area), and therefore spatial variation at small and large scales was considered in the sampling design. An additional set of relevant parameters was analysed, as shown in Table 6.4.

Table 6.4 Environmental characteristics of case study farms' paired fields. SOCIMR=SOC Indicative Management Range, BD=Bulk Density. Low and high perceived SOC fields are indicated "-" and "+" respectively. Standard deviations are in parentheses.

Farms		%Clay w w^{-1}	%SOC w w^{-1}	%SOC-IMR	%N w w^{-1}	C:N	CEC (+) g^{-1}	pH	BD kg dm^{-3}
A	-	51 (2)	2.6 (0.1)	34	0.29	9.0	17.6	7.8	1.06
	+	45 (2)	2.4 (0.2)	35	0.27	8.9	17.6	7.5	1.05
B	-	23 (1)	1.9 (0.1)	37	0.27	7.0	16.9	7.5	1.31
	+	24 (1)	2.5 (0.4)	61	0.21	11.6	18.8	7.5	1.24
C	-	42 (2)	2.6 (0.2)	47	0.28	9.1	17.4	6.5	1.14
	+	42 (4)	3.1 (0.2)	67	0.36	8.7	17.9	6.6	1.04
D	-	20 (2)	1.9 (0.3)	23	0.24	8.2	16.7	6.3	1.28
	+	27 (1)	3.0 (0.7)	50	0.33	8.2	15.9	6.3	0.98
E	-	33 (3)	3.1 (0.4)	44	0.34	9.4	17.5	6.1	1.11
	+	32 (3)	3.8 (0.8)	69	0.3	12.0	16.7	6.7	1.06

In order to comply with the Data Protection Act (MAFF, 1998), the farmers' identities have been withheld, and case study farms have been labelled "A" to

"E". Paired fields on Farms A and D were significantly different in clay content. However, the difference was within textural class boundaries, and therefore the fields were considered spatially similar in texture. All paired fields, except A, were found to be significantly different in SOC, the position in the SOCIMR, and bulk density, in accordance with the farmers' perception. On Farm A the paired field analysis was contrary to the farmer's perception; the fields were similar in SOC and related parameters (Table 6.5).

Table 6.5 Perceived cause of SOC difference in paired fields on case study farms

Farms	Description of farmers' perception
A	The high SOC field was next to an old dairy, and was therefore perceived to have had more FYM applied in the past.
B	The high SOC field had always had all crop residues returned or FYM applied (purchased from neighbour in 1995). The low SOC field had been arable for at least 70 years.
C	The high SOC field was in permanent grassland until 1940-45. Possibly forest sometime before that. The low field had always been arable.
D	The high SOC field is next to an old dairy (therefore likely to have received substantial slurry or FYM additions) and was in grass until 2001. The low field had been arable since the 1970s.
E	The high SOC field had four times more FYM applied than the low SOC field, over the last 10 years (400 vs 100 t ha^{-1}).

After the initial SSI with the case study farmers during the 'national testing phase' (Chapter 5), the identified paired fields were sampled and tested (Table 6.4). The farmer was visited and interviewed again one year later (summer 2004), specifically for SOMFIE performance on the paired fields (Table 6.6).

Table 6.6 SOMFIE performance of the valid paired fields on case study farms. NI=No Impact, NO=Not Observed

SOMFIE		B	C	D	E
Yield	**Yield quantity**	NI, but less effort required to get the yield	NI	≈ 15% higher potato yield in high SOC field	5% higher yield for combinable crops

	Yield stability	High SOC field is 'more reliable' (see drought stress)	-	NO	Yes, can count on good yield in high SOC field. In low SOC field only ok yield in good weather year
	Yield quality	NI	Lower quality yield only in dry growing seasons. Shrivelled, smaller grains	Not for wheat, but quality increase for potatoes (less soil borne skin disease (see disease)	NI
Workability	**Cultivation passes**	Easier to create a seedbed	One extra pass required on low SOC field	High SOC field works better	NO
	Workability window	2 days larger in high SOC field	8 – 9 days larger	NO	1 day larger window in high SOC field
	Workability flexibility	High SOC field more flexible, reduces stress, makes you feel better	Low SOC field much les flexible (sometimes needs spring crop)	High SOC field is more flexible, but cannot quantify.	High SOC field more flexible. Quite valuable.
	Subsoiling	NI	10-15% higher diesel costs in low SOC field and takes 10% more time (needs to drop a gear)	NO	If treated the same more need for subsoiling low SOC field. But more traffic with more FYM also causes more need for subsoiling
	Implement wear	NI	10-15% more wear on low SOC field	NO	NI
Crop establishment	**Seed rate**	10% lower on high SOC field	Could lower seed rate in high SOC field, but does not	NO	Could lower but does not
	Crop levelness	NI	Much more even emergence in high SOC field	-	-
	Fertiliser	20 kg ha^{-1} more P and K on low SOC field	Low SOC field gets 1 N pass extra	10% less N on high SOC field	Obviously less N with FYM
	Lodging	NI	-	-	NI
	Drought stress	In drought year 30% less yield on low SOC field	No high drought stress risk as fields are high in clay. Low SOC field does form bigger cracks and more water	No impact on wheat, but can drop out an irrigation operation for potato.	NI

			stress is observed (see yield quality).		
	Water logging stress	NO	NI	NI	NI
Disease & pests	**Disease**	NI	NI	NI	More fungal disease in low SOC field, but could have other cause
	Slugs	NO	Only the low SOC field gets slugs (I pass yr^{-1})	Less slugs in low SOC field (I slug pellet pass less)	NI
Other	**Erosion/ degradation**	NO	No impact for water erosion, but more wind erosion on high SOC field (fluffier topsoil)	More capping on low SOC field, leading to a seedling (emergence) problem, which impacts yield (see yield)	NI
	Soil biology	High SOC field is fluffier and more seagulls gather behind the tractor while cultivating (earthworm indicator)	NI	NI	NO

6.5 DISCUSSION

Data loss had been anticipated (see Section 3.3), and the extent (50%), was within expectations. The main cause was the relatively high number of texturally heterogeneous fields, and insufficient SOMFIE data collection for SSIs not attended personally by this investigator.

6.5.1 Questionnaire – limitations and value

The questionnaire formed the structured part of the semi-structured interviews. The use of large print descriptive classifications was found to be helpful to the interviewee while thinking about the SOMFIE question. Generally, yield, N fertiliser and number of seed bed passes were answered most readily. Number of biocide passes required most time for the interviewee to answer.

In general, the questionnaire questions appeared to be given well-considered answers, as time was taken to reflect. A well-established rapport (see Section 5.5) and the implementation of the questionnaire at the end of the SSI, also appeared to help the interviewee in providing answers.

6.5.2 Environmental variables

The difficulties in finding appropriate sites in the wet physiotopes was caused by a high percentage of NSI sites (estimated at >70%) designated as "arable/ley", in fact being in permanent grassland. Further inquiry with the farmer revealed most of these fields to have been in permanent grassland when the NSI sampling was performed (around 1980). The lesson learned from this experience must be to allow more time resources in planning for unexpected phenomena when using legacy data (or any unverifiable data).

6.5.3 SOMFIE performance

Farm management variation may have limited the power of the experiment. It could be argued that farms are akin to humic substances (see Section 2.1) in the sense that they are also a 'super mixture'; no two farms are managed exactly the same. The main sources of management variation important to SOMFIE performance measurements are: different tillage implement types (e.g. discs, deep mouldboard, shallow mouldboard); use of powered and non-powered cultivation equipment (e.g. power harrow or Dutch harrow); different varieties (30 varieties for winter wheat are recommended by the HGCA); different degrees of crop management (e.g. from a single N application to six N applications throughout the growing season), winter wheat in different rotations (e.g. three consecutive years alternating with ley grass, or single year alternating with other combinable crops, or with root crops). Also, land use history might have diminished the relationship between SOM and the SOMFIE performance by different proportions of the total SOC being old, or passive SOC, or Black Carbon. This was however not apparent from the C:N ratio data, or obvious from the land use history data.

Taking the various sources of variation introduced in the analyses into account, the only conclusion that can be drawn is that any potential effect of SOM on SOMFIEs is not stronger than the multiple variation from the input variables. Although this variation is substantial, through a robust approach it was controlled to a relatively high degree, as follows:

- environmental variables were considered through selection criteria imposed on the sample extraction from the NSI database,
- heterogeneous fields (farmers' indication) were omitted,
- alternative farming systems (e.g. organic farms) were omitted,
- a target crop was used,
- weather variation was considered in SOMFIE formulation,
- ancillary variables were recorded and included in analyses,
- a robust statistical method was used (see Section 6.3), and the fields ranged across the entire SOC range. Despite a 3-4 times higher SOC value between the low and high groups, no significant difference in arable performance was observed.

These results indicate there are no strong impacts of SOM on arable field performance (and hence on-farm economics). An expert panel study in New Zealand, where overall productivity thresholds were set around 1 % SOC content, indicated a similar relationship (Sparling *et al.*, 2003). This does not necessarily imply that the low to moderate farmer SOMFIE valuations, discussed in the previous chapter, are not valid. They could simply be of a lower magnitude than the variation in the performance analysis. The variation in the results is mirrored by the scientific literature (Chapter 2), which has not reached a consensus on most SOMFIEs (where investigated). The corresponding values of the literature and the farmers' valuations on fuel use (see Section 5.5.3), could not be verified in the performance exercise, because no appropriate SOMFIE could be established.

From a different perspective, it could be argued that SOM is unimportant compared to quality of farm management; for similar SOM measures in environmentally similar fields, the performance ranged from the bottom to the top of the scale (probably mainly caused by farm management). For example, Figure 6.6 shows that a field with 1.5 %SOC can deliver 7.5 or 10 t ha^{-1} (for a 1st winter wheat, averaged over 10 years), and that the difference was not explained by environmental factors. Management factors, other than those captured by the ancillary variables, are a likely source for this variation.

GROWTH REGULATOR PASSES

Several possible explanations can be hypothesised for the observed increase in growth regulator passes with increasing inorganic N application in wet physiotopes compared to no growth regulator increase in dry physiotopes. Firstly, it could be explained by more rainfall in summer in wet than in dry physiotopes (rain collected on/in heavy ears of ripe wheat are a known cause of lodging). Secondly, it could be explained by the existence of a water limitation threshold for wheat between the dry and wet physiotopes (i.e. longer stalks in wet physiotopes). The second mechanism is strengthened by the reported increase in straw and silage yield from fields high in SOM through a perceived increased water holding capacity (as discussed in Section 5.5.3).

6.5.4 Case studies

Paired-field studies on commercial farms have good conditions to achieve the goal of determining the impact of SOM on on-farm economics (see Section 3.3.3), because of constancy of commercial awareness of the farmer, single information source and management (e.g. rotations, cultivation equipment, crop varieties). The main limitation of the case studies is their rarity, and therefore the difficulty of obtaining enough observations for robust statistical analysis. For these reasons, the case studies do not represent well the physiotopes devised in Chapter 4, or the *selected* physiotopes used for SOMFIE differentiation in Chapter 5 (e.g. no case studies were encountered on light soils). In addition, only a section of the SOCIMR was covered (20-27% difference in SOCIMR between fields with low and high SOC contents), where the entire range was covered by the survey. However, the case studies' detailed, verifiable (environmental) observations are invaluable for illustrating how SOMFIEs integrate, and for comparison with survey based SOMFIE perceptions.

Two main aspects of the case studies are important for the research at hand and deserve discussion. Firstly, ideological bias, as discussed in Chapter 3 and 5, was confirmed to be an actual phenomenon that is likely to occur in most research utilising the experiential science of farmers, or agricultural experts (e.g. agronomists). One of the five farmers selected turned out to have based substantial benefits of SOM on two fields, which were in fact identical in %SOC. The farmer in question was a licensed agronomist, and was unanimously perceived to be an interviewee of "outstanding interest, knowledge and reliability" by the research team (including this investigator). Investigation of the nature of his ideology could not be recorded as he died before the final round of SSIs. However, from personal discussion on several soil sampling days it was known that he had been involved in SOC related studies in college. Although circumstantial evidence, this background could have led him to have formed, in the words of Udo (2000), "an expectation that impregnated his sensations". Technological bias (see Section 5.6.2) was excluded by both fields being on the same farm (same equipment used), and environmental bias of investigated factors was excluded by sample analysis.

Checking the environmental evidence behind interviewees' perceptions is a resource consuming activity, because of the need to deal with several linked environmental factors and their spatial heterogeneity in a robust manner. Although no extrapolations on the frequency of ideological bias occurrence can be made based on the results presented here (20% occurrence, n=5), it is recommended that future studies, using SSI data, allocate resources for investigation of this phenomenon, and its ramifications for data confidence.

The second main aspect worth discussion is that the paired-field case studies generally confirmed the results from the 'inter-field comparison on multiple farms' study (Chapter 5). The two case studies with mainly structural OM additions to the high SOC field (B and C), showed no observed impact on yield. Farms D and E, however, had mainly nutritional OM additions to their high SOC field and did report yield benefits. Probably this is to do with increased N mineralization. For a root crop (potato) a substantially larger benefit was perceived than for combinable crops. Apart from illustrating and confirming the established differential effect of nutritional vs structural OM additions, and impact on root crops vs combinable crops, the case studies suggested increased water availability as a potential mechanism behind the yield benefit of SOM. When asked about particularly dry growing seasons, stronger benefits were reported:

- 10-30% higher yield quantity for root crops (5% for cereals) on high SOC field
- Lower yield quality (shrivelled, smaller grains for cereal, more skin diseases for potato) on low SOC field
- Drop one irrigation pass on potatoes on high SOC field.

This appears to reinforce the conclusion of Hudson (1994) that SOM is a more important control on available water content than has been previously reported in the literature. Also, it suggests a more important effect of water limitation in arable ecosystems in England and Wales, particularly for root crops.

6.5.5 Implications for SOC ranges and physiotopes

The explanation of outlying values in the SOCIMR (Figure 6.4, and Section 6.4.2) by measured environmental factors and recorded land use history factors (SSI with farmer) corroborated (or more accurately 'failed to falsify') the upper limit determined by 'robust statistics' (Chapter 4). Although no definitive conclusion on the confidence in the SOCIMR values can be drawn on this result alone, it does build confidence in the 'SOCIMR' concept and associated limit estimates (Figure 4.2, and Section 4.5.2).

The case studies, however, cover only a fifth to a quarter of the range, which appears to imply an oversimplification of the limit estimates. Environmental factors included (e.g. precipitation) and not included (e.g. soil moisture regime/position in the landscape) in the determination of the limit estimates are likely, on account of their proximity, to be more similar for the paired fields than for the NSI sites. This supports a recommendation for more research into additional environmental variables to further differentiate the indicative SOC management range concept (see Section 4.6).

6.6 CONCLUSIONS AND RECOMMENDATIONS

The work described here indicates considerably stronger yield benefits of SOC with root crops than with combinable crops. This is an important observation, for the literature almost entirely concentrates on combinable crops, while root crops such as potato, sugar beet, onion and carrot have a substantial geographic distribution, and economic importance. Potentially, considerable economic benefit can be achieved with better SOM management on fields growing root crops.

This enforces the proposition made in Chapter 5 (Section 5.4.2.1) of arable SOM functionality existing mainly as a secondary buffer function, where its impacts are too ‘subtle’ (relatively low magnitude compared to inherent environmental and management variation) to be detected when looking at time series on experimental stations, comparing sites in average (non-drought) years, or when averaging observations/perceptions over a longer time period (10 years as performed in this work). Targeting specific ‘extreme’ weather years might be the only way of determining the impacts, and particularly the mechanisms, of SOM on farming. Subsequently, measurable effects in these years could then be compared to those in less extreme weather years. It is important that economic modellers include the extreme weather years in their models. Extreme weather years are likely to increase in frequency, and possibly severity, in the foreseeable future, i.e. this century (Fowler and Kilsby, 2003). However, from this work it is evident that the importance of the proposed buffer function is likely to increase concomitantly, potentially leading to substantial economic implications. Adding complexity to future scenarios is the lag change in SOC decomposition rates, and consequently SOC levels, with the climatic changes.

Moreover, the lag in change will be different for different physiotopes, and the change could lead to initial SOMFIE benefits, before disbenefits occur, or vice versa (e.g. N release). SOC models (e.g. Century or RothC, see Section 2.1), can predict these lag changes. However, the dependence of economic models on the interdependence of climate and SOC models (not to mention predicted socio-economic and technological changes) places large question marks around the feasibility, and indeed the purpose, of such an exercise.

It seems of greater importance to perform further research into SOMFIE impacts under more controlled conditions on research farms, with the intention of generating additional fundamental knowledge of the effects found here by experiential science and case studies. At the same time it should be acknowledged that the buffer function of SOM in arable ecosystems, although unlikely to reach historical dimensions (see Section 2.3), is likely to increase in value when climate change will lead to more ‘extreme’ weather years. This should be considered and incorporated into SOM policy design, along with physiotope, OM type (nutritional vs structural) and crop type (root vs combinable) variation.

Chapter 7

DISCUSSION AND CONCLUSIONS

"Plurality should not be posited without necessity"

('Occam's razor')

William of Ockham (1285-1349)

This chapter summarises the results and integrates their discussion. It also critiques the selected methodology before reaching conclusions on the research aim and objectives. Finally, recommendations for future research and policy are suggested.

This work describes fundamental research into SOM contents in arable fields and how they relate to on-farm benefits. The methodologies and results have been presented and discussed individually in Chapters 4, 5 and 6. This chapter serves to summarise and integrate the individual results, leading to conclusions.

7.1 SUMMARY

Political developments, concerning potential sequestration of organic carbon in arable soils to mitigate the enhanced greenhouse effect, and both current and future reform of the Common Agricultural Policy (CAP; see Chapter 1), have created a need for more sound scientific evidence regarding SOM's interaction with the agro-production function. This gave rise to the research question:

Does SOM, or its management, provide arable on-farm benefit, in England and Wales?

A review of the scientific literature (Chapter 2) regarding soil processes involving SOM, revealed an apparent consensus that SOM is beneficial for environmental quality. However, limited experimental evidence was found describing arable on-farm benefits from SOM. Based on evidence found, an initial SOMFIE list was developed. The SOMFIEs were grouped functionally by their mode of impact into (i) direct impacts on yield, (ii) crop related impacts, and (iii) non-crop related impacts. Few reports were found on the experiential science of farmers on SOMFIEs, which is considered to be a potentially rich source of information. Methods of extracting this information were identified and discussed.

Chapter 3 developed a conceptual methodology based on linking soil science to social science. A holistic approach was chosen to 'handle' the complexity induced by integrating disciplines. The overall methodology was based on Bouma's (1997) Holistic-Reductionistic-Holistic conceptual approach, in which iteration is proposed to support an exploration of mechanisms. A reductionistic approach was applied to assess SOMFIE performance, while holistic approaches were employed in the initial phases of the SOMFIE list generation, the case studies, and the integrative discussion.

Commercial farmers were identified as a more appropriate population to sample than research farmers, because of the formers' greater economic awareness. Organic farmers were excluded because they might have an ideologically-based bias when identifying and assessing SOMFIEs. Spatial comparison was preferred over temporal comparison, because the latter is affected by changes in technology and knowledge about soil and crop management. Precision-agriculture farms were found to be uncommon and difficult to locate, and were therefore omitted.

Key elements in the methodology were (i) estimating SOCIMRs from soil survey data using 'robust statistics', (ii) establishing a qualified SOMFIE list by exploring experiential science in the farming community and (iii) making SOMFIEs measurable for testing 'field performance' across the entire SOCIMRs. The conceptual framework was designed to integrate these key elements.

Chapters 4 to 6 sought to answer the three objectives (see Section 3.2), which can be represented in a simplified form by three questions (regarding SOC and associated arable, on-farm benefits):

- what ranges of SOC contents are attainable?
- which (dis)benefits of SOC do farmers perceive?
- are farmers' perceptions validated by measurements?

In the research described in Chapter 4, 14 factors in the NSI database for arable land use (n=2448) were analysed to find the governing environmental factors explaining SOC variation. Clay contents and precipitation were determined to be the most important factors, explaining 25% of SOC variation in arable, non-calcareous, non-flooding soils. Physiotopes were defined on the basis of clay contents and precipitation. For each physiotope a SOCIMR was estimated by a ‘robust confidence interval’ of the NSI sites falling within that physiotope. Substantial differences in SOCIMRs were found to exist. For example, the SOC contents in a dry-sandy physiotope ranged from approximately 0.5-1.6%, while those in a wet-clayey physiotope ranged from about 2.0-5.4%.

In Chapter 5, an exploration of the experiential science of expert and ‘progressive’ commercial farmers in SSIs (n=20) led to a qualified list of indicators of on-farm benefit from SOM (SOMFIEs). It generated five new SOMFIEs beyond those identified from the literature review, and it informed the design of an appropriate question-answer format for use in a survey questionnaire. Farmer SOMFIE awareness and valuation were tested by applying the questionnaire to a stratified random sample of commercial farmers (n=101). Unprompted vs prompted questioning produced a ‘SOMFIE recognition’ measure, which indicated a relatively low level of knowledge and awareness of SOMFIEs. On balance, farmers perceived that benefits of SOM outweighed the disbenefits (i.e. lodging, weeds, and slugs). Decreased N fertiliser requirements, increased yield quantity, and increased ease of tillage were recognised as the most valuable benefits. However, variation of impacts by (i) physiotopes, (ii) SOM management type (structural vs nutritional OM), and (iii) crop type (root crops vs combinable crops) were reported to strongly influence relative and individual SOMFIE importance.

The research described in Chapter 6 showed that, despite robust and consistent sampling along the entire SOCIMR, farmers' perceptions could not be corroborated by field measurements. The low to moderate values of SOM indicated by farmers may be less than the lower limit of detection in the validation methodology (SOMFIE performance), due to multiple sources of data variation. The results imply that SOM contents and management may be unimportant compared to the general quality of farm management; for similar SOM measures in environmentally similar fields, the performance generally ranged from the bottom to the top of the scale. The case studies illustrated the strong influence of physiotopes, SOM management type, and crop type on perceived SOMFIEs.

7.2 SYNTHESIS

7.2.1 Integration of results

For the SOCIMRs an 80% robust confidence interval was used, which was arbitrary and reflected scientific judgement. The only other SOC ranges ('SOC guidelines') reported in the literature were based on adding 0.5 to 0.9% SOC to a lower SOC limit, that was statistically determined from survey data in the Bad Lauchstädt area in Germany (Körschens *et al.*, 1998). The large difference in the ranges between the two studies could be caused by methodological differences and environmental differences of the survey areas. The explanation of outlying values (n=5) in the SOCIMRs in Chapter 6 appears to support the interval chosen, although the paired-field case studies (n=5) indicated that SOCIMRs could be improved by further environmental differentiation.

The two most important factors governing SOC contents (determined by a General Regression Model) were clay content and precipitation. This may indicate two physical protection mechanisms. The first is inclusion of SOM in water stable (micro)aggregates where it is protected from microbial decomposition. Clay content is a proxy for this mechanism, although from scientific perspectives a more precise proxy may be expected by integrating several, additional soil structural factors, i.e. clay mineralogy, fine silt contents, earthworm activity, etc. The second is a soil moisture mechanism, where anaerobic conditions of wetter soils decrease SOM decomposition. Potentially, turnover rates are also reduced by lower soil temperatures accompanying increased soil moisture contents (secondary effect). Precipitation is a proxy for this mechanism, which appears to be 'less precise' than the proxy for the other mechanism, 'clay content'. The impact of free draining subsoils and of landscape position are examples of factors interacting with precipitation. The landscape position could affect soil moisture conditions substantially through both potential evapotranspiration effects (e.g. cloud cover or mist) and the upslope area (e.g. soil moisture supply). For a small number of sites, the land use history information indicated the upper limit for sites with excessively free-draining sub-soils may be up to 50% lower than determined in the SOCIMRs. Therefore, the concept and methodology of SOCIMRs appears valid, but further understanding of the mechanisms and more precise proxies might be achieved by further research.

Actual quantification of SOMFIEs in the literature is limited to 'ease of tillage'. McLaughlin *et al.* (2002) showed a 13 to 18% lower tractor fuel consumption on fields that received very high manure rates (100 t ha^{-1} y^{-1}). Farmers perceived the benefits of greater SOC contents in non-sandy soils to be equivalent to 15 to 20 % reductions in fuel and labour costs (with lower values for straw incorporation and higher values for sewage sludge). Two issues need to be taken into consideration.

Firstly, there is a possibility of the experimental study's results being published in the farming literature before the farmers were interviewed, thereby influencing farmers' perceptions. As far as could be established (by asking interviewees and scanning the recent farming literature), this was not the case. Secondly, the manure rate of 100 t ha^{-1} y^{-1} in the experimental study was found to be a factor 2-4 higher than manure rates commonly applied on commercial farms. This implies that the farmers' perceptions were at least twice as high as measured experimentally. Therefore, the corroboration with the literature remains limited (only one SOMFIE) and further research is needed to explore validation of SOMFIE valuations by farmers.

Both the case study exploration (described in Chapter 6) and the 'SOMFIE measurement evaluation' (developed in Chapter 5) suggest that the function of SOM in retaining soil moisture is the main factor contributing to possible on-farm economic benefit. Extremely dry or (less often) wet growing seasons were often the only situations when benefits were perceived.

SOMFIE bias was discussed in the literature review (Chapter 2) where Oudwater and Martin (2003) reported on the risks of scientifically-biased interview techniques, and interviewee confusion arising from the use of technical language. Ideological bias was discussed in Chapter 3 (Bouma, 1997). Chapter 5 developed the concept of SOMFIE bias further, specifically for spatial and temporal comparisons, and found a risk of technological and environmental bias, depending on the perception basis of the interviewee

(Table 5.12). Environmental bias was subsequently observed as an actual risk in the paired-field case studies in Chapter 6.

7.2.2 Implications for research and society

Viewing the overall picture, there appears to be a paucity of on-farm SOM benefits in arable agro-ecosystems of England and Wales. Certainly, SOM does not seem to be the panacea that it possibly once was, or still is believed to be. Only in particular, marginal, situations do there appear to be substantive benefits from SOM, e.g. arable farms with sloping fields on silty soils; small mixed farms; light soils in the dry part of the country (especially for root crops).

Arable farms with sloping fields are identifiable from soil survey information. These may require management to maintain or enhance SOM contents to optimise economic performance in the long-term.

The current trend in commercial arable farming is to larger units and the progressive elimination of mixed farming from major cereal production areas. It appears that SOM provides only marginal benefits to large-scale cereal-producing units. Nonetheless, where smaller, mixed and more traditional farms remain, there may be worthwhile benefits from SOM management that relate to longer-term buffering capacity from mainly ‘extreme’ weather years. A reform in agricultural policy in England and Wales to mainly small, mixed farms – while maintaining food security and affordability – would increase the importance of SOM, but seems quixotic.

Looking to the future, in the context of climate change, maintaining and managing SOM may provide a degree of buffering against changing and less favourable climatic conditions. Particularly, drier conditions might make SOM valuable because of its effect on soil moisture. Current models, however, predict mainly a more heterogeneous distribution (in space and time) of precipitation, and its effects on SOM dynamics and SOMFIEs are not known.

The evidence presented in this work does not conform to the general idea, or belief (in some cases 'ideology') in scientific communities, farming communities and society at large (possibly our 'collective unconscious'), that SOM is important to on-farm economics in contemporary arable farming. This premiss may be specious, and is possibly caused by cultural SOMFIE bias. For many centuries (before the step changes introduced in agriculture during the 18th, 19th and 20th centuries) SOM was indeed of paramount importance to arable farming. Most agro-production sub-functions were heavily influenced by, or dependent on SOM. However, farming has progressed and most agro-production sub-functions are now managed mainly by technological innovations combined with increased understanding and knowledge of farming practices.

Therefore, the evidence presented in this work may be a step towards a paradigm shift (Kuhn, 1962) regarding the on-farm benefit of SOM in contemporary farming; SOM's importance has shifted from a primary function to a secondary, or buffer, function. It still contributes to most agro-production sub-functions, but its magnitude is relatively low and in many cases only (measurably) occurring in 'extreme' climatic years.

Acceptance of this proposed paradigm shift holds important implications for research. For SOM research, the focus may need to be redirected from general to marginal situations. For research supporting agriculture in general, research may require a move from 'soil quality management' to 'quality soil (or farm) management' (Sojka and Upchurch, 1999; Sojka *et al.*, 2003). For the marginal situations critical SOMFIE thresholds need to be identified, considering:

- Physiotopes
- SOM management type
- Crop type

For on-farm benefit, SOM management type (and intensity) is functionally separated from SOC content, and may be more useful for investigating relationships than measurements of 'active SOC'. Critical thresholds may be unconventional and specific, e.g. the amount or frequency of shallow straw incorporation in silty soils (so that straw breaks up the soil surface) in relation to establishment and yield of root crops (irrespective of SOC content). Critical thresholds should also consider implications for other ecosystem components and services. Environmental trade-offs are likely to counter some on-farm benefits, e.g. nitrate leaching to groundwater from FYM additions on light soils, needs to be considered carefully.

It is important to note that the proposed paradigm shift only concerns the on-farm economic benefit of SOM, within the food production function, whereas this is just one of 23 proposed ecosystem functions of soil (De Groot *et al.*, 2000). No evidence in this work suggests a paradigm shift would be needed regarding the value of SOC and SOM management to other ecosystem components, and associated societal groups or functions. For example, the potential of arable soils to sequester C, thereby mitigating the enhanced greenhouse effect, may prove valuable to the global human population (if SOCIMRs are considered carefully in related policy). Concomitantly, greater SOM contents may conserve biodiversity of soil organisms; greater numbers of soil organisms are likely to positively affect the food chain (e.g. bird populations); and increased water retention in soils richer in SOM may diminish flooding and erosion, with potentially substantial benefit to affected regions. Finally, the intergenerational equity argument – that future generations have a right to benefit from the Earth's resources, and that the current generation does not have the right to deplete a resource irreversibly (Williams, 1997; Sparling *et al.*, 2003) – also applies.

Finally, this study has revealed a need for semantic harmonisation regarding SOM, both in science and society. In science there appears to be a confused concept of what SOM represents, which is reflected in the diversity of SOM definitions (see Section 2.1). In farming both the awareness and understanding of SOM dynamics and functionality is relatively low, possibly caused by inconsistent or unclear language from science. Semantically harmonised communication between science and society is needed to create a platform of understanding, to enhance the quality of interactions between the two groups and to facilitate implementation of future policy.

7.2.3 Overall methodology critique

The holistic part of the methodology extended the understanding of on-farm processes regarding SOM, and the reductionistic part investigated their validity. The SOCIMRs and qualified SOMFIE list and perceptions provided the clearest results. The SOMFIE validation by performance measurements is the most obvious candidate for methodological criticism. Although the methodology of the SOMFIE performance study safeguarded against multiple sources of variation by a robust approach controlling that variation (see Section 6.5.3), it was limited in its findings. It appeared that the lower limit of detection was greater than the potential magnitude of benefits from SOM. Rather than validating the SOMFIE perceptions (as envisaged in the methodology design), it indicated that benefits from SOM may be unimportant relative to quality of farm management. This indication of relative importance is an interesting and relevant output with important implications for future research, as discussed in the previous section (Section 7.3.2).

During the early stages of methodological design, consideration was given to monitoring a large sample of paired-field case studies, by making scientific soil and crop measurements linked to SOMFIEs over two growing seasons. The advantages of a single information source, same management and the use of scientific measurements (rather than qualitative interview data), might have increased the power of the experiment to the level required for detecting potential SOMFIE performance.

However, suitable paired-field case studies are uncommon and onerous to obtain. In addition, this research has shown that SOMFIEs may only occur (or be measurable) in particularly dry (or wet) growing seasons. Therefore, considering methodological integration and available resources, this alternative approach would not have been viable within this project. However, from this study a strong recommendation is put forward for follow-up validation by measurements on paired-field case studies on commercial farms (and research farms).

Considering the available research methods regarding questions in agriculture, it is argued that different methods address different aspects of the question, and integration of ‘method tiers’ yields a more substantive answer than could be achieved by any one method. A pilot study interviewing a selective group of expert farmers enhances insight for scientific investigators into the farming context of the research. Research farmers can provide information on interactions on an integrated level, and semantic compatibility between scientists and farmers. Commercial expert farmers can extend or detail this information to on-farm economic implications. An interview survey on a stratified random sample of commercial farmers provides a wider picture (including marginal situations), which is essential for supporting policy design. Scientific field measurements safeguard against potential bias in interview data and are needed to establish critical thresholds as well as a numeric framework to support policy design. It is proposed that methodologies integrating these method tiers are followed to reach the required comprehensive evidence for supporting policy design.

7.3 CONCLUSIONS

Based on the results presented in this work, it is concluded that in general SOM provides limited on-farm economic benefit. Moreover, this benefit varies substantially with environmental factors (physiotopes), management factors (type of OM management and type of crop), and the factor time (extreme weather years and technological/socio-economic change). Root crops on light/silty soils, especially in the dry part of the country, appeared to benefit the most from SOM. However, for winter wheat in particular (the crop focused on in this study), and possibly for combinable crops in general, it is concluded that the benefits are relatively small and are only substantial in farmers' perceptions in very dry growing seasons (one in 10-30 yr events, suggesting that increased water availability is the main source of benefit from SOM).

The benefits of SOM should also be viewed in the context of other farm management factors, e.g. the apparent trend to tenanted land and contracting out of operations, and the generally short planning horizons of farmers (1-5 yr) compared to the time needed to build up SOC (up to 10-15 yr). It seems that although SOM management might be beneficial for the environment and society at large, the magnitude of on-farm economic benefits *alone*, does not warrant farmers ranking SOM high in their priorities. SOM also has an economic cost. This cost depends on farm type (mixed or arable), OM management type and frequency, and, in cases of off-farm OM supply, on the distance to the OM source. Although not researched in this work, reported costs of OM management vary greatly. Further research into OM management costs and farm management/policy is needed to complement and integrate the results from the research described in this work and inform future policy.

7.3.1 Innovations, limitations and recommendations

The research described in this work has delivered the following innovations:

- Lower and (particularly) upper SOC limit estimates (SOCIMRs) for SOC based physiotopes.
- A qualified list of indicators (SOMFIEs) revealing SOM-farming interactions and valuations that have not been reported in the literature so far.
- Awareness of these interactions in the farming community in England and Wales.
- SOMFIE perception differentiation for physiotopes.
- Reported arable performance of fields ranging from low to high in SOC contents and SOM management.
- A proposed paradigm shift to viewing SOM functionality as mainly a buffer function in contemporary, arable farming in England and Wales.

The methodologies used, however, also imposed several limitations. The area of research, England and Wales, forms the most obvious limitation, and care must be taken in extrapolating results to other regions. Secondly, this work has focused on arable benefits from SOM, and more specifically on winter wheat (field performance). The question of field performance for other crops (particularly root crops) as well as for livestock remains largely unvalidated.

Therefore, recommendations for further research extend to: (i) application and more detailed differentiation of the developed methodology of SOC ranges determination to other regions of the world (where national soil survey data are available), (ii) application and extension of the developed methodology of SOMFIE generation and valuation to other crops and livestock farming, and (iii) verification/falsification of the SOMFIE valuation and performance results by measurements in more detailed studies on research farms, or case studies on commercial farms (particularly for 'extremely' dry growing seasons).

REFERENCES

Akhtar, M., and Malik, A. (2000). Roles of organic soil amendments and soil organisms in the biological control of plant-parasitic nematodes: a review. *Bioresource Technology* **74**, 35-47.

Alvarez, R. (2005). A review of nitrogen fertilizer and conservation tillage effects on soil organic carbon storage. *Soil Use and Management* **21**, 38-52.

Alvarez, R., and Lavado, R. S. (1998). Climate, organic matter and clay content relationships in the Pampa and Chaco soils, Argentina. *Geoderma* **83**, 127-141.

Alvarez-Puebla, R. A., Goulet, P. J. G., and Garrido, J. J. (2005). Characterization of the porous structure of different humic fractions. *Colloids and Surfaces a-Physicochemical and Engineering Aspects* **256**, 129-135.

Amelung, W., Flach, K. W., and Zech, W. (1997). Climatic effects on soil organic matter composition in the great plains. *Soil Science Society of America Journal* **61**, 115-123.

Amelung, W., Zech, W., Zhang, X., Follett, R. F., Tiessen, H., Knox, E., and Flach, K. W. (1998). Carbon, nitrogen, and sulfur pools in particle-size fractions as influenced by climate. *Soil Science Society of America Journal* **62**, 172-181.

Amundson, R. (2001). The carbon budget in soils. *Annual Review of Earth and Planetary Sciences* **29**, 535-562.

Baars, T. (2002). Reconciling scientific approaches for organic farming research, University of Wageningen, Wageningen.

Barrera-Bassols, N., and Zinck, J. A. (2003). Ethnopedology: a worldwide view on the soil knowledge of local people. *Geoderma* **111**, 171-195.

Bauer, A., and Black, A. L. (1994). Quantification of the Effect of Soil Organic-Matter Content on Soil Productivity. *Soil Science Society of America Journal* **58**, 185-193.

Bentley, J. W. (1989). What Farmer's Don't Know Can't Help Them: The Strengths and Weaknesses of Indigenous Technical Knowledge in Honduras. *Agriculture and Human Values - summer 1989*, 25-31.

Bouma, J. (1993). Soil Behavior under Field Conditions - Differences in Perception and Their Effects on Research. *Geoderma* **60**, 1-14.

Bouma, J. (1997). The role of quantitative approaches in soil science when interacting with stakeholders. *Geoderma* **78**, 1-12.

Brady, N. C. (1990). "The nature and properties of soils," 10/Ed. Prentice-Hall.

Brown, M. A., Levine, M. D., Short, W., and Koomey, J. G. (2001). Scenarios for a clean energy future. *Energy Policy* **29**, 1179-1196.

Brunt, L. (2004). Nature or Nurture? Explaining English Wheat Yields in the Industrial Revolution, c.1770. *The Journal of Economic History* **64**, 193-225.

Burdon, J. (2001). Are the traditional concepts of the structures of humic substances realistic? *Soil Science* **166**, 752-769.

Burke, I. C., Yonker, C. M., Parton, W. J., Cole, C. V., Flach, K., and Schimel, D. S. (1989). Texture, Climate, and Cultivation Effects on Soil Organic-Matter Content in Us Grassland Soils. *Soil Science Society of America Journal* **53**, 800-805.

Carter, M. R. (2001). Organic Matter and Sustainability. *In* "Sustainable management of soil organic matter" (R. M. Rees, B. C. Ball, C. D. Campbell and W. C.A., eds.), pp. 9-22. CAB International.

Carter, M. R. (2002). Soil quality for sustainable land management: organic matter and aggregation interactions that maintain soil functions. *Agronomy Journal* **94**, 38-47.

Chan, K. Y., Heenan, D. P., and Oates, A. (2002). Soil carbon fractions and relationship to soil quality under different tillage and stubble management. *Soil & Tillage Research* **63**, 133-139.

Chenu, C., Le Bissonnais, Y., and Arrouays, D. (2000). Organic matter influence on clay wettability and soil aggregate stability. *Soil Science Society of America Journal* **64**, 1479-1486.

Christensen, B. T. (2001). Physical fractionation of soil and structural and functional complexity in organic matter turnover. *European Journal of Soil Science* **52**, 345-353.

Christopher, T. B. S. (1996). Aggregate stability: its relation to organic matter constituents and other soil properties.

Condron, L. M., Cameron, K. C., Di, H. J., Clough, T. J., Forbes, E. A., McLaren, R. G., and Silva, R. G. (2000). A comparison of soil and environmental quality under organic and conventional farming systems in New Zealand. *New Zealand Journal of Agricultural Research* **43**, 443-466.

Cope, D. W. (1976). "Soils in Wiltshire I," The Soil Survey of England and Wales, Harpenden.

Costanza, R., dArge, R., deGroot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., Oneill, R. V., Paruelo, J., Raskin, R. G., Sutton, P., and vandenBelt, M. (1997). The value of the world's ecosystem services and natural capital. *Nature* **387**, 253-260.

De Groot, R. S., Wilson, M. A., and Boumans, R. M. J. (2002). A typology for the classification, description and valuation of ecosystem functions, goods and services. *Ecological Economics* **41**, 393-408.

DeBano, L. F. (2000). Water repellency in soils: a historical overview. *Journal of Hydrology* **231-232**, 4-32.

Defra (2003). "The First Soil Action Plan for England." Department of the Environment, Food and Rural Affairs, London.

Deportes, I., Benoitguyod, J. L., and Zmirou, D. (1995). Hazard to Man and the Environment Posed by the Use of Urban Waste Compost - a Review. *Science of the Total Environment* **172**, 197-222.

Dequeiroz, J. S., and Norton, B. E. (1992). An Assessment of an Indigenous Soil Classification Used in the Caatinga Region of Ceara State, Northeast Brazil. *Agricultural Systems* **39**, 289-305.

Diaz-Zorita, M., Buschiazzo, D. E., and Peinemann, N. (1999). Soil organic matter and wheat productivity in the semiarid argentine pampas. *Agronomy Journal* **91**, 276-279.

Dick, W. A. (1983). Organic-Carbon, Nitrogen, and Phosphorus Concentrations and Ph in Soil Profiles as Affected by Tillage Intensity. *Soil Science Society of America Journal* **47**, 102-107.

Doerr, S. H., Shakesby, R.A., Walsh, R.P.D. (2000). Soil water repellency: its causes, characteristics and hydro-geomorphological significance. *Earth Science Reviews* **51**, 33-65.

Drinkwater, L. E., Letourneau, D. K., Workneh, F., Vanbruggen, A. H. C., and Shennan, C. (1995). Fundamental Differences between Conventional and Organic Tomato Agroecosystems in California. *Ecological Applications* **5**, 1098-1112.

Droogers, P., and Bouma, J. (1997). Soil survey input in exploratory modeling of sustainable soil management practices. *Soil Science Society of America Journal* **61**, 1704-1710.

Droogers, P., Fermont, A., and Bouma, J. (1996). Effects of ecological soil management on workability and trafficability of a loamy soil in the Netherlands. *Geoderma* **73**, 131-145.

Earl, R. (1997). Prediction of trafficability and workability from soil moisture deficit. *Soil & Tillage Research* **40**, 155-168.

Ekwue, E. I. (1990). Organic-Matter Effects on Soil Strength Properties. *Soil & Tillage Research* **16**, 289-297.

Eusterhues, K., Rumpel, C., Kleber, M., and Kogel-Knabner, I. (2003). Stabilisation of soil organic matter by interactions with minerals as revealed by mineral dissolution and oxidative degradation. *Organic Geochemistry* **34**, 1591-1600.

Falloon, P. D., Smith, P., Smith, J. U., Szabo, J., Coleman, K., and Marshall, S. (1998). Regional estimates of carbon sequestration potential: linking the

Rothamsted Carbon Model to GIS databases. *Biology and Fertility of Soils* **27**, 236-241.

Fowler, H. J., and Kilsby, C. G. (2003). A regional frequency analysis of United Kingdom extreme rainfall from 1961 to 2000. *International Journal of Climatology* **23**, 1313-1334.

Franzluebbers, A. J. (2005). Soil organic carbon sequestration and agricultural greenhouse gas emissions in the southeastern USA. *Soil & Tillage Research* **83**, 120-147.

Franzluebbers, A. J., and Arshad, M. A. (1996). Soil organic matter pools with conventional and zero tillage in a cold, semiarid climate. *Soil & Tillage Research* **39**, 1-11.

Franzluebbers, A. J., Haney, R. L., Honeycutt, C. W., Arshad, M. A., Schomberg, H. H., and Hons, F. M. (2001). Climatic influences on active fractions of soil organic matter. *Soil Biology & Biochemistry* **33**, 1103-1111.

Franzluebbers, A. J., Hons, F. M., and Zuberer, D. A. (1994). Long-Term Changes in Soil Carbon and Nitrogen Pools in Wheat Management-Systems. *Soil Science Society of America Journal* **58**, 1639-1645.

Freibauer, A., rounsevell, M.D.A., Smith, P. and Verhagen, J. (2002). "Background paper on carbon sequestration in agricultural soils, under article 3.4 of the Kyoto Protocol," Rep. No. Contract N°.2001.40.CO001.

Freytag, H. E. (1980). Inerte und umsetzbare Anteile der organischen Bodensubstanz. *Arch. Acker- u. Pflanzenbau u. Bodenkunde* **24**, 19-24.

Gerke, H. H., Arning, M., and Stoppler-Zimmer, H. (1999). Modeling long-term compost application effects on nitrate leaching. *Plant and Soil* **213**, 75-92.

Giardina, C. P., and Ryan, M. G. (2000a). Biogeochemistry - Soil warming and organic carbon content - Reply. *Nature* **408**, 790-790.

Giardina, C. P., and Ryan, M. G. (2000b). Evidence that decomposition rates of organic carbon in mineral soil do not vary with temperature. *Nature* **404**, 858-861.

Gill, J. S., Sivasithamparam, K., and Smettem, K. R. J. (2000). Soil types with different texture affects development of Rhizoctonia root rot of wheat seedlings. *Plant and Soil* **221**, 113-120.

Glaser, B., Lehmann, J., and Zech, W. (2002). Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal - a review. *Biology and Fertility of Soils* **35**, 219-230.

Glaser, B., and Strauss, A. (1967). "The discovery of grounded theory: strategies for qualitative research," Aldine Publishing Company.

Golchin, A., Oades, J. M., Skjemstad, J. O., and Clarke, P. (1994). Soil-Structure and Carbon Cycling. *Australian Journal of Soil Research* **32**, 1043-1068.

Grace, P. R., Oades, J. M., Keith, H., and Hancock, T. W. (1995). Trends in wheat yields and soil organic carbon in the permanent rotation trial at the Waite Agricultural Research Institute, South Australia. *Australian Journal of Experimental Agriculture* **35**, 857-864.

Greenland, D. J., Rimmer, D., Payne, D. (1975). Determination of the structural stability class of English and Welsh soils, using a water coherency test. *Journal of Soil Science* **26**, 294-303.

Hansen, B., Alroe, H. F., and Kristensen, E. S. (2001). Approaches to assess the environmental impact of organic farming with particular regard to Denmark. *Agriculture Ecosystems & Environment* **83**, 11-26.

Hassink, J. (1997). The capacity of soils to preserve organic C and N by their association with clay and silt particles. *Plant and Soil* **191**, 77-87.

Hayes, M. H. B., and Clapp, C. E. (2001). Humic substances: Considerations of compositions, aspects of structure, and environmental influences. *Soil Science* **166**, 723-737.

Haynes, R. J., and Naidu, R. (1998). Influence of lime, fertilizer and manure applications on soil organic matter content and soil physical conditions: a review. *Nutrient Cycling in Agroecosystems* **51**, 123-137.

HGCA (2001). Take-all control in winter wheat: planning. *In* "Topic sheet 49".

Hollis, J. M., Thanigasalam, P., Hallet, S. H., Mayr, T. R., and Jarvis, N. (1995). "SEISMIC: User manual." Cranfield University, Silsoe.

Hudson, B. D. (1994). Soil Organic-Matter and Available Water Capacity. *Journal of Soil and Water Conservation* **49**, 189-194.

Janzen, H. H. (2004). Carbon cycling in earth systems - a soil science perspective. *Agriculture Ecosystems & Environment* **104**, 399-417.

Jenkinson, D. S., Adams, D. E., and Wild, A. (1991). Model Estimates of Co2 Emissions from Soil in Response to Global Warming. *Nature* **351**, 304-306.

Jenkinson, D. S. a. R., J.H. (1977). The turnover of soil organic material in some of the Rothamsted classical experiments. *Soil Science* **123**, 298-305.

Jenny, H. (1994). "Factors of soil formation, a System of Quantitative Pedology," Dover Publications, inc., New York.

Jenny, H., Leonard, C.D. (1934). Functional relationships between soil properties and rainfall. *Soil Science* **38**, 363-381.

Johnson, E., and Heinen, R. (2004). Carbon trading: time for industry involvement. *Environment International* **30**, 279-288.

Johnston, A. E. (1986). Soil Organic-Matter, Effects on Soils and Crops. *Soil Use and Management* **2**, 97-105.

Kalembasa, S. J., and Jenkinson, D. S. (1973). A comparative study of titrimetric and gravimetric methods for the determination of organic carbon in soil. *Journal of the Science of Food and Agriculture* **24**, 1085-1090.

Karbozova-Saljnikov, E., Funakawa, S., Akhmetov, K., and Kosaki, T. (2004). Soil organic matter status of Chernozem soil in North Kazakhstan: effects of summer fallow. *Soil Biology & Biochemistry* **36**, 1373-1381.

Karlen, D. L., Erbach, D. C., Kaspar, T. C., Colvin, T. S., Berry, E. C., and Timmons, D. R. (1990). Soil Tilth - a Review of Past Perceptions and Future-Needs. *Soil Science Society of America Journal* **54**, 153-161.

Kelle, U. (2000). Computer-Assisted Analysis: Coding and Indexing. *In* "Qualitative Researching" (M. a. G. Bauer, G., ed.), pp. 282-298. Sage, London.

King, J. A., Bradley, R. I., Harrison, R., and Carter, A. D. (2004). Carbon sequestration and saving potential associated with changes to the management of agricultural soils in England. *Soil Use and Management* **20**, 394-402.

Knorr, W., Prentice, I. C., House, J. I., and Holland, E. A. (2005). Long-term sensitivity of soil carbon turnover to warming. *Nature* **433**, 298-301.

Kononova, M. M. (1958). "Die Humusstoffe des Bodens, Ergebnisse und Probleme der Humusforschung," Deutscher Verlag der Wissenschaften, Berlin.

Körschens, M., and Klimanek, E. M. (1980). Relations between the Content of Organic-Matter in the Soil and Major Soil Properties as Investigated in the Static Experiment at Lauchstadt. *Archiv Fur Acker Und Pflanzenbau Und Bodenkunde-Archives of Agronomy and Soil Science* **24**, 25-30.

Körschens, M., Weigel, A., and Schulz, E. (1998). Turnover of soil organic matter (SOM) and long-term balances - Tools for evaluating sustainable productivity of soils. *Zeitschrift Fur Pflanzenernährung Und Bodenkunde* **161**, 409-424.

Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. *Science* **304**, 1623-1627.

Lausch, A., and Thulke, A. A. (2001). The analysis of spatio-temporal dynamics of landscape structures. *In* "Landscape balance and landscape assessment" (R. Krönert, U. Steinhardt and M. Volk, eds.), pp. 113-136. Springer Verlag.

LeBissonnais, Y., and Arrouays, D. (1997). Aggregate stability and assessment of soil crustability and erodibility .2. Application to humic loamy soils with various organic carbon contents. *European Journal of Soil Science* **48**, 39-48.

Leinweber, P., Schulten, H. R., and Korschens, M. (1995). Hot-Water Extracted Organic-Matter - Chemical-Composition and Temporal Variations in a Long-Term Field Experiment. *Biology and Fertility of Soils* **20**, 17-23.

Lettens, S., Van Orshoven, J., Van Wesemael, B., and Muys, B. (2004). Soil organic and inorganic carbon contents of landscape units in Belgium derived using data from 1950 to 1970. *Soil Use and Management* **20**, 40-47.

Lindman, H. R. (1974). "Analysis of variance in complex experimental designs," W. H. Freeman & Co, San Francisco.

Locke, M. A., and Bryson, C. T. (1997). Herbicide-soil interactions in reduced tillage and plant residue management systems. *Weed Science* **45**, 307-320.

Loveland, P., and Webb, J. (2003). Is there a critical level of organic matter in the agricultural soils of temperate regions: a review. *Soil & Tillage Research* **70**, 1-18.

Loveland, P. J. (1989). The National Soil Inventory of England and Wales. *In* "Element Concentration Cadasters in Ecosystems" (eds Lieth, H. and Markert, B.), pp. 73-80. VCH Verlagsgesellschaft, Weinheim.

Loveland, P. J., Bellamy, P., Bradley, R. I., and Webb, J. (1997). "Critical levels of soil organic matter." Ministry of Agriculture, Fisheries and Food.

Low, A. J. a. P., F.J. (1973). Some examples of the effect of soil physical conditions on the tractive effort required during ploughing. *J. Sci. Fd Agric* **24**, 1011-1020.

MacCarthy, P. (2001). The principles of humic substances: an introduction to the first principle. *In* "Humic Sunstances: Structures, Models and Functions" (A. a. D. Ghabbour, G., ed.), pp. 19-30.

MAFF (1998). "Code of Good Agricultural Practice for the Protection of Water," Rep. No. Revised 1998. MAFF.

MAFF (2000). "Fertiliser Recommendations - for Agricultural and Horticultural Crops (RB209)," 7/Ed. The Stationary Office, London.

Martens, D. A., Emmerich, W., McLain, J. E. T., and Johnsen, T. N. (2005). Atmospheric carbon mitigation potential of agricultural management in the southwestern USA. *Soil & Tillage Research* **83**, 95-119.

McDonald, G. K. (1995). Grain-Yield Trends of Field Pea (Pisum-Sativum L) in South Australia. *Australian Journal of Experimental Agriculture* **35**, 515-523.

McLaughlin, N. B., Gregorich, E. G., Dwyer, L. M., and Ma, B. L. (2002). Effect of organic and inorganic soil nitrogen amendments on mouldboard plow draft. *Soil & Tillage Research* **64**, 211-219.

Moberg, A., and Jones, P. D. (2005). Trends in indices for extremes in daily temperature and precipitation in central and western Europe, 1901-99. *International Journal of Climatology* **25**, 1149-1171.

Motavalli, P. P., Palm, C. A., Parton, W. J., Elliott, E. T., and Frey, S. D. (1995). Soil pH and organic C dynamics in tropical forest soils: Evidence from Laboratory and simulation studies. *Soil Biology & Biochemistry* **27**, 1589-1599.

Muneer, M., and Oades, J. M. (1989). The Role of Ca-Organic Interactions in Soil Aggregate Stability .3. Mechanisms and Models. *Australian Journal of Soil Research* **27**, 411-423.

Munkholm, L. J., Schjonning, P., and Petersen, C. T. (2001). Soil mechanical behaviour of sandy loams in a temperate climate: case studies on long-term effects of fertilization and crop rotation. *Soil Use and Management* **17**, 269-277.

Nichols, J. D. (1984). relation of organic carbon to soil properties and climate in the southern great plains. *Soil Sci. Soc. Am. J* **48**, 1382-1384.

Nortcliff, S. (2002). Standardisation of soil quality attributes. *Agriculture Ecosystems & Environment* **88**, 161-168.

Oades, J. M. (1988). The retention of organic matter in soils. *Biogeochemistry* **5**, 35-70.

Oudwater, N., and Martin, A. (2003). Methods and issues in exploring local knowledge of soils. *Geoderma* **111**, 387-401.

Pandit, N. R. (1996). The Creation of Theory: A Recent Application of the Grounded Theory Method. *The Qualitative Report* **2 (4)**.

Parton, J. W., Schimel, D.S., Cole, C.V. and Ojima, D.S. (1987). Analysis of Factors Controlling Soil Organic Matter Levels in Great Plain Grasslands. *Soil Science Society of America Journal* **51**, 1173-1179.

Parton, W. J. (1996). The CENTURY model. *NATO ASI Series* **138**, 283-291.

Paustian, K., Six, J., Elliott, E. T., and Hunt, H. W. (2000). Management options for reducing CO2 emissions from agricultural soils. *Biogeochemistry* **48**, 147-163.

Pawluk, R. R., Sandor, J. A., and Tabor, J. A. (1992). The Role of Indigenous Soil Knowledge in Agricultural- Development. *Journal of Soil and Water Conservation* **47**, 298-302.

Pendall, E., Bridgham, S., Hanson, P. J., Hungate, B., Kicklighter, D. W., Johnson, D. W., Law, B. E., Luo, Y. Q., Megonigal, J. P., Olsrud, M., Ryan, M. G., and Wan, S. Q. (2004). Below-ground process responses to elevated CO2 and temperature: a discussion of observations, measurement methods, and models. *New Phytologist* **162**, 311-322.

Persson, L., and Olsson, S. (2000). Abiotic characteristics of soils suppressive to Aphanomyces root rot. *Soil Biology & Biochemistry* **32**, 1141-1150.

Post, W. M., Peng, T. H., Emanuel, W. R., King, A. W., Dale, V. H., and Deangelis, D. L. (1990). The Global Carbon-Cycle. *American Scientist* **78**, 310-326.

Powers, J. S., and Schlesinger, W. H. (2002). Relationships among soil carbon distributions and biophysical factors at nested spatial scales in rain forests of northeastern Costa Rica. *Geoderma* **109**, 165-190.

Powlson, D. (2005). Climatology - Will soil amplify climate change? *Nature* **433**, 204-205.

Pulleman, M. M., Bouma, J., van Essen, E. A., and Meijles, E. W. (2000). Soil organic matter content as a function of different land use history. *Soil Science Society of America Journal* **64**, 689-693.

Reeves, D. W. (1997). The role of soil organic matter in maintaining soil quality in continuous cropping systems. *Soil & Tillage Research* **43**, 131-167.

Ritsema, C. J., and Dekker, L. W. (1996). Water repellency and its role in forming preferred flow paths in soils. *Australian Journal of Soil Research* **34**, 475-487.

Rodgers-Gray, B. S., and Shaw, M. W. (2000). Substantial reductions in winter wheat diseases caused by addition of straw but not manure to soil. *Plant Pathology* **49**, 590-599.

Rousseeuw, P. J., and Croux, C. (1992). Explicit scale estimators with high breakdown point. *In* "L1 Statistical Analysis and Related Methods" (Y. Dodge, ed.), pp. 77--92. North Holland, Amsterdam.

Rousseeuw, P. J., and Croux, C. (1993). Alternatives to the Median Absolute Deviation. *Journal of the American Statistical Association* **88**, 1273-1283.

Rühlmann, J. (1999). A new approach to estimating the pool of stable organic matter in soil using data from long-term field experiments. *Plant and Soil* **213**, 149-160.

Russel, J. C., and McRuer, W. G. (1927). The relation of organic matter and nitrogen content to series and type in virgin grassland soils. *Soil Science* **24**, 421-452.

Schjønning, P., Christensen, B. T., and Carstensen, B. (1994). Physical and Chemical-Properties of a Sandy Loam Receiving Animal Manure, Mineral Fertilizer or No Fertilizer for 90 Years. *European Journal of Soil Science* **45**, 257-268.

Schlesinger, W. H. (2000). Carbon sequestration in soils: some cautions amidst optimism. *Agriculture Ecosystems & Environment* **82**, 121-127.

Schmidt, M. W. I., Skjemstad, J. O., Czimczik, C. I., Glaser, B., Prentice, K. M., Gelinas, Y., and Kuhlbusch, T. A. J. (2001). Comparative analysis of black carbon in soils. *Global Biogeochemical Cycles* **15**, 163-167.

Schnitzer, M. (1991). Soil Organic-Matter - the Next 75 Years. *Soil Science* **151**, 41-58.

Shepherd, M. A., Harrison, R., and Webb, J. (2002). Managing soil organic matter - implications for soil structure on organic farms. *Soil Use and Management* **18**, 284-292.

Siewert, C. (2001). "Investigation of the thermal and biological stability of soil organic matter," Shaker Verlag, Aachen.

Sillitoe, P. (1998). Knowing the land: soil and land resource evaluation and indigenous knowledge. *Soil Use and Management* **14**, 188-193.

Six, J., Bossuyt, H., Degryze, S., and Denef, K. (2004). A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics. *Soil & Tillage Research* **79**, 7-31.

Six, J., Elliott, E. T., and Paustian, K. (2000a). Soil structure and soil organic matter: II. A normalized stability index and the effect of mineralogy. *Soil Science Society of America Journal* **64**, 1042-1049.

Six, J., Paustian, K., Elliott, E. T., and Combrink, C. (2000b). Soil structure and organic matter: I. Distribution of aggregate-size classes and aggregate-associated carbon. *Soil Science Society of America Journal* **64**, 681-689.

Skjemstad, J. O., Clarke, P., Taylor, J. A., Oades, J. M., and McClure, S. G. (1996). The chemistry and nature of protected carbon in soil. *Australian Journal of Soil Research* **34**, 251-271.

Skjemstad, J. O., Reicosky, D. C., Wilts, A. R., and McGowan, J. A. (2002). Charcoal carbon in US agricultural soils. *Soil Science Society of America Journal* **66**, 1249-1255.

Skjemstad, J. O., and Taylor, J. A. (1999). Does the Walkley-Black method determine soil charcoal? *Communications in Soil Science and Plant Analysis* **30**, 2299-2310.

Sleutel, S., De Neve, S., Hofman, G., Boeckx, P., Beheydt, D., Van Cleemput, O., Mestdagh, I., Lootens, P., Carlier, L., Van Camp, N., Verbeeck, H., Vande Walle, I., Samson, R., Lust, N., and Lemeur, R. (2003). Carbon stock changes and carbon sequestration potential of Flemish cropland soils. *Global Change Biology* **9**, 1193-1203.

Smith, P., Powlson, D. S., Smith, J. U., Falloon, P., and Coleman, K. (2000a). Meeting Europe's climate change commitments: quantitative estimates of the potential for carbon mitigation by agriculture. *Global Change Biology* **6**, 525-539.

Smith, P., Powlson, D. S., Smith, J. U., Falloon, P., and Coleman, K. (2000b). Meeting the UK's climate change commitments: options for carbon mitigation on agricultural land. *Soil Use and Management* **16**, 1-11.

Soane, B. D. (1990). The Role of Organic-Matter in Soil Compactibility - a Review of Some Practical Aspects. *Soil & Tillage Research* **16**, 179-201.

Sohi, S. P., Mahieu, N., Arah, J. R. M., Powlson, D. S., Madari, B., and Gaunt, J. L. (2001). A procedure for isolating soil organic matter fractions suitable for modeling. *Soil Science Society of America Journal* **65**, 1121-1128.

Sollins, P., Homann, P., and Caldwell, B. A. (1996). Stabilization and destabilization of soil organic matter: Mechanisms and controls. *Geoderma* **74**, 65-105.

Spain, A. V., Isbell, R. F., and Probert, M. E. (1983). Soil organic matter. *In* "Soils: an Australian viewpoint" (C. Australia, ed.). Melbourne and Academic Press, London.

Sparling, G., Parfitt, R. L., Hewitt, A. E., and Schipper, L. A. (2003). Three approaches to define desired soil organic matter contents. *Journal of Environmental Quality* **32**, 760-766.

SSSA (1987). "Glossary of soil science terms," Soil Science Society of America, Madison, WI, USA.

StatSoft (2003). STATISTICA (data analysis software system), version 6, www.statsoft.com.

Stibbe, E., and Terpstra, R. (1982). Effect of Penetration Resistance on Emergence and Early Growth of Silage Corn in a Laboratory Experiment with Sandy Soil. *Soil & Tillage Research* **2**, 143-153.

Stuart, K., and Jenny, H. (1984). My Friend, the Soil - a Conversation with Jenny,Hans. *Journal of Soil and Water Conservation* **39**, 158-161.

Stumpe, H., Garz, J., Schliephake, W., Wittenmayer, L., and Merbach, W. (2000). Effects of humus content, farmyard manuring, and mineral-N fertilization on yields and soil properties in a long-term trial. *Journal of Plant Nutrition and Soil Science-Zeitschrift Fur Pflanzenernahrung Und Bodenkunde* **163**, 657-662.

Sundquist, E. T. (1993). The Global Carbon-Dioxide Budget (Vol 259, Pg 934, 1993). *Science* **259**, 1812-1812.

Tilston, E. L., Pitt, D., and Groenhof, A. C. (2002). Composted recycled organic matter suppresses soil-borne diseases of field crops. *New Phytologist* **154**, 731-740.

Tisdall, J. M., and Oades, J. M. (1982). Organic-Matter and Water-Stable Aggregates in Soils. *Journal of Soil Science* **33**, 141-163.

Udo, K. (2000). Computer-assisted analysis: coding and indexing. *In* "Qualitative Researching" (M. Bauer and G. Gaskell, eds.), pp. 282-298. SAGE, London.

Utomo, W. H., and Dexter, A. R. (1981). Soil Friability. *Journal of Soil Science* **32**, 203-213.

VandenBygaart, A. J., Gregorich, E. G., and Angers, D. A. (2003). Influence of agricultural management on soil organic carbon: A compendium and assessment of Canadian studies. *Canadian Journal of Soil Science* **83**, 363-380.

Verberne, E. L. J., Hassink, J., Dewilligen, P., Groot, J. J. R., and Vanveen, J. A. (1990). Modeling Organic-Matter Dynamics in Different Soils. *Netherlands Journal of Agricultural Science* **38**, 221-238.

Verheijen, F. G. A. (2001). The spatial distribution of soil water repellency and its relation to plant species, soil moisture content and soil moisture redistribution, in semi-arid SE Spain. MSc thesis, University of Amsterdam, Amsterdam.

Veron, S. R., Paruelo, J. M., Sala, O. E., and Lauenroth, W. K. (2002). Environmental controls of primary production in agricultural systems of the Argentine Pampas. *Ecosystems* **5**, 625-635.

Wallace, A. (1994). Soil Organic-Matter Is Essential to Solving Soil and Environmental-Problems. *Communications in Soil Science and Plant Analysis* **25**, 15-28.

Wang, H. L., Magesan, G. N., and Bolan, N. S. (2004). An overview of the environmental effects of land application of farm effluents. *New Zealand Journal of Agricultural Research* **47**, 389-403.

Warkentin, B. P. (1999). The return of the "other" soil scientists. *Canadian Journal of Soil Science* **79**, 1-4.

Wattel-Koekkoek, E. J. W., Buurman, P., van der Plicht, J., Wattel, E., and van Breemen, N. (2003). Mean residence time of soil organic matter associated with kaolinite and smectite. *European Journal of Soil Science* **54**, 269-278.

Watts, C. W., and Dexter, A. R. (1994). Traffic and Seasonal Influences on the Energy Required for Cultivation and on the Subsequent Tilth. *Soil & Tillage Research* **31**, 303-322.

Watts, C. W., and Dexter, A. R. (1997). The influence of organic matter in reducing the destabilization of soil by simulated tillage. *Soil and Tillage Research* **42**, 253-275.

Watts, C. W., and Dexter, A. R. (1998). Soil friability: theory, measurement and the effects of management and organic carbon content. *Eur J Soil Science* **49**, 73-84.

Webb, J., Bellamy, P., Loveland, P. J., and Goodlass, G. (2003). Crop residue returns and equilibrium soil organic carbon in England and Wales. *Soil Science Society of America Journal* **67**, 928-936.

West, T. O., and Post, W. M. (2002). Soil organic carbon sequestration rates by tillage and crop rotation: A global data analysis. *Soil Science Society of America Journal* **66**, 1930-1946.

Whetten, D. A. (1989). What constitutes a theoretical contribution? *Academy of Management Review* **14**, 490-495.

Winklerprins, A. (1999). Local soil knowledge: A tool for sustainable land management. *Society & Natural Resources* **12**, 151-161.

Zimmerer, K. S. (1994). Local Soil Knowledge - Answering Basic Questions in Highland Bolivia. *Journal of Soil and Water Conservation* **49**, 29-34.

Zonneveld, I. S. (1989). The land unit - A fundamental concept in landscape ecology, and its applications. *Landscape Ecology* **3**, 67-86.

APPENDIX 1

Life of Carbon

"…for the love of the thing…"

The element carbon is the basis of life as we know it. However, although life may be filled with carbon; carbon is filled with life too! The life of carbon is an exhilarating story of freedom and captivity, of cooperation and competition, of burning passion and chilled sleep. Only 0.03 percent of the atmosphere is carbon dioxide, yet it is this gas that forms the source of carbon in photosynthesis where it is transferred from the mineral into the organic part of the global carbon cycle. The – possible - life of carbon before it is plucked out of the air in the stomata of a leaf would be hard to phrase more eloquently than Primo Levi did in his book 'The Periodic Table' (1975):

"

[…] Our character lies for hundreds of millions of years, bound to three atoms of oxygen and one of calcium, in the form of limestone: it already has a very long cosmic history behind it, but we shall ignore it. […] Its existence, whose monotony cannot be thought of without horror, is a pitiless alternation of hots and colds, that is, of oscillations (always of equal frequency) a trifle more restricted and a trifle more ample: an imprisonment for this potentially living personage, worthy of the Catholic Hell.

[…] A blow of the pickax detached it and sent it on its way to the lime kiln, plunging it into the world of things that change. It was roasted until it separated from calcium, which remained so to speak with its feet on the ground and went to meet a less brilliant destiny, which we shall not narrate. Still firmly clinging on to two of its three former oxygen companions, it issued from the chimney and took the path of the air. Its story, which once was immobile, now turned tumultuous.

It was caught by the wind, flung down on the earth, lifted ten kilometres high. It was breathed in by a falcon, descending into its precipitous lungs, but did not penetrate its rich blood and was expelled. It dissolved three times in the water of the sea, once in the water of a cascading torrent, and again was expelled. It travelled with the wind for eight years: now high, now low, on the sea and among the clouds, over forests, deserts, and limitless expanses of ice; it then stumbled into capture and the organic adventure. […]".

What an adventure it is! Floating on the air's gradient current, Carbon is lured inside the stomata of a leaf. In the stroma of a chloroplast Carbon feels a shiver of energy as a photon excites the thylakoid membrane and pretty Phosphorus touches him. However, when Carbon opens his eyes, mysterious Phosporus has left him and he finds himself wet, attached to a water molecule. What follows is a journey through the Sap Rivers of the plant until he is joined with other newcomers to form a more complex carbohydrate.

The above is intended to be illustrative of the dynamism of C and SOC. It should not be regarded to be either complete or scientific fact.

Now that a plant has taken firm hold of it, carbon dwells among the living for a while. It either pops back to a gaseous state by a wild fire devouring the plant or by the breath, or gaseous digestion of an animal to which the plant looked too tasty to resist. On the other hand, it continues its organic life by reaching the soil, and thereby this thesis. It does so as a result of being in a form that was too hard to be digested, or by the grace of death. Death of the plant, or death of an animal that ate the plant. This animal could be you, or me. As the artist Tom Waits sang:

“
♫ *We’re all gonna be just dirt in the ground* ♪
“

Although death caused it to enter the soil, carbon goes on to sustain a myriad of underground life. There is so much life in a spadeful of soil that it dazzles the mind: 100 billion bacteria (10,000 species), 50 kilometers of fungi (500 species), 100,000 protozoa (100s of species), 10,000 nematodes (50 species), 5,000 insects, arachnids, molluscs and worms (100s of species), and about 500 meters of plant roots from dozens of species (Ritz, 2003).

If it had happened to enter the soil in a location of year round wetness (such as a bog or swamp), or where it was buried by sand blown onto the soil, it began an organic sleep that can last hundreds, nay, thousands of years. Our Carbon entered the soil in an arable field and went on to be included in countless different molecules. Were it chained to a small number of fellow carbon atoms and atoms of oxygen, hydrogen and nitrogen it is eaten by microbes, stripped of its nitrogen, and again returned to the atmosphere as carbon dioxide, within days, weeks, or months. Were it chained to many fellow carbon atoms, and fewer nitrogen atoms, it could sit in the soil for years. Plates of clay, rafting on the soil solution, or in the gut of an earth worm, collided with our Carbon, eventually covering it completely, like filled pastry. Protected by this armoured coating of clay the millions of ruthless microbial jaws cannot reach it easily. But the little buggers persevere and again it is returned as a gas after a few years, or maybe up to a decade. Via chemical reactions, carbon atoms are embedded in huge, three dimensional structures forming molecules of humus. As humus ranks very low on the microbial menu, it is by this collective effort – the power of numbers - that carbon may stay in the soil for longest; it may be decades or centuries before the structure of a humus molecule decays, releasing its individual compounds, including our Carbon.

So, all of the carbon that went into the soil has gone out of it again, including our Carbon who took the long road, leaving its organic life behind – passing through this thesis - and restarting its atmospheric life.

Frank Verheijen
Summer 2004

The above is intended to be illustrative of the dynamism of C and SOC. It should not be regarded to be either complete or scientific fact.

The above is intended to be illustrative of the dynamism of C and SOC. It should not be regarded to be either complete or scientific fact.

APPENDIX 2

Scientist	**Körschens**			**Sparling**			**Sohi**			**Misc.**		**Siewert**		
Method	Hot water extractable C			Hot water soluble C			Sonication-density			DNA extraction		Thermogravimetry		
Nr. of fractions	2 fractions	**Time**	**Chem.**	2 fractions			3 fractions	**Time (days)**	**Chem.**	2 fractions		2 fractions		**Chem.**
Fraction description	Cinert = 0.04 * (% clay + fine silt) or that part of C, which remains in soil over many decades even under bare fallow and without any fertilisation	Many decades		rest			OM = organomineral	20.000	Not available	Diversity of microbes in soil		Biologically stable SOM components 460-650 ºC	NA	NA
	Cdec = decomposable C = 15 * Chwe Chwe = C hot water extractable		Carbohydrates + N-containing compounds (soil biomass + root exudates)	Chws			IALF = intra-aggregate light fraction	500	Low O-alkyl/alkyl-C			Biodegradable SOM components 200-450 ºC	NA	NA
							FLF = free light fraction	100	High O-alkyl/alkyl-C			C lost in 0-190 ºC trajectory		
Basic principle	Biological/chemical fractionation.			Biological fractioning, variation on HWE, uses 70ºC for 18 h instead of 100ºC for 1 h			Physical fractionation.			Biological fractionation (microbial)		Thermal/chemical fractionation		
Advantage	Cheap, fast			cheap			no seasonal fluctuations in IALF			Reasonably fast, direct fractionation		Fast, non-laborious. Timepath allows thermal fingerprint of SOM, including total carbon		

Disadvantage	Seasonal fluctuations	Seasonal fluctuations, not as fast as HWE-C. No empiric relation to Cdec	Laborious, expensive (?)	Variability in cell lysis, shearing of DNA. Large differences between soil types. Seasonal fluctuations	Relatively new technique in SOM Seasonal fluctuations
Notes	Chwe fraction is not well defined. It contains parts of the microbial biomass, simple organic compounds and compounds which are hydrolysable or depolymerizable in water	Good correlations were found between HWS-C and microbial C for soils < 10% organic C		Method assumes that soil fertility is linearly related to soil microbial diversity. Quantification not yet possible	Has been correlated to Chwe and basal respiration

Scientist	**Mulvaney**		**Lawrence**		
Method	Illinois soil nitrogen test for amino-sugar-N		'hot' mustard extraction method of sampling earthworms		
Nr. of fractions	2				
Fraction description	Potentially minerizable soil N and ^{15}N		Earthworm density		
Basic principle	Biological fractionation		Biological fractionation (soil macro fauna)		
Advantage					
Disadvantage	New method, not well established. Seasonal fluctuations		Not possible to use on stored air dry samples		
Notes	Soil sample is heated at 120 ºC for five hours. Amino sugar N is then converted to gaseous ammonia which collect in a Petri dish in a closed container				

APPENDIX 3

SOMFIE performance questionnaire

For each category, the SOMFIE performance indicator question, as posed in the SSIs, is given below. The interviewee was shown a large print laminated overview of the classes for each categorical SOMFIE.

Yield quantity

"What is the quantity of a 1st winter wheat yield, averaged over the last 10 years?"

Yield stability

"If it is a particularly bad/good year, how low and how high would you expect the 1st winter wheat yield to drop/rise?"

1 = yield varies by 50%
2 = yield varies by 25%
3 = Yield varies by 10%
4 = Yield does not vary significantly

Standard deviation:

Lower:
Upper:

Number of passes to create a seed bed

"When growing a 1st winter wheat, how many passes do you need to make a seedbed?"

(all individual passes are noted)

Workability flexibility

"How would you rate the flexibility of the field in terms of workability?

1= totally inflexible (needs to be worked meticulously)
2= very inflexible (have to give first priority to this field when planning)
3= reasonably flexible (can change this field in planning if need be)
4 = very flexible (can always use field to adapt planning)"

Number of biocide passes

"How many biocide application passes does the field receive for a 1st WW – on average?"

Drought stress

"How many years out of the last 10 years, did you observe drought stress affecting a first winter wheat crop?"

Waterlogging stress

"How many years out of the last 10 did you observe water logging stress affecting the crop?"

Biological activity

"How would you rate the overall biological status of the soil (e.g. earthworms, soil insects, fungi, microbes etc.)?

1= Little biological life (very few earthworms, soil insects etc.)
2= alive (some earthworms, soil insects etc.)
3= very alive (many earthworms, soil insects etc.)
4= extremely alive (very many earthworms, soil insects etc.)"

Growth regulator passes

"When growing a first winter wheat, how many biocide application passes (that is herbicides, fungicides, pesticides) would you need, averaged over the last 10 years?"

Ancillary variables

What week of the year – time of the month - do you on average drill 1-st WW?

APPENDIX 4

Field history information

Date:
Farm:
Location:
Interviewer:
Interviewee:

Land use history

Going back as far as farmer can remember. Note when information is exogenetic

What's the field's name and/or number?	
How long in arable?	
What was landuse before arable?	For how long?
What is the current rotation?	
Has rotation changed (leys, set aside, different crops)?	
Has tillage practice changed (minimum tillage, no-till)?	
Liming history?	Quantity and frequency?
Drainage installed (tile/pipe drains)?	Since when. Still operational?
How often do you moleplough?	
Does the field receive irrigation?	
How often do you subsoil? How deep?	Whole field: Headlands + tramlines only:
How deep do you cultivate/plough?	
How variable is the field in terms of soil type?	
How many biocide application passes does the field receive for a 1st WW – on average?	Autumn Spring F H P

How much inorganic fertiliser does the field receive for a 1st WW – on average? N, P, micronutrients **What fertiliser type?**	Number of N passes:

OM amendment history

- What organic amendments does the field receive since 1995? (quantities + frequencies)
- Organic amendment history (back as far as possible)? Prompting:

	Yes/no, until what year?	Quantity and frequency? Estimate.
Stubble burnt		
Straw chopped in after harvest		
Straw brought in and used for crop protection		
Straw sold of the farm or used on other field		
FYM		
Slurry application		
Sewage sludge application		
Poultry manure application		
Mushroom compost application		
Other compost application		
Shoddy		
Soot		
Set aside		
Grass ley		
Other		

APPENDIX 5

OM amendments to soil in England and Wales

From the farmer interviews across England & Wales a picture of historic and current OM inputs to soil (other than FYM, slurry, ley-grass, and crop residues) emerged. As farms across the country were visited this picture has a national base, however, as this concerns only a very small percentage of all farms in England and Wales, the picture presented below is not necessarily comprehensive.

- Sewage sludge. Human faeces are applied to arable land in several ways. When treated and worked into a fibrous material it is called 'sewage cake'. When treated further into a dry material it is called 'biosolids'. Prices seem to vary substantially, according to the product and to the transporting distance (sometimes delivered for free, sometimes a fee is charged to pick it up). Generally farmers were aware of pathogenic dangers of sewage sludge, but not of mineral contamination dangers (e.g. heavy metals) and its potential longer term ramifications.
- Straw cover. In some parts of E&W root crops (carrots particularly) are bedded down with straw to prevent frost damage (mainly East Anglia). Large quantities of OM input can be achieved when the bedding is incorporated into the soil the next growing season.
- Poultry manure. Farms in proximity to poultry units are keen to receive its waste (muck) that is high in N. Very different qualities were perceived for chicken, duck (wet product) or turkey (often mixed with sawdust) muck.
- Compost. Mushroom compost is used when in proximity to mushroom farm.
- Slaughter waste. Also referred to as 'blood & bone' appears to have been a low scale practice throughout E&W. Delivered and applied for free mostly. Perceptions of crop vigour, yield increases, and lodging are an order of magnitude higher than any other OM amendment. The BSE crisis in the 1990s appears to have stopped this practice.
- Shoddy & feathers. In the 1950s and 1960s wool waste was carted (by train) from Yorkshire to as far as Bedfordshire for incorporation in very sandy soils. Root crop growers expected to get a water retention benefit. For similar reasons instances of feather incorporation were encountered.
- Slag & Soot. Farms in proximity to metal works reported to have applied 'slag', which was described as a waste product of the steal industry. This practice seems to be current. It appears to have been common practice throughout E&W to transport soot (in bags) from urban areas to apply to heavy soils (up to the 1960s). Farmers expected to get a workability benefit.

- Sugar beet lime. An organic lime, which is a by-product of sugar factories, was reported as a recent OM amendment to soil.
- Pigs in rotation. When asked if they managed SOM some farmers replied that they had put pigs in arable rotation. A new practice that is akin to the old ley-grass system (although apparently short term, i.e. 1 or 2 years only).
- Wood chippings & paper pulp. Both OM amendments were encountered, however wood chippings on a very limited scale and paper pulp as experimental. Water retention benefit was expected.

APPENDIX 6

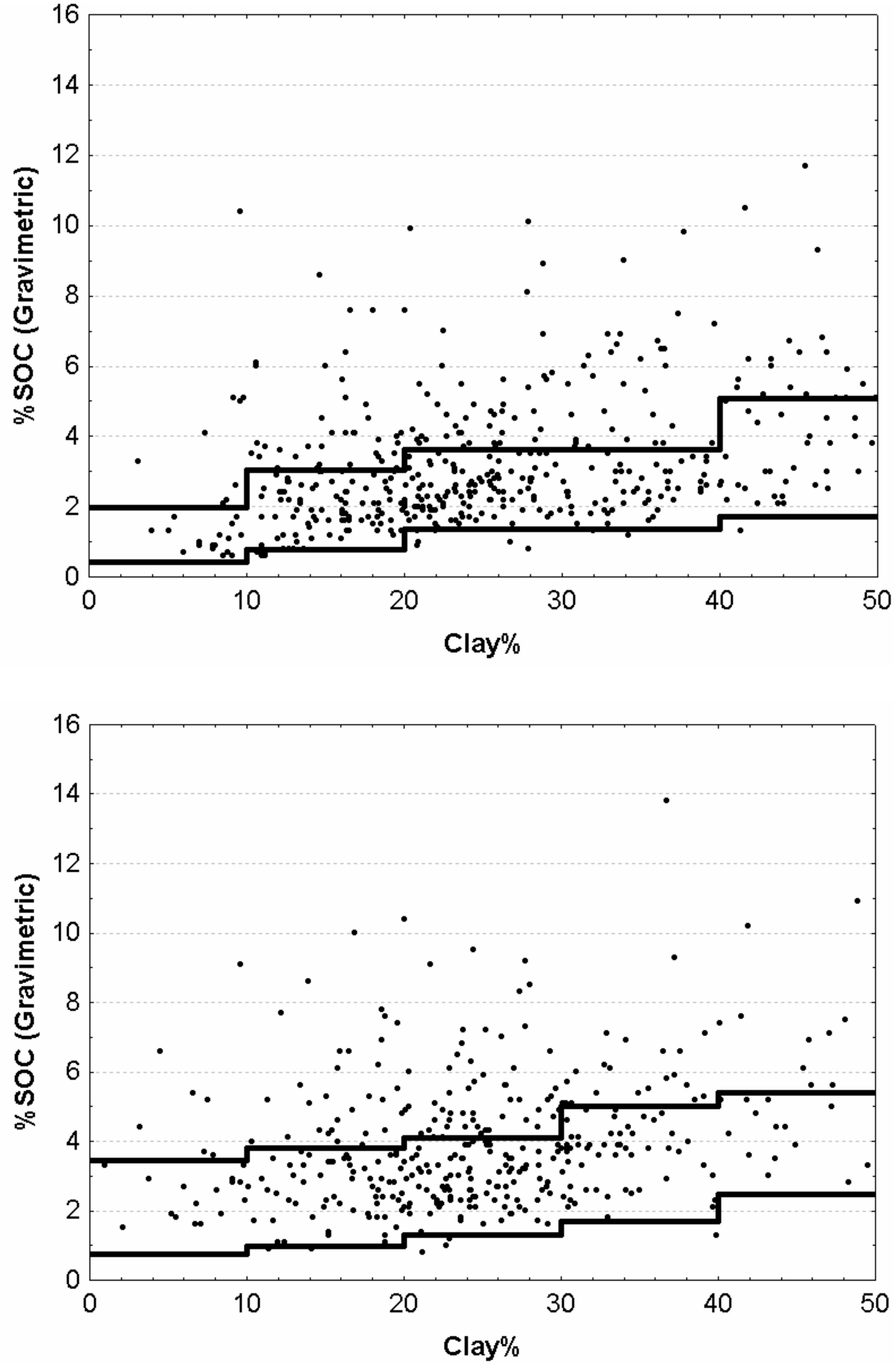


Figure 4.3b/c SOCIMRs for intermediate (b) and wet (c) soils (b = 650-800 average annual precipitation, n = 622; and c = 800-1100 mm yr^{-1} average annual precipitation, n = 440) under arable and ley-arable farming.

APPENDIX 7

Table 4.4

Precipitation (mm yr^{-1})	Dry < 650		Intermediate 650 - 800		Wet 800 - 1100		Permanent grass 0 - 1100	
Limit estimate	**upper**	**lower**	**upper**	**lower**	**upper**	**lower**	**upper**	**lower**
%clay								
5	1.58	0.52	1.98	0.42	3.46	0.74	4.13	0.97
15	2.33	0.67	3.03	0.77	3.81	0.99	4.98	1.62
25	2.75	1.05	3.63	1.37	4.08	1.32	5.51	2.09
35	3.53	1.27	3.63	1.37	5.00	1.70	5.45	2.15
45	4.18	1.42	5.07	1.73	5.41	2.49	6.48	3.12