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Exploring temperate food forestry

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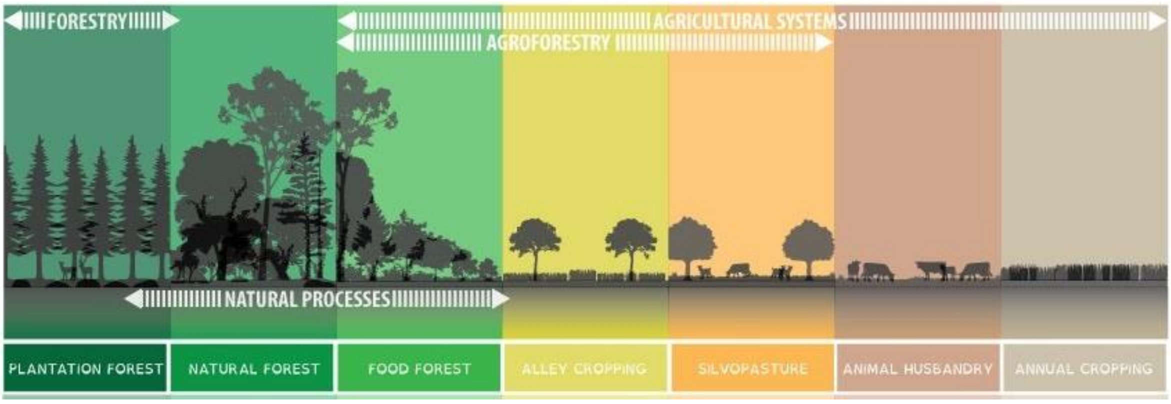

A comparative case study assessing soil health at Food Forest Ketelbroek, forest nature reserve "De Bruuk" and a conventional farm in Groesbeek, the Netherlands

Suzy Rebisz

MSc Thesis

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Exploring food forestry as a sustainable land management practice: starting at the soil

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Master thesis Soil Physics and Land Management Group submitted in partial fulfilment of the degree of Master of Science in International Land and Water Management at Wageningen University, the Netherlands

Student name	Suzy Rebisz
Student ID	940415682050
Study	MSc International Land and Water Management
Chair group	Soil Physics and Land Management Group
Code Number	SLM-80336
Date	12 December 2019
Supervisor	Jerry Maroulis
Examiner	Aad Kessler

Disclaimer:

The views expressed and the outcomes of this report remain responsible to the author and does not represent the views of Wageningen University. The data supporting the findings of this study are available within this thesis and the appendix. Great attention was given to this thesis; however, minor errors may occur, my apologies in advance.

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Contact:

Please contact suzy.rebisz@gmail.com for comments, questions, improvements or access to further datasets and scripts used for the analysis of this study.

Foreword

This thesis is the culmination of my efforts and enthusiasm to understand the practice of food forestry. This thesis also draws upon the works of many writers who have documented the practice of agroforestry and food forestry to date. I have drawn immense knowledge and inspiration from the words of researchers, scholars and above all, the practitioners practicing food forestry and agroforestry. It is on their shoulders (or perhaps paperwork) of which this thesis stands on. May this body of work be of service to fellow peers, academics, researchers, farmers, practitioners and any person interested in co-creating biodiverse and food productive landscapes.

Acknowledgements

This thesis project has been supported by many people in many ways. Firstly, I would like to thank my family for their unconditional support throughout this thesis process. Without their understanding, kindness and love, much of this work would not exist. Secondly, I am entirely grateful to the open-handed attitude of the farmers Wouter, Pieter and Henk, and to the forest ranger Jaap, for allowing me to do research on their fields. Thirdly, I am grateful to Jeroen for connecting me to the *Green Deal Voedselbossen* network and to Walter and Thomas for collaborating and sharing their research data. Fourthly, much of my appreciation goes to my fellow housemates Brecht, Isabella, Moon, Joran, Wim and Piet who have made it a happy home to return to after a day of work. Thank you, Sølve, for being a thoughtful friend with considerate editing skills. I would also like to thank Annika for being a caring friend (and teacher) over the last six years. Many thanks to Jonas, Thalisa, Arno, Esther, Jurre and Ester for sharing their passion and knowledge about (agro-) food forestry. Thank you, Maria, for keeping me sharp and critical about the realities of our complex food system. Thank you, Lucas, for being a supportive friend and for the interesting discussions about agriculture in practice. Thank you, Giannis, for the warm support and your help with data collection. I highly appreciate Dainius for his kind, optimistic attitude and for befriending me with RStudio. Thank you, Laura, for being an example to me on how to complete a double degree with a smile on your face. My appreciation also goes out to my significant other, Damian, for your loving kindness and thought-provoking conversations about the food we eat and the (eco-)systems behind it. Thank you Jerry, my supervisor, friend and supporter over the last two years. You have guided my enthusiasm with great understanding and have helped shape this thesis through your fine-tuning feedback. I warmly appreciate the care you put into this process.

Abstract

Food forestry, a form of agroforestry, is defined as an intensive agroecosystem with primarily woody, perennial plants mimicking a forest ecosystem. Since 2017, the Dutch government has recognised food forestry as a means towards stimulating economic growth without a compromise on the environment. The benefits of agroforestry systems on ecosystem services are increasingly being recognised by the scientific community. However, food forests remain understudied, particularly on soil health in temperate regions. This thesis addresses this knowledge gap through a soil health assessment at three locations in the Netherlands: food forest Ketelbroek, forest nature reserve “De Bruuk” and a conventional arable farm in Groesbeek. Soil health was examined through fieldwork, laboratory assessment and data compilation. Eleven soil quality indicators were examined and categorised into 3 types: 1. physical indicators, i.e., soil texture, -colour, -temperature, aggregate stability, bulk density, soil moisture content, soil resistance (0-80cm); 2. chemical indicators, i.e., pH, organic matter (OM), organic carbon (OC) and 3. biological indicators, i.e., earthworm abundance and species. A random-stratified sampling design was followed with five samples taken per study site (one per stratum). At every location, one sample was taken at the topsoil (0-5cm) and subsoil (30-35cm). All soil health indicators were related to soil threats, soil processes and ecosystem services. Through a literature study, ranges and thresholds were formulated for loess soil and used as a benchmark. Statistically significant differences were found amongst the locations. Apart from aggregate stability in the top- and subsoil and organic matter and carbon content in the subsoil, results show that soil conditions were better at food forest Ketelbroek than the conventional arable farm. With the inclusion of historical data and (unpublished) follow-up research, temporal trends show SOM and SOC levels having doubled in the last decade at food forest Ketelbroek; from approximately 4% in 2009 to 8.8% in 2019. Overall, this study suggests that food forestry can be a sustainable form of land management practice for sandy loam soils in a temperate climate, but far more research is needed to validate the practice of food forestry. This study also suggest that food forest Ketelbroek can mitigate soil threats such as OM decline, compaction and biodiversity loss. Long-term monitoring would be needed to investigate the extent of this. Recommendations for this study are to increase the sample size with ≥3 per stratum and to include more biological indicators, e.g. through nematode studies, litter decomposition rates or measuring soil respiration. Soil health can be assessed in numerous ways; therefore, integrative soil quality as a framework is highly recommended to further explore the effects and impacts of food forestry at soil, land and ecosystem level.

Nederlandse samenvatting

Voedselbosbouw wordt gedefinieerd als een intensief agro-ecosysteem. Deze vorm van agroforestry bestaat uit voornamelijk houtachtige, meerjarige planten die een bosecosysteem nabootsen. Sinds 2017 wordt voedselbosbouw door de Nederlandse overheid erkend als een vorm van landbouw die kan bijdragen aan economische groei zonder het milieu te schaden. De voordelen van agroforestry systemen voor ecosysteemdiensten worden in toenemende mate erkend door de wetenschappelijke gemeenschap. Echter, voedselbosbouw is onvoldoende onderzocht, in het bijzonder het effect op bodemgezondheid in gematigde klimaatzones. Deze scriptie draagt bij aan het opvullen van dit kennis hiaat door beoordeling van de bodemgezondheid op 3 locaties in Nederland: voedselbos Ketelbroek, bosnatuurreservaat "De Bruuk" en een gangbaar akkerbouwbedrijf in Groesbeek.

Bodemgezondheid werd onderzocht aan de hand van veldmetingen, laboratoriumanalyses, en aanvullende bodemgegevens. Elf bodemgesteldheidsindicatoren werden gebruikt, verdeeld in 3 categorieën: 1. fysische indicatoren, te weten bodemtextuur, -kleur, -temperatuur, aggregaat stabiliteit, bodemdichtheid, bodemvochtgehalte, bodemweerstand (0-80cm); 2. chemische indicatoren, te weten pH, organische stof (OM), organische koolstof (OC) en 3. biologische indicatoren, te weten soorten en aantallen regenwormen.

Een willekeurig gestratificeerd bemonsteringsontwerp werd gevolgd waar 5 monsters genomen werden per studie locatie (één per stratum). In elke locatie werd één monster genomen van zowel de toplaag (0 - 5 cm) en de ondergrond (30 - 35 cm). Vervolgens werden bodemgesteldheidsindicatoren gerelateerd aan bodembedreigingen, bodemprocessen en ecosysteemdiensten. Via een literatuurstudie werden streefwaarden en drempels geformuleerd voor lössgrond, de bodemsoort in het studiegebied.

In de data werden statistisch significante verschillen gevonden tussen de drie studiegebieden. Met uitzondering van aggregaatstabiliteit (in de toplaag en ondergrond) en organische stof en koolstofgehalte (in de ondergrond), toonden de resultaten aan dat de bodemomstandigheden in voedselbos Ketelbroek beter waren dan die van het gangbare akkerbouwbedrijf. Uit historische gegevens en aanvullende onderzoek (niet gepubliceerde gegevens) bleek bovendien dat SOM- en SOC-niveaus verdubbelden in het laatste decennium op voedselbos Ketelbroek, van ongeveer 4.0% in 2009 tot 8,8% in 2019.

Al met al suggereert deze studie dat voedselbosbouw een duurzame vorm van landbeheer kan zijn voor zandige leemgronden in een gematigde klimaatzone, maar dat er meer onderzoek nodig is om dit te valideren. De resultaten suggereren ook dat voedselbos Ketelbroek bodembedreigingen zoals de achteruitgang van organisch stofgehalte, bodemverdichting en verlies van biodiversiteit kan mitigeren. Een langdurige vervolgstudie zou nodig zijn om de omvang hiervan te bepalen. Voor een betere beoordeling van de bodemgezondheid van agro-ecosystemen wordt aanbevolen de steekproefomvang te vergroten met ≥3 per stratum en meer biologische indicatoren op te nemen, bijvoorbeeld door middel van nematodenonderzoek, afbraaksnelheid van strooisel of het meten van bodemrespiratie. Bodemgezondheid kan op verschillende manieren worden beoordeeld. Op basis van dit onderzoek wordt integrale bodemkwaliteit als kader ten zeerste aanbevolen om de effecten van voedselbosbouw op bodem-, land- en ecosysteemniveau verder te onderzoeken.

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List of abbreviations

ACT	Academic Consultancy Training at Wageningen University
AGFORWARD	AGroFORestry that Will Advance Rural Development (EU Project)
ANOVA	Analysis of Variance
ASL	Above Sea Level
CF	Conventional farm
DB	Forest “De Bruuk”
EASAC	European Academies' Science Advisory Council
EPA	Environmental Protection Agency, USA
EU	Europe
EURAF	European Agroforestry Federation
FAO	Food and Agricultural Organization of the United Nations
FF	Food Forest Ketelbroek
ICRAF	International Centre for Research in Agroforestry
ISRIC	World Soil Information / International Soil Reference and Information Centre
iSQAPER	Interactive Soil Quality assessment in Europe and China for Agricultural productivity and Environmental Resilience (EU Project)
KNMI	Koninklijk Nederlands Meteorologisch Instituut - Royal Netherlands Meteorological Institute
PDOK	Publieke Dienstverlening Op de Kaart
RECARE	Preventing and remediating degradation of soils in Europe through Land Care (EU Project)
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
Tukey HSD	Tukey Honest Significant Difference
UK	United Kingdom
USA	United States of America

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1 Introduction

Food forestry and various agroforestry systems are increasingly being highlighted as agroecosystems with large potential to address current challenges such as unsustainable land use, biodiversity loss and climate change (De Stefano & Jacobson, 2017; Elevitch, Mazaroli, & Ragone, 2018; Fagerholm et al., 2016; Park, Turner, & Higgs, 2018; Wilson & Lovell, 2016). Recently, the Dutch government signed the *Green Deal Voedselbossen*, thus identifying the practice of food forestry as part of the path towards "green growth" (RVO, 2017; p.2). This *Green Deal* also highlights the need for food forestry research in order to investigate its potential societal, environmental and economic contribution.

The most general description of a food forest is a land-use system with mostly woody, perennial plants (edible and non-edible, native and non-native) that mimic a forest ecosystem (Crawford, 2010; Jacke, 2008; Limareva, 2014; W. van Eck, 2018 pers. comm., 2nd October). A food forest can also be described as a "perennial polyculture of multi-purpose plants" (Jacke & Toensmeier, 2002, p. 1). This inherent multi-functionality of food forestry systems has implied a multitude of opportunities and benefits in addressing major challenges in the Anthropocene (Elevitch et al., 2018; FAO, 2015; Kremen & Merenlender, 2018). These implied benefits are often based on documented benefits of agroforestry, either in practice or through research (Nair, 2014). Food forestry is considered a form of agroforestry.

Agroforestry is increasingly recognised as a sustainable land management practice (Brown, et al., 2018; Dollinger & Jose, 2018; FAO, 2017; Wilson & Lovell, 2016). Agroforestry is an umbrella term for tree-incorporated productions systems; Nair (2014) defines agroforestry as the practice of growing trees with crops and sometimes with farm animals, in interactive combinations over time and/or space for a variety of objectives. Current research suggests that "integrating trees on farms can prevent environmental degradation, improve agricultural productivity, increase carbon sequestration, generate cleaner water, and support healthy soil and healthy ecosystems while providing stable incomes and other benefits to human welfare." (Brown et al., 2018, p. 1). Through further review, Dollinger and Jose (2018) concludes that "agroforestry has the ability to enrich soil organic carbon better than mono-cropping systems, improve soil nutrient availability and soil fertility [...] which would positively influence soil health" (Dollinger & Jose, 2018, p. 213).

Within the scientific and agronomic community, food forestry remains largely unrecognised as a farming system. Tree-incorporated farming systems, such as food forestry, is often seen as a novel practice using agroforestry concepts and techniques (Nair, 2014). Due to this being perceived as a novel land management practice, few studies have assessed whether the benefits of agroforestry are also true for food forestry and to what extent. The *Green Deal Voedselbossen* highlighted the need for researching the effects of food forestry on "biotic aspects such as on biodiversity, soil life and ecological functionality and abiotic aspects such as on soil, water and microclimate" (RVO, 2017; pg.3). This study aims to contribute quantitative and qualitative data on these aspects, starting with the soil.

The effects of land management practices are often examined through a soil health assessment (Duval, Galantini, Martínez, López, & Wall, 2016; Pardon et al., 2017; World Bank., 2006). Soil health is defined as "the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans" (NRCS *in* Bünemann et al., 2018; pg. 108). This study explores the effect of food forestry on soil through a comparative case study; assessing soil health at food forest Ketelbroek, nature reserve "De Bruuk", and a conventional arable farm in Groesbeek, the Netherlands.

In addition to land management practices, pedo-climatic conditions and associated soil threats also have an influence on soil health. Therefore, soil conditions are described, and the soil health assessment is linked to soil threats, soil processes and ecosystem functions/services. The soil health assessment consists of eleven proxy-indicators; a mix of physical indicators, i.e., soil texture, -colour, -temperature, aggregate stability, bulk density, soil moisture content, soil resistance (0-80cm); chemical indicators, i.e., pH, organic matter (OM), organic carbon (OC) and biological indicators, i.e., earthworm abundance and species. These indicators are measured at the topsoil (0-5cm) and subsoil (30-35cm) and compared relative to each site and to a benchmark. To a large extent, this thesis is a baseline study to quantify soil health. Analysing trends are attempted yet much more data and research are needed to monitor the effects of food forestry practices.

This thesis is divided into Chapters and begins with the introduction (Chapter 1). This is followed by a literature study to first establish conceptual clarity between agroforestry systems and food forestry (Chapter 2). Then the purpose of this study is defined, including the research questions (Chapter 3). The research concepts and methods are then explained (Chapter 4), followed by an analysis of the geology, hydrology and climatic conditions of the study area (Chapter 5). Results are shown with supportive tables and figures (Chapter 6), followed by a discussion of the results, concept and methods (Chapter 7). A summary of the conclusions is made (Chapter 8) and ends with a summary of recommendations (Chapter 9).

2 Literature Study

This literature study serves to conceptualize the concept of food forestry in relation to agroforestry. To contextualize this thesis, a description is given below on relevant terminology, research into agroforestry practices in relation to temperate food forests, the principles of food forestry, and current research on temperate food forests.

2.1 Terminology

The practice of food forestry is often context-specific, thereby making it a difficult concept to define. Food forests are also often related to concepts such as multi-strata systems, agroforestry, homegardens, permaculture, analog forestry, etc (Crawford, 2010; Limareva, 2014; Nair, 2014; M. Hendriks, 2018. *pers. comm.*, 2nd October). For more clarity, a list of definitions is given below for common concepts connected to food forestry (Table 2.1). It should be noted that these definitions are not static as there may be variations over time and in specific contexts.

There are also several synonyms used to refer to food forests. In the Netherlands, *voedselbos* is a popular term, derived from the literal translation of 'food forest'. In the United Kingdom (UK) however, the use of the term 'forest garden' is more popular. The British terminology was first named by Hart, a pioneer in forest gardening since the 1960s. The term 'edible forest gardens' is also used (Jacke, 2008). The definitions given for each of these synonyms in Table 2.1 are based on terms used by the practitioners. Although the definitions have a slightly different wording, the message is similar: a land-use system with mainly perennials which mimics a forest ecosystem. In this study, the term food forestry is used as this case study is based in the Netherlands. Here, a food forest is defined as a land-use system with mainly woody, perennial plants that mimics a forest ecosystem (Crawford, 2010; Jacke, 2008; Limareva, 2014; W. van Eck, 2018 pers. comm., 2nd October).

Table 2.1: A list of relevant terminology (compiled from Nair, 2014; Agroforestry Research Trust, 2018; Jacke & Toensmeier, 2008; Holmgren, 2018; IAFN, 2018)

Terminology	Definition
Agroforestry	"Purposeful growing of trees, crops, sometimes with animals, in interacting combinations for a variety of objectives. Agrisilviculture = trees + crops; Silvopasture = trees + pasture/animals; Agrosilvopasture = trees + crops + animals/pasture." (Nair, 2014, p. 270).
Analog forestry	An approach to ecological restoration which uses natural forests as guides to create ecologically stable and socio-economically productive landscapes (IAFN, 2018).
Edible forest garden	"Edible forest gardening is the art and science of putting plants together in woodland-like patterns that forge mutually beneficial relationships, creating a garden ecosystem that is more than the sum of its parts." (Jacke, 2008, p. 1).
Food forest	"A land-use system with mainly woody, perennial plants (edible and non-edible, native and non-native) that attempts to mimic a forest ecosystem" (W. van Eck, 2018 pers. comm., 2nd October).
Forest gardening	A synonym for food forest. "A designed agronomic system based on trees, shrubs and perennial plants. These are mixed in such a way as to mimic the structure of a natural forest" (Agroforestry Research Trust UK, 2018, p. 1).

Homegardens	“A subsistence farming system consisting of integrated mixtures of multipurpose trees and shrubs in association with crops and sometimes livestock around homes, the whole unit managed intensively by family labour.” (Nair, 2014, p. 270).
Multipurpose tree (and shrub)	“A tree/shrub that is grown for multiple products and/or services.” (Nair, 2014, p. 270).
Multi-storied or multi-strata system	“An arrangement of plants forming distinct layers from the lower (usually herbaceous) layer to the uppermost tree canopy.” (P.K.R. Nair, 2014, p. 270).
Permaculture	“An integrated, evolving system of perennial or self-perpetuating plant and animal species useful to man.” (Mollison & Holmgren, 1978 *in* Holmgren, 2018).

2.2 Agroforestry

2.2.1 Defining the concept

Agroforestry systems stems from indigenous and traditional farming practices (Nair, 2014; M. Hendriks, 2018. *pers. comm.*, 2nd October). Literature often links the history of agroforestry to homegardening, dating back to 10,000 BC in moist tropical regions (Nair, 2014). *Homegardening* is defined as a “subsistence farming system consisting of integrated mixtures of multipurpose trees and shrubs in association with crops and sometimes livestock around homes, the whole unit managed intensively by family labour” (Nair, 2014, p. 270).

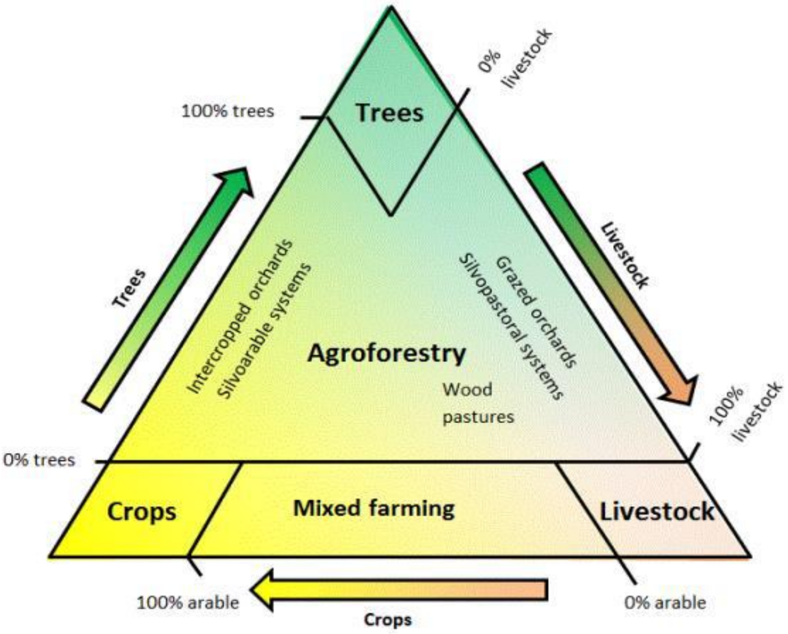


Figure 2.1: The agroforestry triangle (an adaptation from the AGFORWARD project in van Noordwijk, Coe and Sinclair, 2016)

A food forest is one of many land-use systems that fall under the umbrella term: agroforestry. An agroforestry system is generally defined as the purposeful growing of trees, crops, sometimes with animals, in various combinations over time and/or space for a variety of objectives (Nair, 2014; van Noordwijk, et al., 2016). Figure 2.1 illustrates this interplay between trees, crops and livestock. This agroforestry triangle distinguishes five main production typologies: arable farming (i.e. 100% crops), productive forests and tree plantations (i.e. 100% trees), livestock farming (i.e. 100% animals), mixed farming (between crops and livestock) and agroforestry systems. The ratio of one core component (i.e. trees, crops or livestock) with another determines the type of agroforestry system it is. For example, a tree and crop dominated agroforestry system is often termed a silvoarable system or an intercropped orchard (Figure 2.1). There are many possibilities and therefore, many land-use systems.

2.2.2 Classification of agroforestry systems

An overview of the various agroforestry systems, sub-systems and practices has been compiled by Nair (1985), shown in Figure 2.2. Here, Nair typifies agroforestry systems according to the interaction of three core components: woody perennials, pastures/animals and agricultural species. The ratio between these core components are distinguished into four different categories: silvopastoral systems, agrosilvipastoral systems, agrisilvicultural systems and other systems. Each of these agroforestry systems are related to sub-systems and practices.

Agroforestry systems are found and documented most often in the sub-tropics than in temperate or semi-arid regions. Classifying (temperate) food forestry systems remains a challenge due to the variability of these three core components. For example, temperate food forests typically have a multi-strata structure with multi-purpose trees. This can be considered an agrisilvicultural system, with sub-systems/practices such as multi-species tree gardens and multipurpose trees/shrubs on farmland (outlined in red in Figure 2.2). Alternatively, a food forest can also be classified as an 'other system', such as multipurpose tree lots (outlined in green in Figure 2.2).

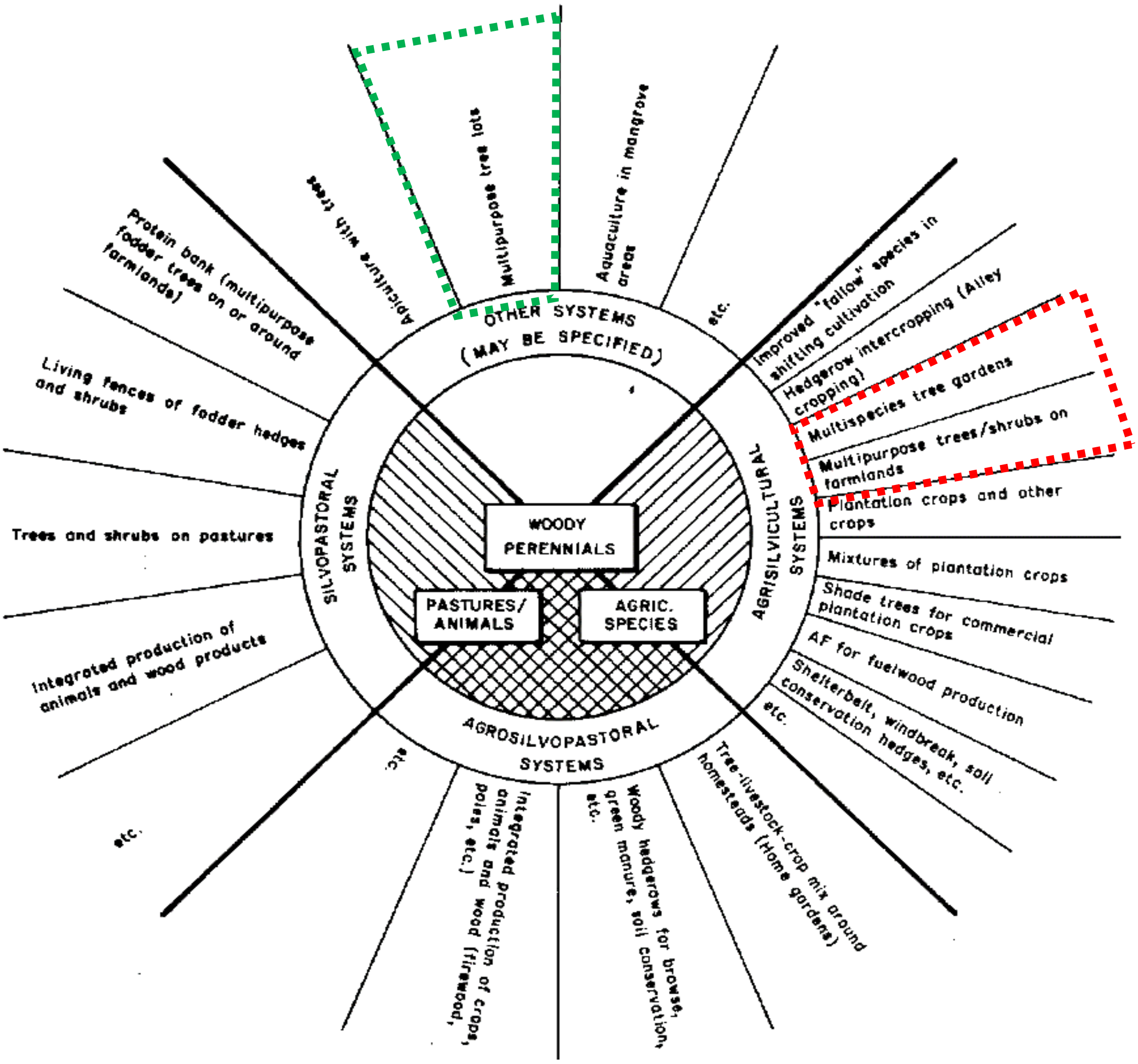


Figure 2.2: Categorization of agroforestry systems (labelled inside ring band) with related sub-systems and practices (outer examples), based on the interplay of core components (woody perennials, agricultural species and pastures/animals). Green and red boxes reflect where food forestry can be classified into (Nair, 1985)

As such, temperate food forest, like agroforestry systems, are difficult to (sub-) categorise because some practices are multi-functional and therefore not easily distinguishable. Other reasons for the difficulty in categorizing food forest systems is that some systems (also) have a non-agricultural function or are practiced on non-agricultural land. These practices are yet to be categorised.

The diversity within food forests and agroforestry systems reflects the large variability of systems and practices.

Figure 2.3 illustrates this through gradations of productive ecosystems and shows agroforestry systems to range from an orchard with livestock (i.e. silvopasture) or an orchard with crops (i.e. alley cropping) to a food forest.

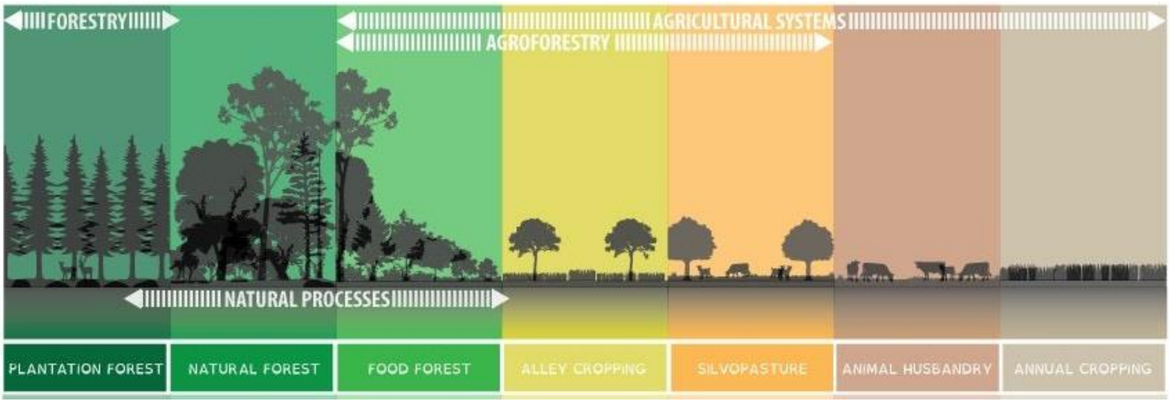
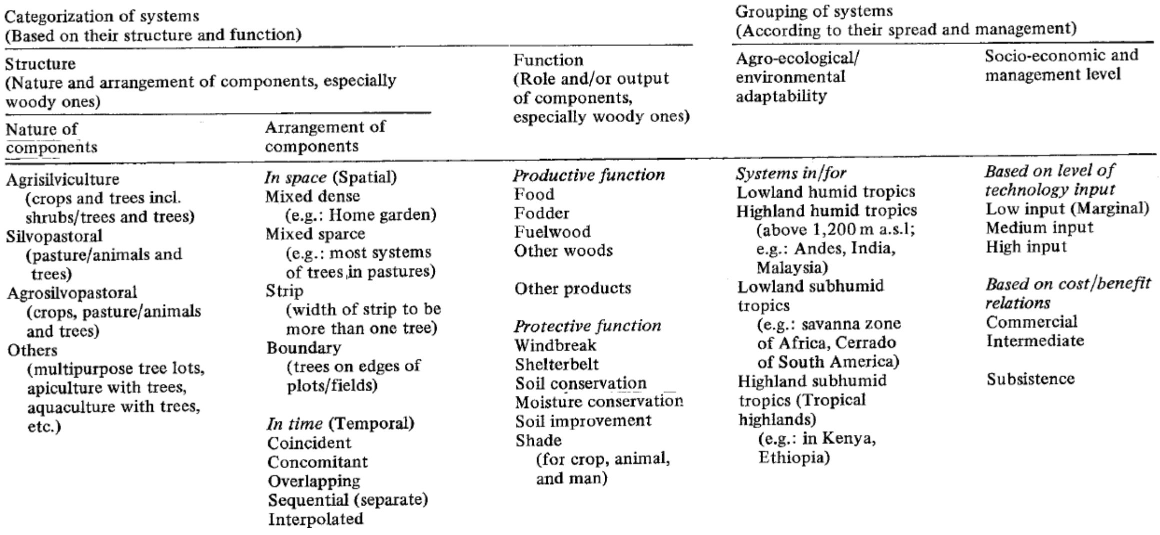


Figure 2.3: A continuum of types of ecosystems, clustering agricultural systems, agroforestry systems and forestry systems (Stichting Voedselbosbouw Nederland, 2019)

Classifying agroforestry systems based on the structure of the system is simply one classification criterion. Nair (1985) developed an agroforestry classification system (Table 2.2) based on several criteria (structure, function, agro-ecological conditions, management level and socio-economic conditions)(Nair, 1985; Nair, 2014). The structure of agroforestry systems is sub-divided into structural differences through the 'nature of the components' (i.e. ratio of trees, crops and animals) and 'the arrangement of components', both in space and in time (Nair, 1985).

Table 2.2: Major approaches in classification of agroforestry systems and practices (Nair, 1985)



Categorization of systems (Based on their structure and function)			Grouping of systems (According to their spread and management)	
Structure (Nature and arrangement of components, especially woody ones)		Function (Role and/or output of components, especially woody ones)	Agro-ecological/ environmental adaptability	Socio-economic and management level
Nature of components	Arrangement of components			
Agrisilviculture (crops and trees incl. shrubs/trees and trees) Silvopastoral (pasture/animals and trees) Agrosilvopastoral (crops, pasture/animals and trees) Others (multipurpose tree lots, apiculture with trees, aquaculture with trees, etc.)	*In space* (Spatial) Mixed dense (e.g.: Home garden) Mixed sparce (e.g.: most systems of trees in pastures) Strip (width of strip to be more than one tree) Boundary (trees on edges of plots/fields) *In time* (Temporal) Coincident Concomitant Overlapping Sequential (separate) Interpolated	*Productive function* Food Fodder Fuelwood Other woods Other products *Protective function* Windbreak Shelterbelt Soil conservation Moisture conservation Soil improvement Shade (for crop, animal, and man)	*Systems in/for* Lowland humid tropics Highland humid tropics (above 1,200 m a.s.l; e.g.: Andes, India, Malaysia) Lowland subhumid tropics (e.g.: savanna zone of Africa, Cerrado of South America) Highland subhumid tropics (Tropical highlands) (e.g.: in Kenya, Ethiopia)	*Based on level of technology input* Low input (Marginal) Medium input High input *Based on cost/benefit relations* Commercial Intermediate Subsistence

2.2.3 Research into agroforestry systems

There is increasingly more research on agroforestry systems since the establishment of the International Centre for Research in Agroforestry (ICRAF) in 1977, currently known as the World Agroforestry Centre (Nair, 1993).

Agroforestry as a sustainable land management approach

Research shows that agroforestry systems are a sustainable land management (SLM) approach, especially improving soil conditions (Dollinger & Jose, 2018; FAO, 2017; Motavalli, Nelson, Udawatta, Jose, & Bardhan, 2013). Agroforestry was described as "one of the best land use strategies to contribute to food security while simultaneously limiting environmental degradation." (Wilson & Lovell, 2016, p. 1). Dollinger & Jose (2018) made clear that "agroforestry has the ability to (1) enrich soil organic carbon better than mono-cropping systems, (2) improve soil nutrient availability and soil fertility due to the presence of trees in the system, and (3) enhance soil microbial dynamics, which would positively influence soil health" (Dollinger & Jose, 2018, p. 213).

Agroforestry as a strategy to mitigate and adapt to climate change

Agroforestry is also seen as a strategy to mitigate and adapt to climate change ((Hernández-Morcillo, Burgess, Mirck, Pantera, & Plieninger, 2018; Jose, 2009; Park & Higgs, 2018). Mutuo, *et al.* (2005) had shown that agroforestry systems can "increase aboveground and soil C stocks and reduce soil degradation, as well as mitigate greenhouse gas emissions." (Mutuo et al., 2005, p. 43). These researchers also quantified the potential of agroforestry systems in the humid tropics as being able to sequester carbon "over 70 Mg C ha^{-1} [in vegetation], and up to 25 Mg ha^{-1} in the top 20 cm of soil." (Ibid.). The mitigation of carbon and other greenhouse gasses for agroforestry systems in temperate climate zones remain unknown. Secondly, Mutuo, *et al.* (2005) points out that "less is known about the potential C changes in the soil at greater depths" (Mutuo et al., 2005, p. 45). These present opportunities for further research.

2.2.4 Development of agroforestry research in Europe

ICRAF has mainly carried out research on agroforestry systems in the tropics, sub-tropics, arid and semi-arid regions since 1978. In comparison, there is limited research into temperate agroforestry systems. In Europe, agroforestry research started in the 1990's; in 1992 the Agroforestry Research Trust was formed in the UK, with Martin Crawford (a prominent practitioner of food forestry) currently serving as Trust Director. In 2011, the European Agroforestry Federation (EURAF) was formed. With wide-scale research on agroforestry systems in Europe provided through the EU funded AGFORWARD project (2014-2017), at least six other agroforestry practices were identified in the literature (Table 2.3). However, the AGFORWARD researchers acknowledge there may be more practices and categories that are undocumented. For instance, forest gardening is recognised as another style of practice (Figure 2.4), whereas in the AGFORWARD report, forest gardening is unmentioned.

The AGFORWARD report shares Lundgrens & Raintree (1982) and Leakey's (1996) thoughts on other types of temperate, European, agroforestry systems by stating: "[there are also] more novel silvoarable and silvopastoral systems such as alley cropping, woodland chicken, and food forestry." (as cited in den Herder et al., 2016; p.5). The authors of this report recognize that these practices "take advantage of the interactive benefits from combining trees and shrubs with crops and/or livestock to create an integrated and sustainable land-use system" (Ibid.). Nair *et al.* (2017) has also described *Cinderella* agroforestry systems which are location-specific and with unrecognised potential; being “unique in terms of its production, environmental, and sociocultural attributes; but none [being] described in quantitative terms of ecology and production.” (Nair et al., 2017, p. 901). Bound on this literature study, it can be concluded that food forests may not be defined as a typical agroforestry system, but rather as a novel system, which is yet to be clearly defined.

Table 2.3: Six agroforestry practices identified in the European literature (by Mosquera-Losada et al. 2009 as cited in den Herder et al., 2015)

Agroforestry practice	**Brief description**
Silvoarable agroforestry	Widely spaced trees inter-cropped with annual or perennial crops. It comprises alley cropping, scattered trees and line belts.
Forest farming	Forested areas used for production or harvest of natural standing specialty crops for medicinal, ornamental or culinary uses
Riparian buffer strips	Strips of perennial vegetation (tree/shrub/grass) natural or planted between croplands/pastures and water sources such as streams, lakes, wetlands, and ponds to protect water quality.
Improved fallow	Fast growing, preferably leguminous woody species planted during the fallow phase of shifting cultivation; the woody species improve soil fertility and may yield economic products.
Multipurpose trees	Fruit and other trees randomly or systematically planted in cropland or pasture for the purpose of providing fruit, fuel wood, fodder and timber, among other services, on farms and rangelands.
Silvopasture	Combining trees with forage and animal production. It comprises forest or woodland grazing and open forest trees.

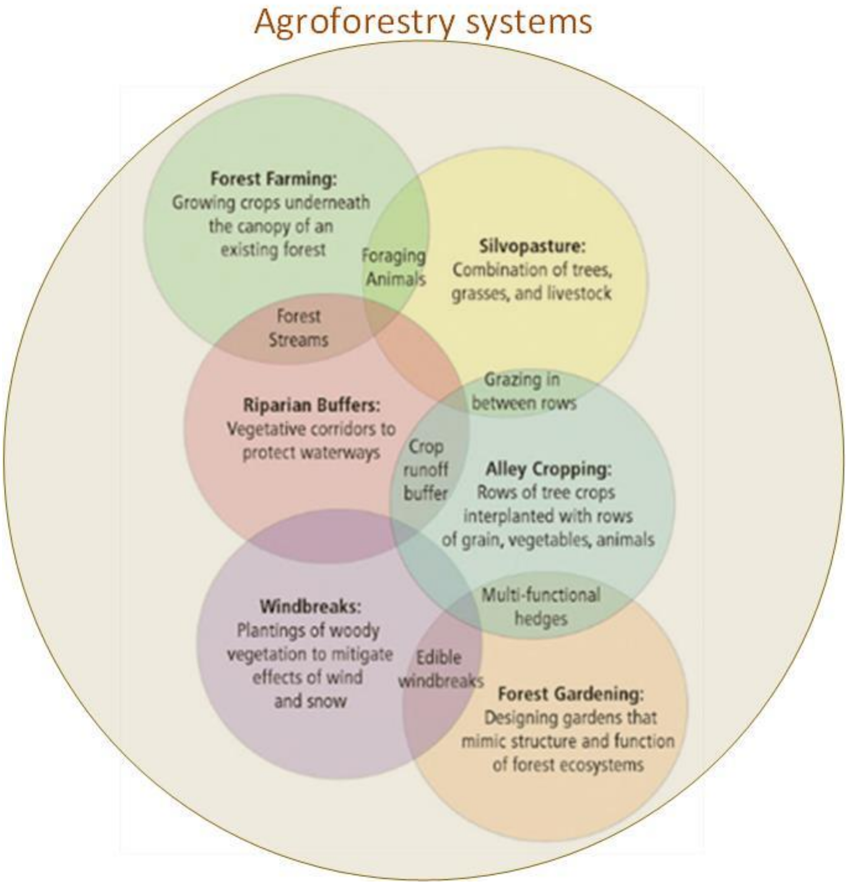


Figure 2.4: A schematic representation of the various temperate agroforestry practices (adapted from Mudge and Gabriel, 2014)

2.3 Food forestry

2.3.1 Principles of temperate food forestry

The most general and broadest description of a food forest is: “a diverse planting of edible plants that attempts to mimic the forest ecosystems and patterns found in nature.” (Project Food Forest, 2016, p. 1). In the Dutch context, a food forest is defined, by the Green Deal (2017), according to the following criteria:

- a human-designed productive ecosystem mimicking a natural forest ecosystem which contains a high diversity of perennials and/or woody plants; of which parts are food sources for humans (i.e. fruits, seeds, leaves, stalks, etc.)
- the presence of a canopy layer
- the presence of at least three niches or productive layers (e.g. lower canopy layer, shrub layer herbaceous layer, groundcover layer, underground layer and climbing layer)
- the presence of a rich forest soil life
- a robust size; minimally 0.5ha in an ecologically rich environment and minimally 20ha in a degraded landscape.

Based on observations of a natural forest, Robert Hart initiated the framework for (temperate-based) food forestry by describing “seven dimensions”, shown in Figure 2.5 (Limareva, 2014). The first known temperate food forest was planted by Hart in the 1960s in the UK (ibid.). These seven dimensions represent seven possible productive layers within a food forest, with Table 2.4 providing an overview of these seven layers and an edible species example for each layer.

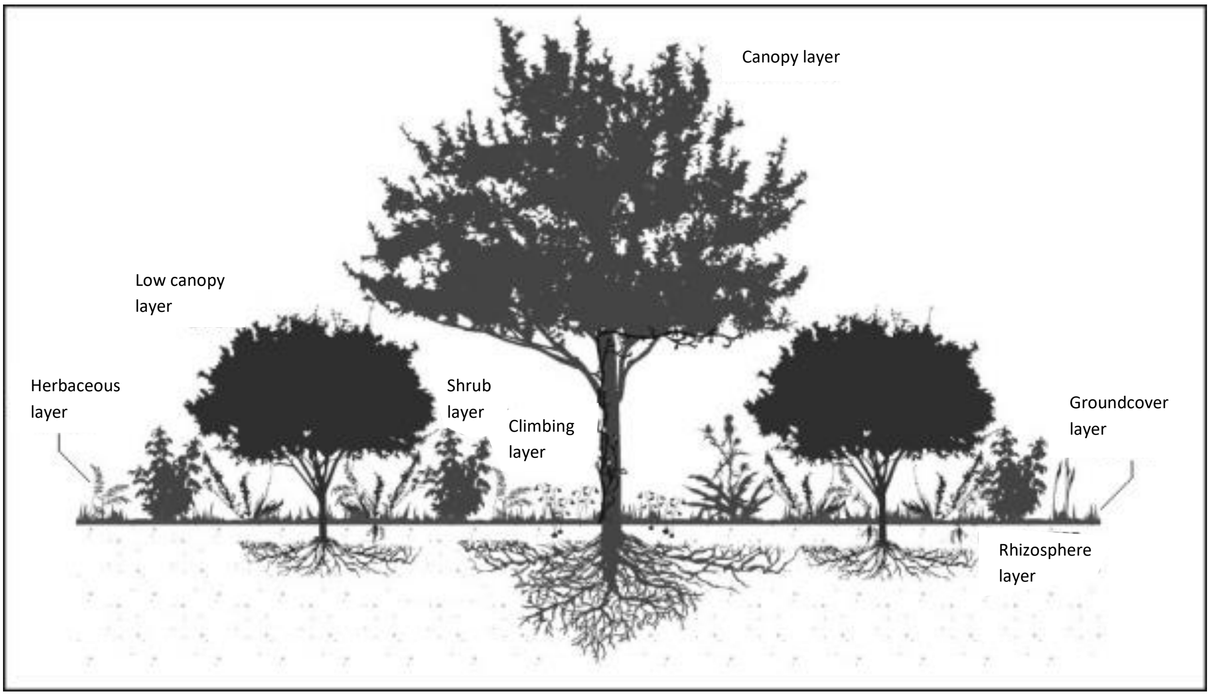


Figure 2.5: The seven dimensions in a forest garden (Clynewood, et al., 2014 in Limareva, 2014)

Table 2.4: Overview of the seven productive layers within a food forest with edible species as examples for each layer (adapted from Agroforestry Research Trust UK, 2018)

Layer	Example of edible species + [Latin name] + (edible part)
Rhizosphere layer (a.k.a. 'root layer')	Liquorice [Glycyrrhiza spp] (roots)
Ground cover layer	Creeping raspberry [Rubus calycinoides] (berries)
Herbaceous layer	Mint [Mentha spp] (leaves)
Shrub layer	Berries [Rubus spp] (berries)
Low canopy layer	Japanese peppers [Zanthoxylum spp] (peppercorns)
Climbing layer	Hardy kiwis [Actinidia spp] (berries)
Canopy layer	Chestnuts [Castanea spp] (nuts)

In 2013, Kitsteiner (2013) developed the seven layer concept into a nine layer approach, by adding the aquatic/wetland layer and the mycelial/fungal layer (Figure 2.6). Kitsteiner (2013) looked beyond the typical forest structure and also looked beyond the forest edges. Ponds, streams or larger water bodies such as wetland areas, can provide numerous ecosystem services. These ecosystems can either be found naturally at the edge of, or within, a (food) forest or created to increase the layers of biodiversity and productivity. The fungal layer was added to recognise the importance of fungal activity in the above and below-ground; such as its ability to produce mushrooms, decompose biomass, transport nutrients and for its ability to retain and transport soil moisture (Kitsteiner, 2013). Limareva (2014) also suggested to add a permacultural garden to the south side of a food forest to include the possibility of growing annuals next to perennials. This permacultural garden could be considered as a 10th layer in the food forest (Limareva, 2014). Overall, food forests are composed through conscious design, knowledge and practice with perennial plants, leading to planting compositions being shaped over time and space. This practice incorporates space for plant-to-plant and plant-to-soil interactions and stimulates symbiosis rather than competition between plants and soil life.

Overall, this process aims to mimic natural succession and speed up forest succession (i.e. evolution of the forest). All these layers within a food forest (apart from a permaculture garden) make part of a natural forest succession, in particular secondary succession. This is where an ecosystem is given space and time to evolve into a young or climax forest stadium. Over time soil is built up and enriched with a corresponding increase in biodiversity and biomass increases with every stage within a forest succession following its own cycle of evolution, as shown in the top half of Figure 2.7. Food forests are created in consideration of these cycles of evolution (W. van Eck, 2018 pers. comm., 2nd October). Due to relatively low sunlight levels in the Netherlands compared to the tropics, food forests are often desired to reach a young 'food forest edge' stadium (stage 4 and 5 in Figure 2.7) instead of reaching a climax food forest (stage 6). This is because of a limited availability of sunlight hours in the northern hemisphere compared to the southern hemisphere and more edible species, such as the *Rosaceae family*, being able to flourish in the pioneering stage compared to the climax stage (T. Blom, 2018, pers. comm., Thursday 22nd March).

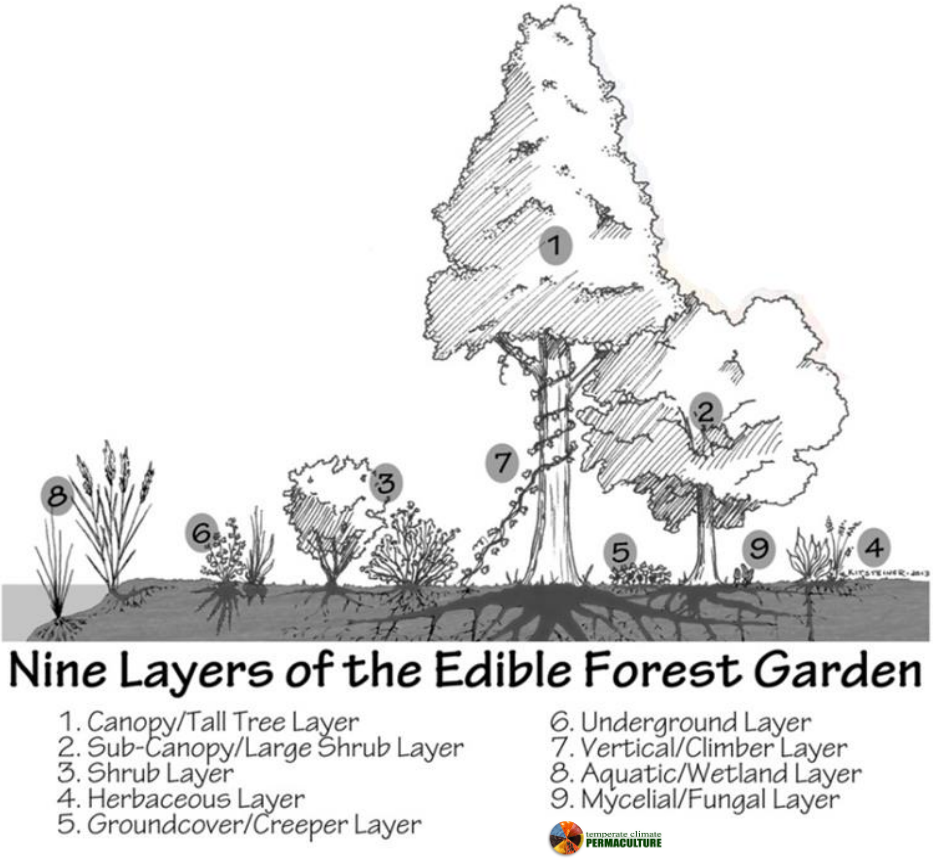


Figure 2.6: The nine layers of the edible forest garden (Kitsteiner, 2013)

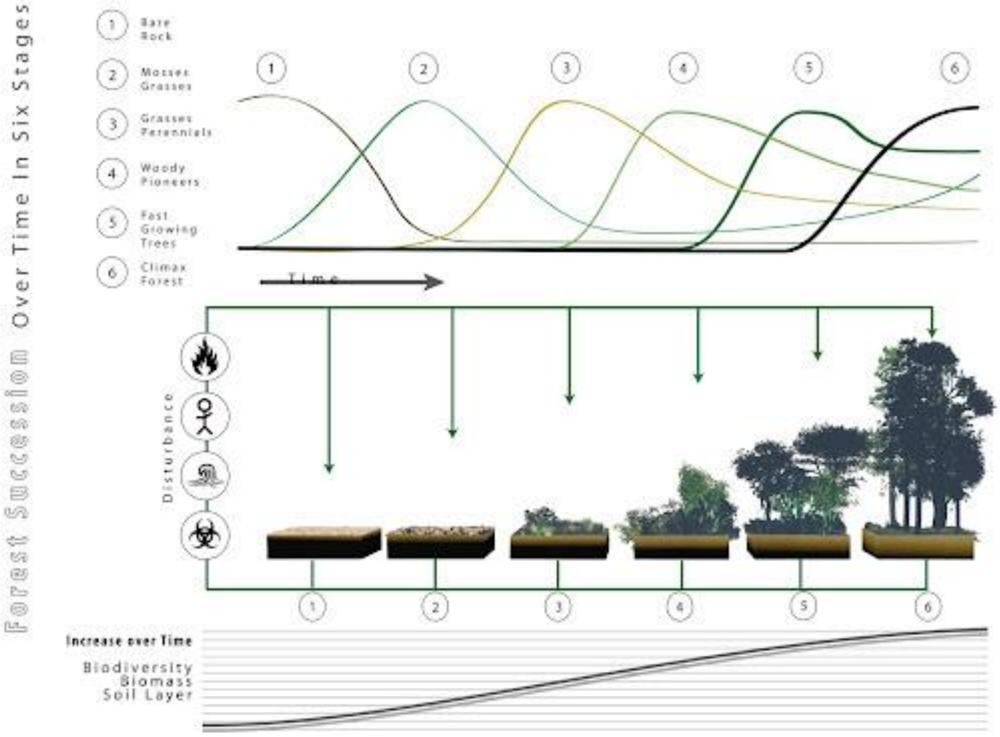


Figure 2.7: An illustration of forest succession over time (Kitsteiner, 2012)

2.3.2 Research into temperate food forestry

In the Netherlands, organisations such as *Stichting Voedselbosbouw NL*, *Food Forestry Development, Circle Ecology*, *Stichting BOTH ENDS* and *Van Akker naar Bos, HAS Den Bosch* and *Van Hall Larenstein (Velp)* are pioneering the development of food forestry. This is achieved through educating, designing, planning, implementing, practicing and researching food forests. In 2015, the Permaculture Association UK set up the Food Forest International Research Network and their initial survey counted over 150 forest gardens worldwide (T. Walisch, 2018, pers. comm., 14th January). Despite these numbers, there are still limited scientific studies on temperate food forests compared to sub-tropical agroforestry systems.

From this initial literature review, only a handful of scientifically-based research studies on temperate food forestry have been identified, of which most were master's thesis projects. For example, West (2016) explored the ´wisdom, knowledge and practice' in Crawford's forest garden. Limareva (2014) explored the ecological principles in natural temperate forest ecosystems in depth and focussed on the lessons learnt from food forest Ketelbroek, the Netherlands. Vargas Poveda (2016a, 2016b) developed tools to facilitate temperate forest garden development from case studies in the UK and in Denmark and also developed a toolkit for formulating forest garden archetypes. Bakker (2016) also carried out a sustainability assessment investigating the soil properties, water quality and flora and fauna biodiversity levels at food forest Ketelbroek. The following year, Breidenbach, *et al.* (2017) investigated the biodiversity levels of the same food forest in comparison with nearby nature reserve "De Bruuk". On a conceptual level, Park and Higgs (2018) presented a monitoring framework containing "14 criteria, 39 indicators, and 109 measures" (Park & Higgs, 2018, p. 1) as a guide to systematically assess food forestry projects. Despite few peer-reviewed articles on temperate food forestry systems, there appears to be a growing interest from academia and society to practice and understand the practice of (temperate) food forestry.

3 Purpose of this Study

3.1 Objectives

This study aims address the knowledge gap in our understanding about the effects of temperate food forestry on soil aspects. This is explored through a comparative case study assessing soil health at food forest Ketelbroek, an unmanaged forest area at nature reserve “De Bruuk” and a conventional arable farm. At each site, the key objectives were:

1. To characterize the general settings.
2. To investigate specific soil properties at the topsoil and subsoil layer.
3. To investigate the development of soil organic matter, in the topsoil, over time.

3.2 Personal motivation

A personal goal of mine is to contribute towards the development of biodiverse agroecosystems and I see enormous potential in food forestry. As a student, I would like to use my academic potential to know more about the effects and impacts of food forestry practices, starting in the Netherlands. Knowing myself as more of a generalist than a specialist, I enjoy approaching this project with a system’s thinking perspective.

3.3 Research questions

The main research question (MRQ for short) that guides this study is:

MRQ: How does soil health at food forest Ketelbroek compare to a conventional farm and the forest nature reserve area “De Bruuk”?

To answer this main question, two sub-research questions (SRQ) were formulated:

SRQ1: What settings characterise the three study sites, in terms of:

A. Geo-hydro-pedology
B. Climatic conditions
C. Land management approach

SRQ2: What do soil quality indicators reveal about the land management system practiced at each site, in terms of:

A. the topsoil layer
B. the subsoil layer
C. over time

The following chapter describes the research methods used to answer these research questions.

4 Research Concepts and Methods

To address the research questions, a mixed method approach was adopted to combine quantitative and qualitative data collection. This involved a quantitative study using soil quality indicators to assess soil properties at each site. In addition, qualitative data was collected through desktop research and informal interviews in order to gain insight about the soil management practices and to collect historical data. These research methods are discussed in more detail below. The underlying key research concepts of soil quality and soil health are first explained below.

4.1 Research concept

Soil quality and soil health

In this thesis, the terms soil quality and soil health are used interchangeably and considered equivalent. As stated by the Natural Resources Conservation Service, USA: "soil health, also referred to as soil quality, is defined as the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans" (NRCS *in* Bünemann et al., 2018; pg. 108). This definition reflects how soil is regarded as a living ecosystem compared to the more classical thought of soils being an inert structure consisting of biological, physical and chemical properties. Soil quality often refers to inherent soil properties, e.g. soil texture, and dynamic properties, e.g. organic matter content. Both inherent and dynamic properties can be influenced by soil management approaches and this influences the functioning of the soil. Internally and externally driven soil processes are diverse, site-specific, interrelated and can widely contribute to ecosystem services, as visualised by Figure 4.1. The variability and interactions between 'pressures' and 'drivers' determine the 'state' of the soil, with subsequent 'impact' on soil and ecosystem functioning, and its 'response' in terms of the delivery of ecosystem goods and services." (Bünemann et al., 2018; pg. 109).

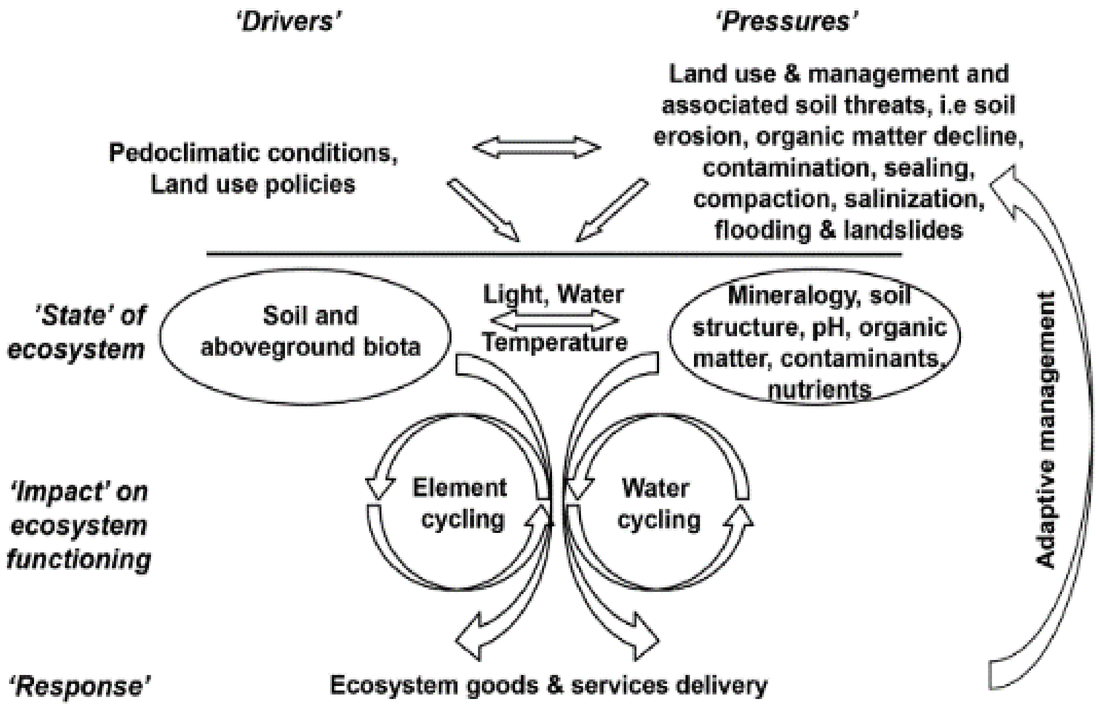


Figure 4.1: "The Driver, Pressure, State, Impact, Response framework applied to soil" (modified from Brussaard et al. 2007 in Bünemann et al., 2018; pg. 109)

As mentioned before, soil health is increasingly being connected to the idea of soils as a living ecosystem, composed of both inherent and dynamic properties and acknowledging “the capacity for emergent system properties such as the self-organization of soils, e.g. feedbacks between soil organisms and soil structure, and the adaptability [of soils] to changing conditions” Bünemann et al., 2018; pg. 108). Much remains to be studied about such soil system properties, whilst currently, most soil properties and processes are often studied in a practical yet reductionist approach. In this study, both classical and emerging approaches are considered with the aim to merge practicality and innovation.

Soil threats

As defined by Berge *et al.* (2017; pg. 31), soil threats are “processes or agents that deteriorate (some of) the functions of soils and the services that soils provide, or that change the state of soils and – if prolonged – are expected to damage soil functions and services in the long run. While some of these processes (or pressures, drivers) occur naturally, emphasis [...] is on threats caused by human activity through agricultural soil management.” A list of soil threats were initially defined by the European Commission (2002) and expanded on by other studies (Table 4.1). This is because some soil threats in this list were more specific, such as ‘erosion by wind’ or ‘-water’, and some new soil threats were also added, such as ‘loss of aboveground biodiversity’ and ‘spread of soil borne diseases’ in light of new information (Berge et al., 2017). Berge et al. (2017) attempted to rank these identified soil threats according to their urgency to society. This was done through a qualitative evaluation. It is suggested to read Chapter 4 in ‘Preserving agricultural soils in the EU´ by Berge et al. (2017) for a detailed explanation of each soil threat.

Table 4.1 European soil threats identified by various studies (Modified and adapted from Berge et al., 2017, p. 32)

	Soil threat	**Louwagie *et al.* 2009**	**Jones *et al.*, 2012**	**Stolte *et al., 2016***	**Berge *et al.*, 2017**
1	Erosion by wind	▨	▨	▨	▨
2	Erosion by water	▨	▨	▨	▨
3	Floods and land slides	▨	▨	▨	▨
4	Degradation of peat soils				▨
5	Carbon loss in mineral soils	▨	▨	▨	▨
6	Compaction	▨		▨	▨
7	Salinisation and sodification	▨	▨	▨	▨
8	Contamination	▨		▨	▨
9	Acidification		▨		▨
10	Loss of soil fertility				▨
11	Desertification		▨	▨	▨
12	Loss of aboveground biodiversity				▨
13	Loss of soil biodiversity	▨	▨	▨	▨
14	Spread of soil borne diseases				▨
15	Sealing (land-take)		▨	▨	▨

Following recommendations from Bünemann et al. (2018), soil quality indicators are related to soil threats to adopt a more functional approach in assessing soil health. In this study, the selected soil quality indicators are clustered around three soil threats: SOM decline, compaction, and biodiversity loss. These soil threats (and their corresponding indicators) are connected to all listed soil processes and soil-based ecosystem functions/services (illustrated in Figure 4.2).

Sustainable soil and land management

An underlying concept for this study is sustainable soil management and sustainable land management. "Soil management is sustainable if the supporting, provisioning, regulating, and cultural services provided by soil are maintained or enhanced without significantly impairing either the soil functions that enable those services or biodiversity." (FAO, 2017, p. 3). These services relate to ecosystem services, which are termed as soil-based ecosystem functions/services in this study. As mentioned earlier, these ecosystem functions are connected to soil process, soil threats and soil quality indicators (Figure 4.2). Sustainable land management is also an underlying concept of this study. This is defined as "the stewardship and use of land resources, including soils, water, animals and plants, to meet changing human needs, while simultaneously ensuring the long-term productive potential of these resources and the maintenance of their environmental functions." (IPCC, 2019b, p. 4 & FAO, 2015).

4.2 Research methodology

Soil health assessment

There is a plethora of biotic and abiotic entities that make part of the soil ecosystem, yet much remains unknown as to how much they contribute to the functioning of soils (Brussaard *et al.* 2006). Due to this, coupled with a diversity of soil sampling techniques and a mixture of goals associated with any soil assessment, there remains no universal framework for assessing and comparing soil health. Despite this, there are many soil quality indicators that have been developed (as a proxy) to identify certain soil properties (Bünemann et al., 2018). Research has shown that land management practices, certain soil fauna groups and soil structure do influence the functioning of a soil (Brussaard *et al.* 2006). Examining soil indicators can provide a way to assess the condition of soil.

In this study, given time and funding limitations, eleven soil quality indicators were selected based on what they reflect, practical feasibility and in relation to EU soil threats (Table 4.2 & Figure 4.2). Eight soil quality indicators were assessed using a benchmark and the remaining three were included as background soil information (these being soil colour, -texture and -temperature) All indicators, aside from soil texture and colour, are dynamic soil properties. For this study's purposes, comparing a food forest with a forest are for reference purposes only. A comparison between a food forest and arable farm is more relevant as they are both productive agroecosystems. Forest "De Bruuk" is designated as a nature area with no production value (for humans). Establishing optimum soil ranges are, therefore, relevant for agroecosystem.

Table 4.2: A complete overview of every soil quality indicator, summarized according to their type and significance (soil quality indicator with an asterisk is adopted from Baas' research).*

Soil quality type	Indicator	Explanation	Significance	Source
Physical	Soil texture	Ratio between sand, silt and clay.	Soil texture affects physical and chemical soil properties.	(Gooren, Peters, Riksen, & Gertsen, 2017)
	Soil colour	Determining the colour of the soil.	Soil colour gives an indication of the soil composition (i.e. organic matter content and presence of essential nutrients).	(Munsell, 2017)
	Soil temperature	The temperature of the soil (°C)	Soil temperature directly affects plant growth and influences soil moisture content, aeration and availability of plant nutrients. Optimum soil temperature for soil life is between 25°C and 35°C.	(Agriinfo.in, 2015)
	Aggregate stability	Indicates the stability of the soil against "mechanical or physicochemical destructive forces" (Eijkelkamp Soil & Water BV, n.d.)	This shows how susceptible the soil is to soil erosion from water and indicates the stability of the soil structure.	(Eijkelkamp Soil & Water BV, n.d.; USDA, 1996)
	Bulk density	Indicates the ratio between soil particles and non-soil particles.	Characterizes the soil structure. Soil structure supports vital processes: ability for plant root growth, soil aeration/exchange of gases, water infiltration and drainage capacities of the soil.	(CDPR, 2014)
	Soil moisture content	Indicates percentage of water present in the soil.	Soil moisture acts as a medium for transferring nutrients and minerals. It can also influence the stability of soil structure.	(Johnson, 1992; R. Schulte, O'Sullivan, & Creamer, 2018)
	Soil resistance	Assessing how dense, i.e. compacted, the soil is by measuring the resistance exerted by the soil.	A compacted soil adversely affects the growth of plants due to less room for aeration, water infiltration and increased difficulty for root penetration.	(Keesstra, 2017)
Chemical	pH	Indicates the level of soil acidity or basicity.	Level of soil pH influences plant nutrient availability in the soil and is a fundamental influence on soil properties, such as on SOM and aggregate stability.	(Rayment & Higginson, 1992)
	Soil organic matter & carbon content (SOM & SOC)	Organic matter is the process of on-site biological decomposition, which can also lead to the build-up of humus, make nutrients available for uptake and stores and releases carbon through soil respiration.	The level of SOM influences vital soil processes: nutrient availability, cation exchange capacity, soil structure, water holding capacity and source of energy to soil biota. SOM is also an indicator for soil organic carbon content (SOC = SOM x 0.5).	(FAO, 2005; Geissen, 2015)
Biological	Earthworm abundance (per m^2)*	Number of earthworms present in soil sample.	Earthworms play a significant role in soil structure and contribute to the build-up of healthy soils through the creation of macro-aggregates, increase the decomposition process of plant biomass, soil particles and microbes into (smaller) organic matter and disperse organic matter across soil layers.	(Baas, 2018)

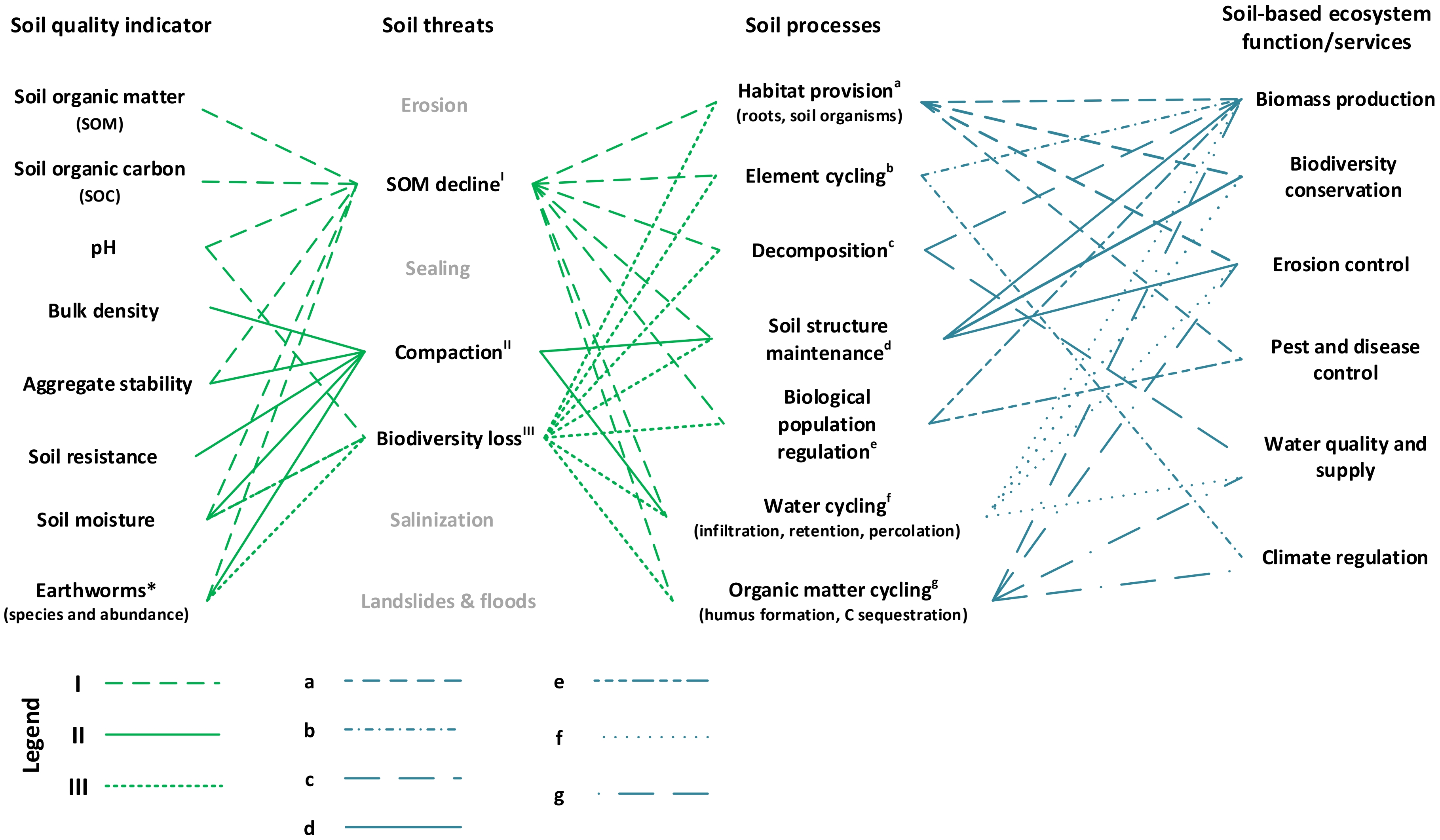


Figure 4.2: A visualization of selected soil quality indicators in relation to soil threats, soils processes and soil-based ecosystem functions/services. Relationship is colour and pattern coded; green lines show connections between three soil threats in relation to soil quality indicators and soil processes. Blue lines reflect the interrelationship from soil processes with soil-based ecosystem. Within green and blue connections, each sub-theme adheres to a patterned outline (denoted by superscript and legend; e.g. SOM decline has green dashed lines and habitat provision has blue dashed lines, etc.). Soil quality indicator with an asterisk is adopted from Baas' research. (Adapted from Brussaard, 2012 in Bünemann et al., 2018)*

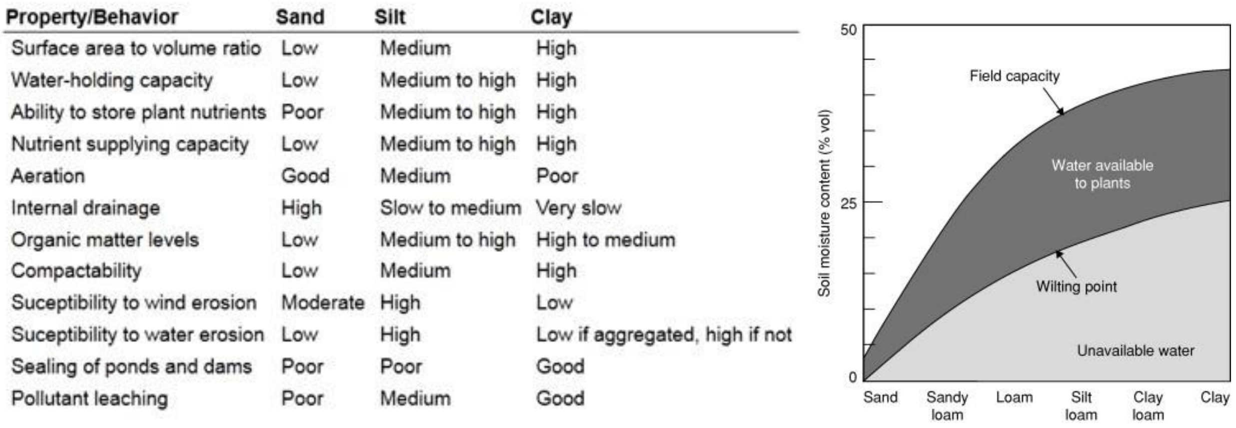
The results from these soil quality indicators are compared to a benchmark relevant for loess soil with a (sandy) loam soil texture (Table 4.3). Also, basic soil indicators such as soil texture, colour, temperature and moisture content were measured to determine local soil conditions. These basic soil properties shape soil properties and soil processes as they are often interrelated. For example, soil texture characterises several soil properties (Table 4.4), such as bulk density (Figure 4.3).

Table 4.3: A benchmark system showing every soil quality indicator and their respective colour-coded ranges for loess soils, where red are sub-optimal values, light-green are tolerable values and green are optimum values

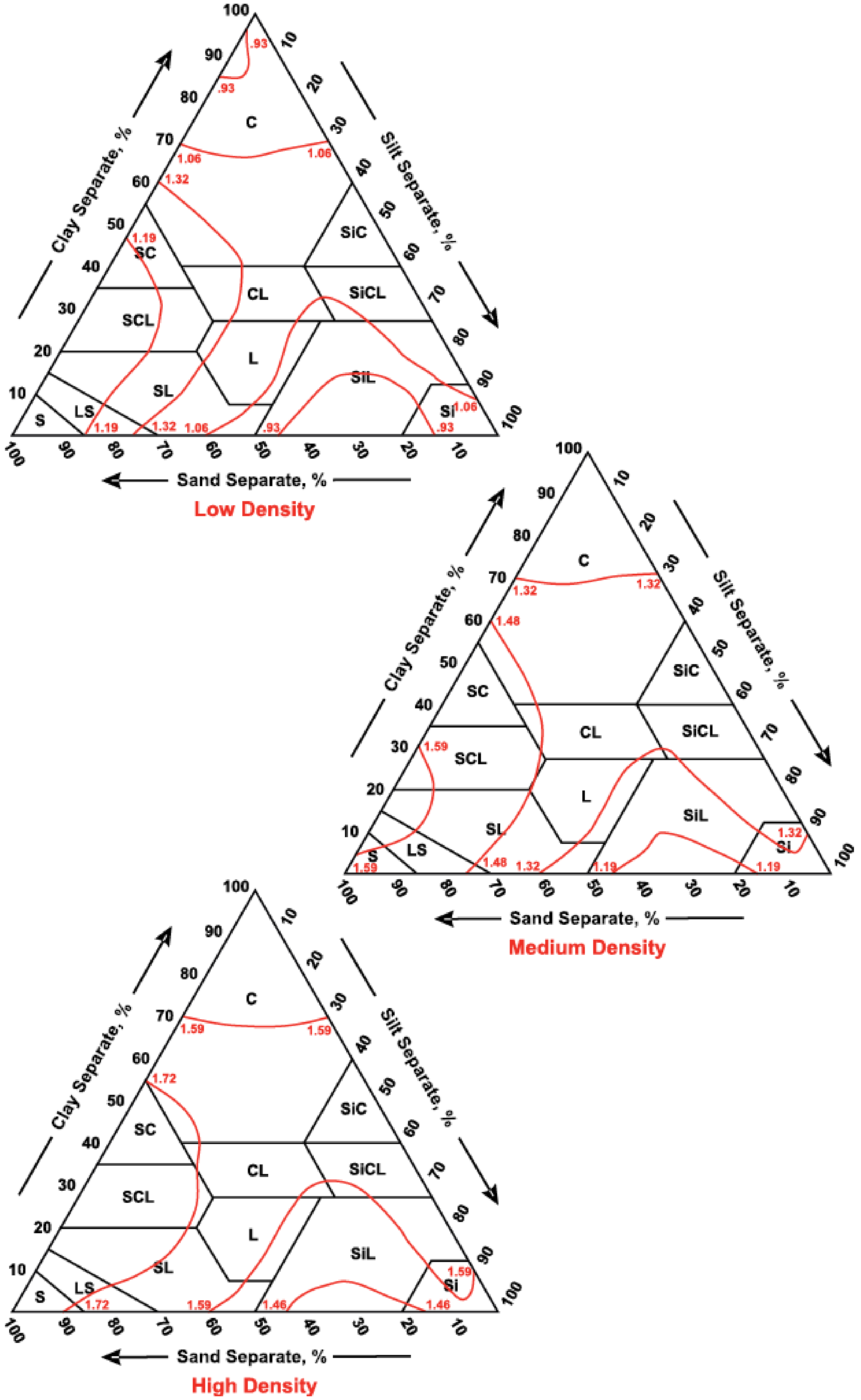
Indicator		Range			Source
		Low	*Medium*	*High*	
Physical	**Aggregate stability (%)**	< 0.3	0.3 - 0.5	> 0.5	(Ohio State University, 2018)
	Bulk density (g/cm³)	>1.32	1.32 - 1.72	>1.72	(USDA, n.d.)
	Soil moisture (%)	< 20	20 - 40	> 40	(Tsoar, 2005)
	Soil resistance (kPa)	≤ 250		> 250	(Hanegraaf, Haan, & Visser, 2019)
Chemical	**pH**	< 5.5	5.5 - 7.5	> 7.5	(FAO, 2015; Moebius-Clune et al., 2017)
	Soil organic matter content (%)	< 2	2 - 4	> 4	(Morari et al., 2016 in Stolte et al., 2016)
	Soil organic carbon (%)	< 1	1 - 2	> 2	(EEA, 2012; Aksoy, Yigini, & Montanarella, 2016)
Biological	**Earthworm abundance (per m²)**	<120	120 - 250	>250	(Pfiffner, 2014)

Legend
Optimum range
Tolerable range
Threshold

Table 4.4: An overview showing the effect of different soil textures on soil properties, with the effect on soil moisture content visualised (Goldy, 2012; Tsoar, 2005)



Property/Behavior	Sand	Silt	Clay
Surface area to volume ratio	Low	Medium	High
Water-holding capacity	Low	Medium to high	High
Ability to store plant nutrients	Poor	Medium to high	High
Nutrient supplying capacity	Low	Medium to high	High
Aeration	Good	Medium	Poor
Internal drainage	High	Slow to medium	Very slow
Organic matter levels	Low	Medium to high	High to medium
Compactability	Low	Medium	High
Suceptibility to wind erosion	Moderate	High	Low
Suceptibility to water erosion	Low	High	Low if aggregated, high if not
Sealing of ponds and dams	Poor	Poor	Good
Pollutant leaching	Poor	Medium	Good



Low Density

Medium Density

High Density

Figure 4.3: Low, medium and high bulk density classes across different soil textures (Rawls and Brakensiek, 1983 in USDA, n.d.)

4.2.1 Sampling design

The forest, food forest and conventional farm were sampled using a random-stratified sampling design. In the case for the forest and food forest, sampling was based on sub-dividing the field into non-overlapping strata according to "spatial or temporal proximity of the units, or on the basis of pre-existing information or professional judgment" (EPA, 2002; pg. 13). In the context of a (food) forest, the term 'units' were defined as habitats, tree species or tree-crop combinations (Slier et al., 2018b). Sampling locations for this study were also based on the sampling locations of a previous soil study by Bakker (2016). His sampling methodology was based on "[...] 'sampling zones' [...] indicated on aerial maps of the study sites in a semi-regular systematic grid. In the field, sample sites were chosen within the sampling zones, based on accessibility and local field conditions" (Bakker, 2016; pg. 14). This is also considered a random-stratified sampling approach. For coordinates of this study's sample locations (based upon Bakker's previous study), refer to 11.2. In the case for the conventional farm, samples were taken at random as there were no previous sample points to follow.

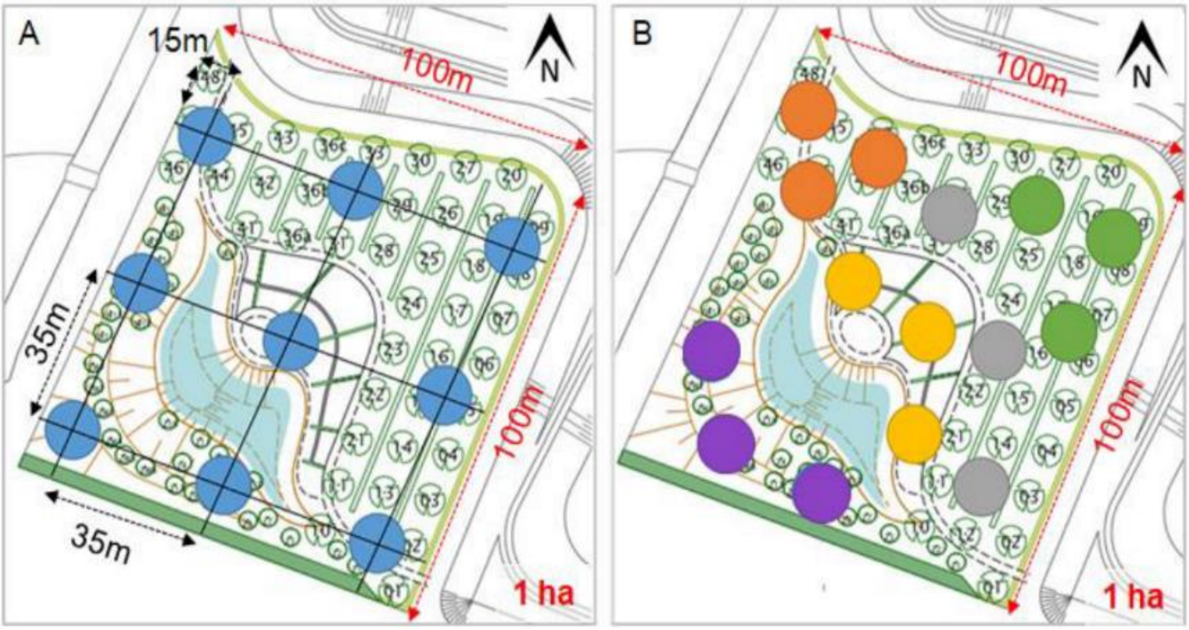


Figure 4.4: Two sampling designs, systematic (A) and random-stratified (B), for the case of food forest EcoVredeGaard (EVG). The systematic approach entails sampling at equally spaced locations. The random-stratified approach entails sampling at random within pre-defined habitats (in EVG these are "nut-tree habitat (purple), herb-shrub habitat (yellow), fruit-tree and shrub habitat (grey), fruit-tree and shrub habitat in lowland (green), no-management area (orange)". (Slier et al., 2018; pg. 63)

Considering time and feasibility, five sample locations were taken per land management system. For food forest Ketelbroek, five samples were taken; in the northern shrubs with various grass species (FF1), southern shrubs with fruit bushes (FF2), deep food forest with seven productive layers (FF3), in a lane with mainly nut trees (FF4) and in the open food forest with comfrey and nut trees (FF5) One sample was taken per stratum. The sampling locations at “De Bruuk” forest and the arable field are shown in Figure 4.7 & Figure 4.8.

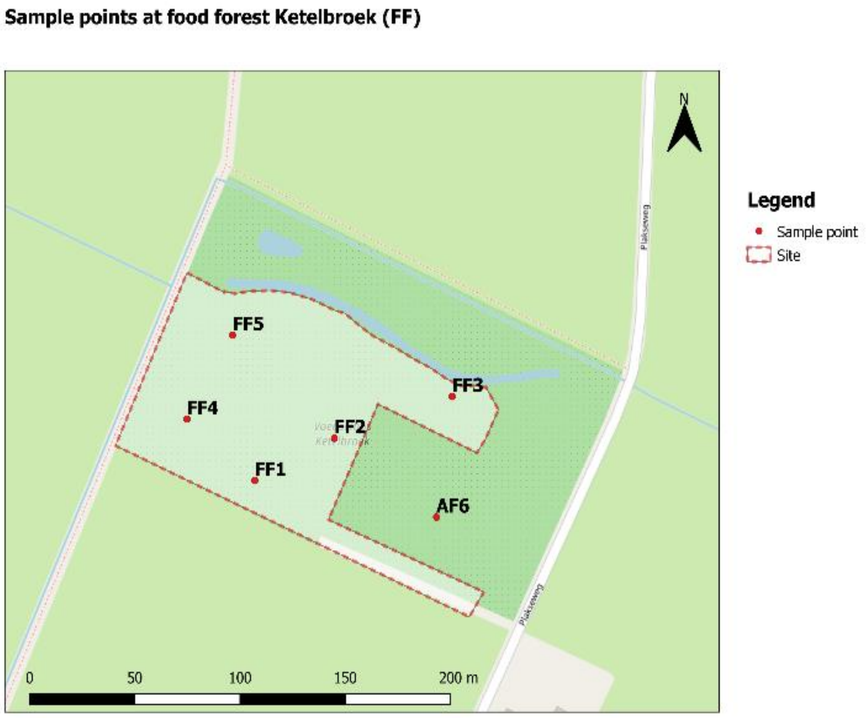


Figure 4.5: A map showing sample locations at food forest Ketelbroek (coded with FF# for food forest)

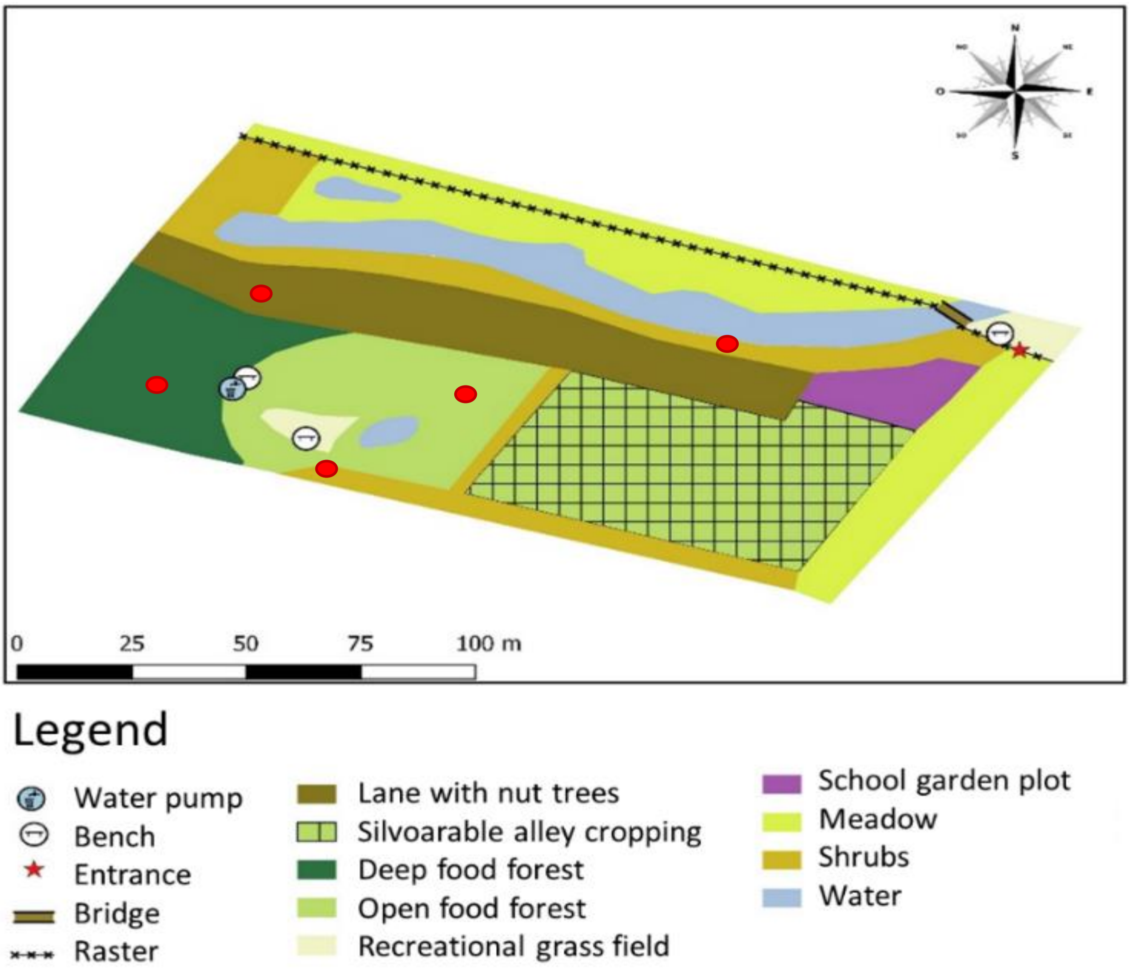
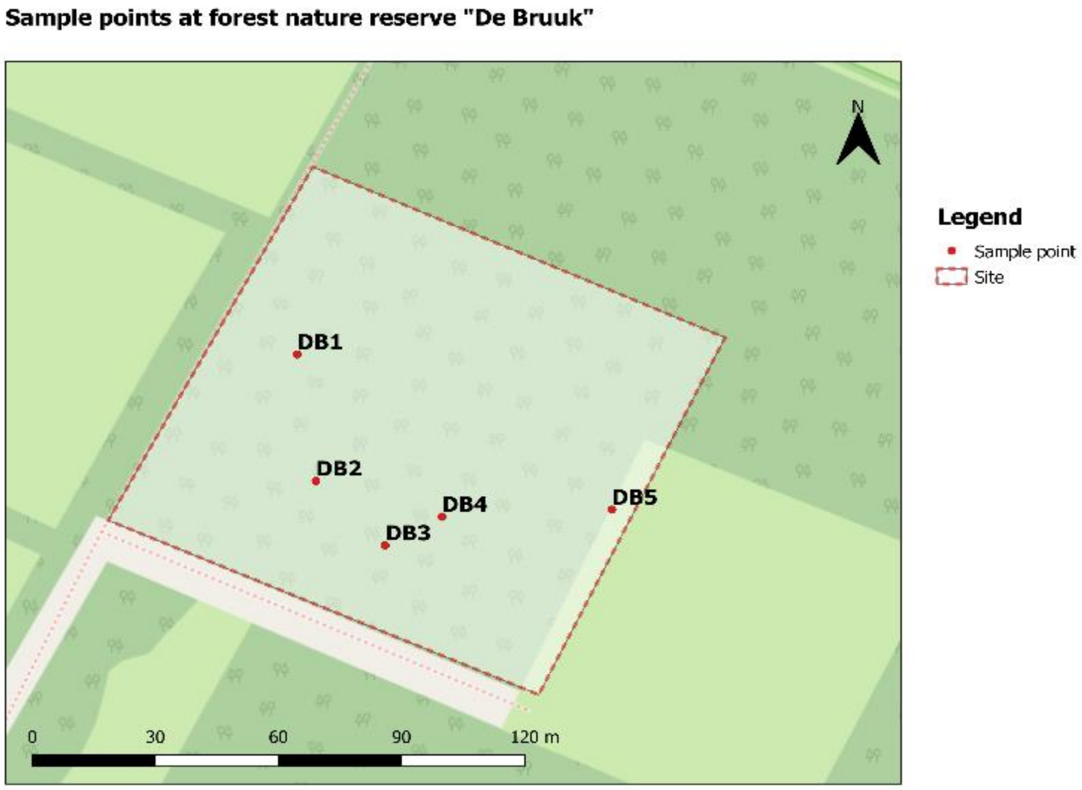
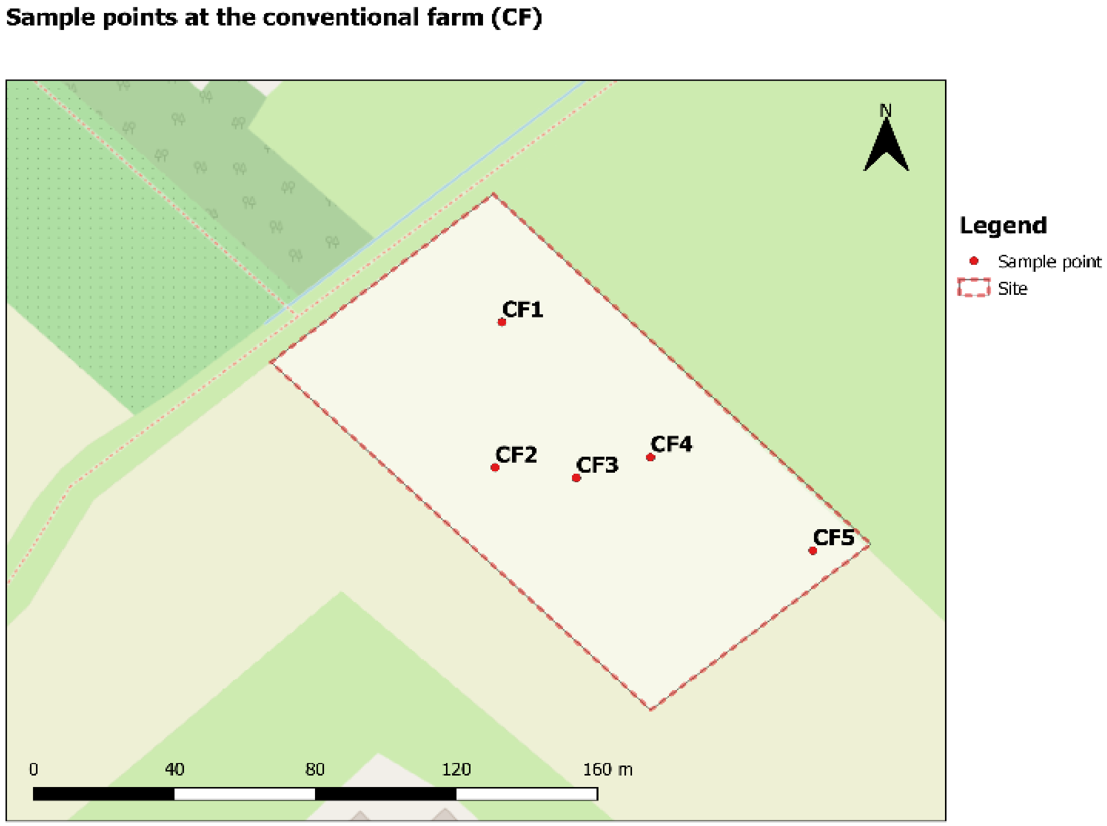


Figure 4.6: A schematic map showing sample locations in different zones of food forest Ketelbroek (adapted from Baas, 2018)



Sample points at forest nature reserve "De Bruuk"

Figure 4.7: A map showing sample locations at nature reserve "De Bruuk" (coded with DB# for "De Bruuk")



Sample points at the conventional farm (CF)

Figure 4.8: A map showing sample locations at the arable field (coded with CF# for conventional farm)

4.2.2 Sampling methods

All soil samples, except for soil compaction tests, were taken on 09 April 2018 at food forest Ketelbroek, at nature reserve “De Bruuk” on the 12th of April and at the arable field on 18th of April. Soil compaction was measured at all three sites on 21st of April. At each sample location, eleven soil properties were assessed (summarized in Table 4.5) and all sampling locations were recorded via GPS. A brief explanation of each soil indicator, sampling method and laboratory analysis is given below.

Table 4.5: A summary of every soil indicator and sampling method (soil quality indicator with an asterisk is adopted from Baas' research)*

Indicator	**Method**	**Source**
Soil texture	Soil texture guide (by hand)	(Gooren et al., 2017)
Soil colour	Munsell colour chart	(Munsell, 2017)
Soil temperature (°C)	Thermometer	(Agriinfo.in, 2015)
Aggregate stability	Wet-sieving method	(Eijkelkamp Soil & Water BV, n.d.; USDA, 1996)
Bulk density (g/cm^3)	100cc ring sample, drying and weighing	(CDPR, 2014)
Soil moisture content (%)	Oven drying and weighing (Thermogravimetric method)	(Johnson, 1992)
Soil resistance (mPa)	Penetrologger	(Keesstra, 2017)
pH	Potentiometric method (H2O + glass electrode	(Rayment & Higginson, 1992)
Soil organic matter content (SOM) (%)	Loss on Ignition	(Adapted from Bakker, 2016; Heiri, Lotter, & Lemcke, 2001; Slier et al., 2018)
Soil organic carbon content (SOC) (%)	Calculated from SOM value: SOC = SOM x 0.5	(Geissen, 2015 & Slier *et al.* 2018)
Earthworm abundance (per m^2)*	Adaptation of ISO/DIS 23611-1 (2 stacked soil samples of Ø 80 mm till soil depth of 50cm or groundwater level taken.)	(Baas, 2018)

Physical soil properties

Field measurements & Laboratory analysis

Soil texture was estimated using a standardized soil texture guide (shown in 11.3). Soil colour was assessed visually using the Munsell colour chart. Soil temperature was taken (in °C) at every sample location.

Aggregate stability

Aggregate stability was measured using the standardized wet sieving approach. Duplicates were made for each soil sample. For the standard operating procedures, see 11.4.

Bulk density

Five measurements were taken at 0-5cm soil depth and five measurements at 30-35cm soil depth at each study site using a 100cc ring. Standard operating procedures were followed, as outlined by the California Department of Pesticide Regulation (CDPR, 2014). The formula used to calculate soil bulk density was:

$$\frac{M_d}{V} = \frac{Weight\ of\ soil\ dried}{Volume}$$

Expressed in g/cm^3

Soil moisture

The soil moisture content was calculated from the same sample used for calculating bulk density. Soil moisture was calculated using the following formula:

$$Soil\ moisture = \frac{w_w - w_d}{w_d} \times 100 = \frac{weight\ of\ wet\ soil - weight\ of\ dry\ soil}{weight\ of\ dry\ soil} \times 100$$

Expressed in percentage (%)

Soil resistance

Soil resistance was measured three times using a penetrologger at each sampling location. The insertion cone of the penetrologger was fixed with a 1cm^2 base area, which is standard practice for soil research (Eijkelkamp, 2013). The resistance of the soil is expressed in kPa (kiloPascal).

Chemical soil properties

pH

Soil pH was measured using the H_2O extraction method at a soil to water ratio of 1 : 2.5, using 10g of soil, mixed with 25ml of distilled water, shaken for 1 minute and measured using a glass electrode. Duplicates were taken and averaged.

Soil organic matter (SOM)

At each study site, five soil samples of ±25grams were taken at 0-5cm soil depth and five samples at 30-35cm soil depth. The loss-on-ignition method was used to indicate SOM. For the standard operating procedure used, refer to Appendix 11.5.

$$SOM = \frac{w_d - w_c}{w_c} \times 100 = \frac{weight\ of\ dry\ soil - weight\ of\ combusted\ soil}{weight\ of\ combusted\ soil} \times 100$$

Expressed in percentage (%)

Soil organic carbon (SOC)

This was calculated from the SOM result, with the assumption that the total SOC is half the amount of the SOM (Hoosbeek *in* Slier et al., 2018).

$$SOC = \frac{SOM}{2}$$

Expressed in percentage (%)

4.3 Data composition

Parallel to this study, thesis research by W.Baas focussed on soil biodiversity (Baas, 2018). His research involved investigating species diversity and abundance of earthworms (e.g. A. Caliginosa, L. Rubellus, L. Castaneus, O. Cyaneum, A. Rosae and E. Tetraedra). Our research sites were near identical, and we have agreed to share data, as marked with an asterisk in Figure 4.2. Hence, Baas's earthworm study results (a biological soil indicator) were incorporated within this report to make this soil quality assessment richer.

A historical comparison with soil data was also made possible due to soil data collected by M. Bakker in 2016 at food forest Ketelbroek. His data on soil pH, SOM and bulk density were acknowledged in this report when analysing soil health over time at food forest Ketelbroek.

Through cooperation with T. Westhoff, further inter-seasonal soil data was collected in the winter (February), spring (April) and summer (July) of 2019. Organic matter in the topsoil were measured at all three sites and mentioned in this report.

4.4 Data processing

Data was processed using Excel and RStudio. Statistical analysis was performed using the functions: aov (analysis of variance) and Tukey HSD to test for statistically significant differences. Graphical visualisations were also made using RStudio, Microsoft Visio and Word.

5 Study Area

To set the context of this study, the land management approaches per study site are described as well as the geological, hydrological, pedology and climatic conditions. Food forest Ketelbroek, nature reserve "De Bruuk" and the conventional farm are located in Groesbeek, the Netherlands (Figure 5.1 & Figure 5.9). This area is elevated at 16m. ASL and situated in between hills (Figure 5.2 & Figure 5.3).

Figure 5.1: A map showing the research area (red dot) in Groesbeek, province of Gelderland, the Netherlands

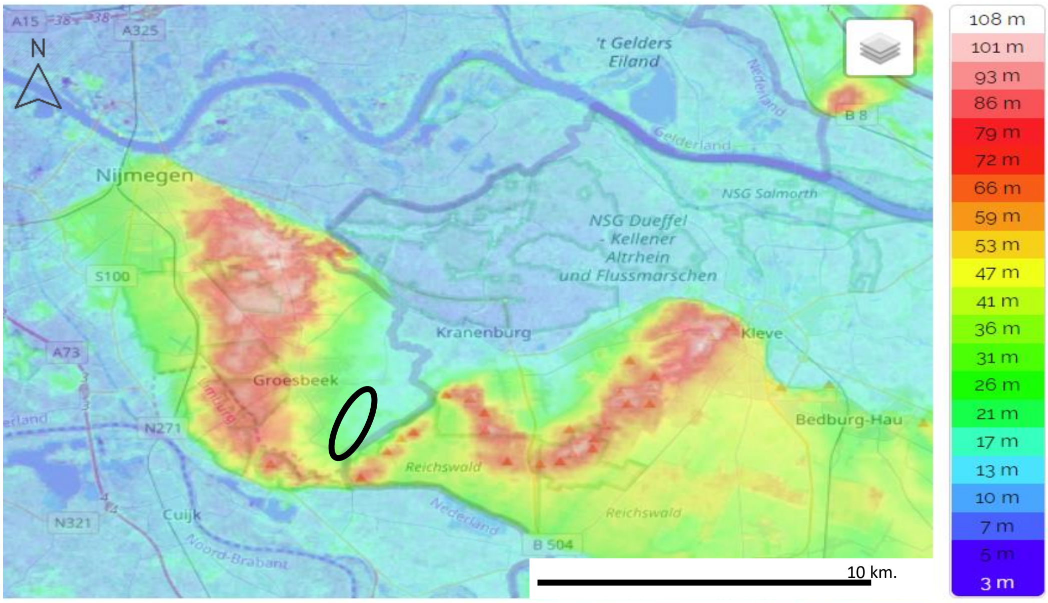


Figure 5.2: A map showing the research site within Groesbeek and the surroundings of the glacial moraines (Topographic-map.com, 2019)

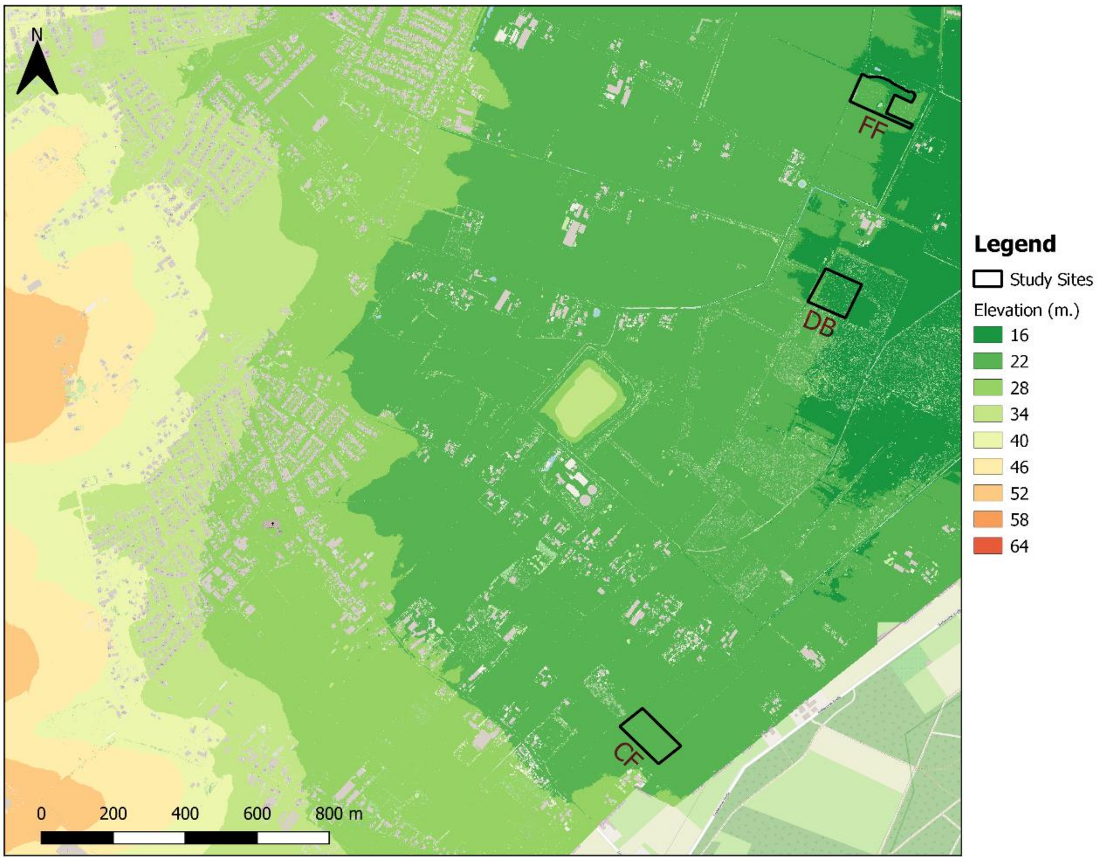


Figure 5.3: An elevation map showing the research sites (boxed in black)

5.1 Land management approach

This section describes each study site in terms of their form, function and approach.

5.1.1 Conventional field (CF)

Form and function

This conventional arable farm functions to produce food and feed. In 1996, this field was a grass field/meadow and later, in 2007, it was turned into an arable field. The sampling area is approximately 1.2 ha in size.

Management approach

Sampling was carried out in a winter wheat field at a stage of five months old. Winter wheat seeds were planted in mid- December of 2017 and harvested mid- August 2018. Before planting, limestone ($CaCO_3$) was distributed over the fields to reduce acidity levels in the soil. The soil was also ploughed, and no fertilizers were applied for the crop being grown at the time.

The cropping rotation follows a six-year rotation scheme, where for one season either winter wheat, sugar beets, potatoes or maize (silage or corn) is grown consecutively, followed by a 2-year fallow period. The farmer also plants white mustard *(Sinapsis alba),* a green manure, to cover the soil during the winter period to prevent soil erosion and increase soil organic matter content. Before seeding, the green manure is ploughed into the soil to increase organic matter content. This is followed by planting seeds according to the crop rotation scheme. Agrochemicals (fertilizer, pesticide, herbicide and fungicide) are applied and are dosage-dependent per crop. Soil amendments are also applied, often following advice from an agricultural agency who performs a soil assessment every 4 years (for the latest soil assessment in 2016, refer to Appendix 11.1). Cow manure is applied occasionally, especially when growing beets, which is sourced from neighbouring farms. In return, the farmer provides hay to this farmer in order to source farm inputs as locally as possible. These management practices are integrative approaches towards closing nutrient cycles where possible.

Figure 5.4: An aerial map of the arable field in Groesbeek; red outline represents the whole arable field and the red dotted outline marks the research boundaries

5.1.2 Food forest Ketelbroek (FF)

Form and function

This is the oldest known food forest in the Netherlands, which was planted in 2009 by Wouter van Eck and companion Pieter Jansen. It is estimated that there are more than 400 plant species present in the food forest, of which approximately 200 have been planted (W. van Eck, 2018, pers. comm., 26 February). Ketelbroek is 2.5 ha in size and is predominantly surrounded by meadows which produce hay. There are a few agricultural fields in the surroundings which cultivate wheat, maize beetroots and/or potatoes, often in rotation. Before 2009, Ketelbroek was a conventional field growing maize silage.

Figure 5.5: Aerial view of food forest Ketelbroek (Bosplus.be, 2019)

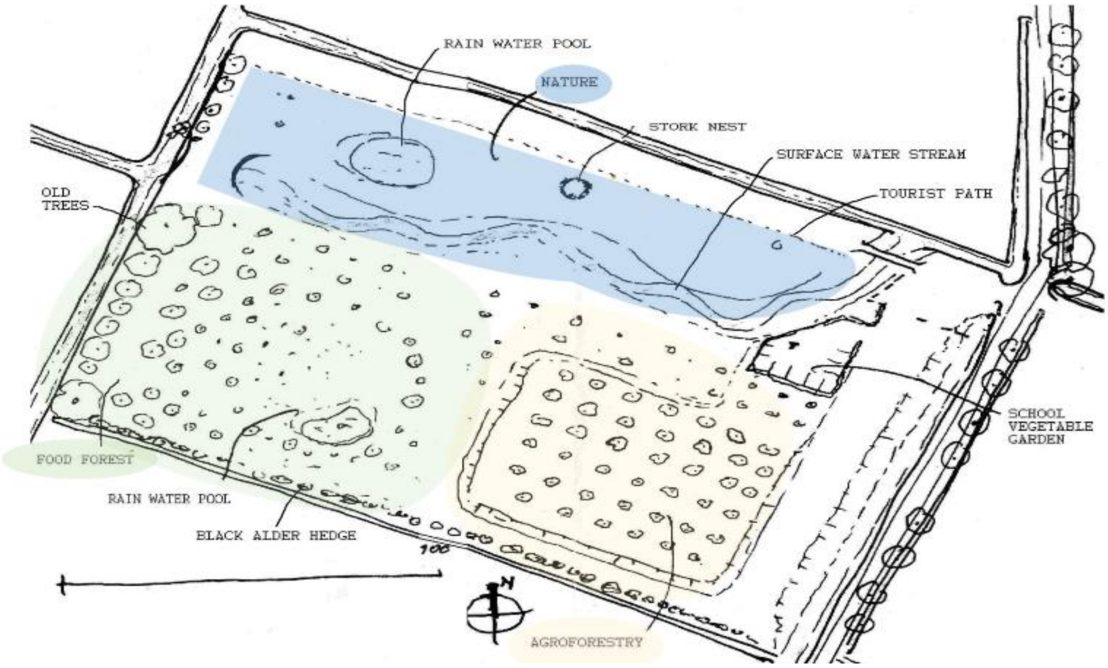


Figure 5.6: Design map of food forest Ketelbroek (created by Xavier San Giorgi with adaptations by Limereva in Bakker, 2016)

Figure 5.6 illustrates the design map of food forest Ketelbroek, focussing on three coloured themes: food forest, agroforestry and nature. Figure 4.6 shows a more detailed map where parts of the food forest are classified according to the dominance of certain plant species and/or plant compositions. These can be regarded as sub-zones within the food forest. Each themed section (Figure 5.6) contains at least one or more of these sub-zones:

- The agroforestry section contains a 0.5 ha silvoarable alley cropping system
- The food forest portion is a 1.2 ha designed polyculture consisting of a deep- and open food forest area, a lane of nut trees and shrubs
- The nature segment which is a 0.6 ha wetland area with neighbouring meadows

There is also a small plot (0.09 ha) used by the local school as a vegetable garden. There are also canals on the north, east and west sides of the food forest. The objective of this land use system is to "provide an example where agriculture and nature support each other" (W. van Eck, 2018, pers. comm., 26 February). Other objectives of food forest Ketelbroek include being a place for recreation, education, research and a habitat for wildlife, both flora and fauna.

Management approach

Prior to 2009, this field was a former maize field using fertilizers, ploughing and machinery for sowing and harvesting every season. Since 2009, there has been no application of fertilizer, ploughing or the use of heavy machinery. van Eck also calls his approach "lazy farming", which highlights that after planting, little maintenance is carried out. The main task is to harvest, often by hand (W. van Eck, 2018, pers. comm., 26 February).

An exception being in 2012, where the northern part of the food forest (now the nature area) was excavated, removing the top soil layer and moved, to what now is, the silvoarable alley cropping area (a.k.a. rational food forest). This was done for two reasons: to create a wetland area and to raise the ground level of the field for deeper rooting depth for trees and plants. Due to this relatively recent soil disturbance in these two areas, this research only focussed on the undisturbed food forest portion.

5.1.3 Nature reserve “De Bruuk” (DB)

Form and function

In 1940, this nature reserve was the first protected grassland reserve in the Netherlands (Pierson, 2011; Staatsbosbeheer, 2009). In 2009, it became part of the Natura 2000 network due to the presence of “molinia meadows on calcareous, peaty or clayey-silt-laden soils (Molinion caeruleae)”, in Dutch terms: *blauwgraslanden* (Natura 2000, 2017). This nature reserve is owned by Staatsbosbeheer and has a total area of 109 ha consisting of grassland, marshland and wet forest habitats (Staatsbosbeheer, 2009). The research site is situated in the forested area and is approximately 1.2 ha (Figure 5.7). This study area is taken as a conceptual reference point for comparison with the conventional farm and the food forest.

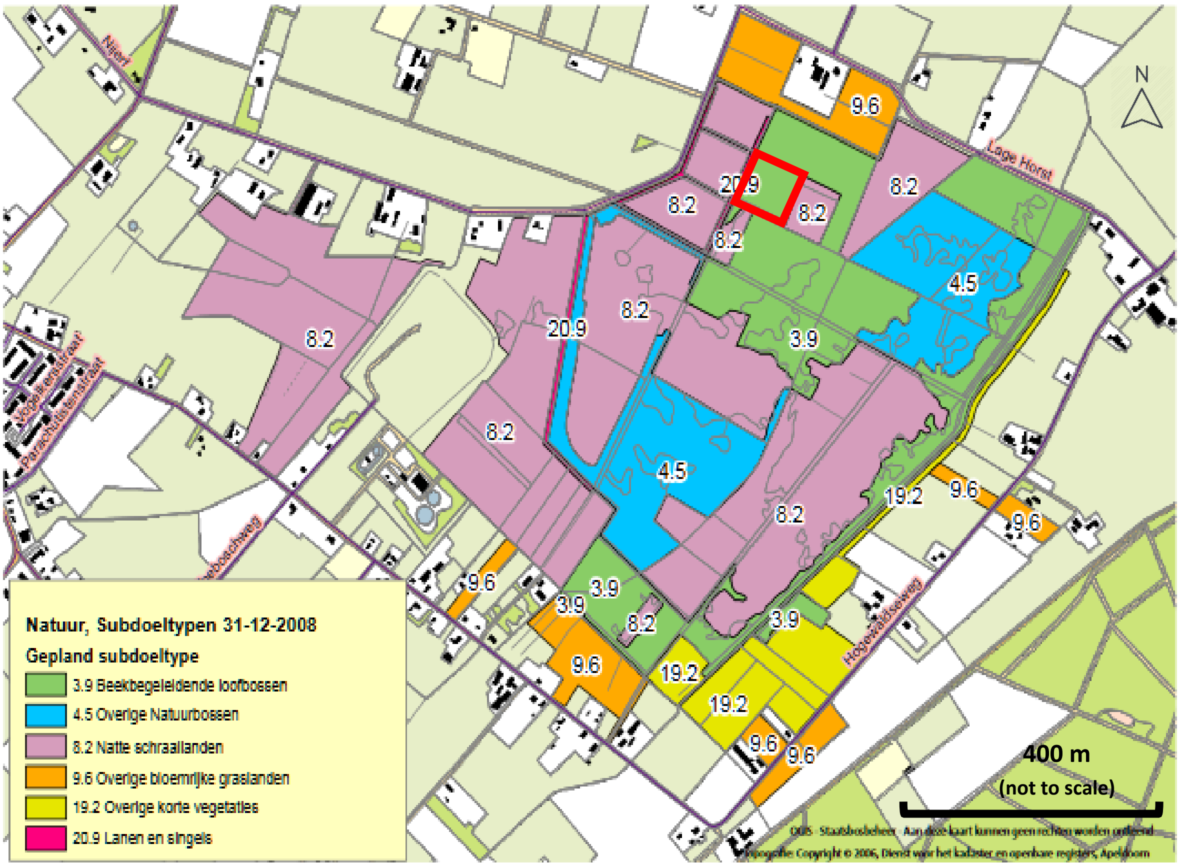


Figure 5.7: A map of nature reserve "De Bruuk" with the study site outlined in red (Pierson, 2011)

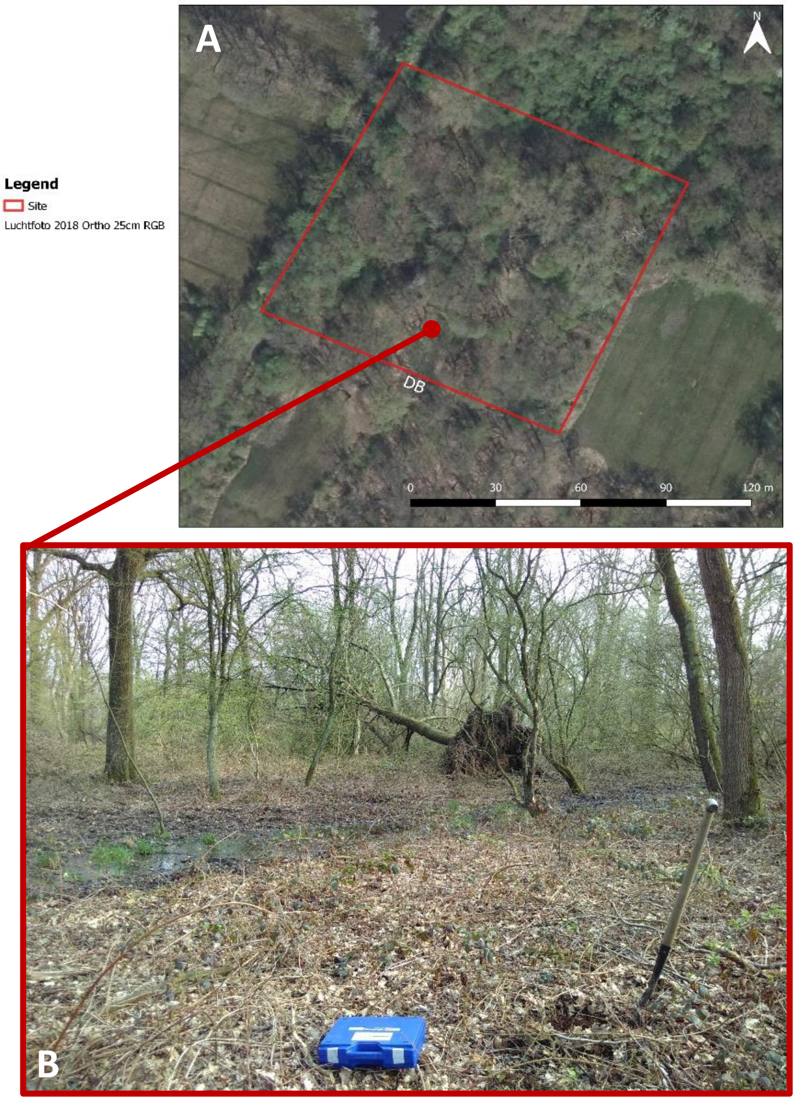


Figure 5.8: An aerial view (A) and ground-level view (B) of the swamp forest in the northern part of "De Bruuk"

The most prominent tree species is the common oak *(Quercus robur)*. Common shrubs are the common hawthorn (*Crataegus spp.*) and brambles (*Rubus spp.*) on the forest floor. Other trees are also present in this area, such as birch (*Betula spp.*), bird cherry (*Prunus padus*), hazels (*Corylus avellana*), ash (*Fraxinus excelsior*), white poplar (*Populus alba*) and black alder (*Alnus glutinosa*) (Gijsbertsen *in* Baas, 2018; DLG, 2016). In the northern part of the research plot the oaks are past their prime years and have now turned into a forest swamp (Figure 5.8)

The function of “De Bruuk” is to increase biodiversity. Particular emphasis is placed on restoring natural water flows, increasing the presence of molinia and moist alluvial forests (DLG, 2016; pg. 70).

Management approach

The management approach for the forested area in “De Bruuk”, carried out by Staatsbosbeheer, is to leave these areas unmanaged, although undesired exotic tree species are removed from time to time. Undesired species include the northern red oak *(Quercus rubra)* and the black cherry *(Prunus serotina)* (Gijsbertsen *in* Baas, 2018). The goal is to develop this area into a peat forest (‘laagveenbos’ in Dutch) (Gijsbertsen *in* Baas, 2018; Staatsbosbeheer, 2009). General management efforts include maintaining a high-water table to support the formation of swamps.

5.2 Geology, hydrology and pedology

The area of Groesbeek was shaped during the Saale glacial, approximately 300,000 to 130,000 years ago, creating a valley between the Nijmeegse hillside and Reichswald hillside (Staatsbosbeheer, 2009). These hillsides are glacial moraines, ranging from a height of 60-105 m (Ibid.). During the end of the last Ice Age, approximately 12,000 years ago, loess particles originating from the North Sea were deposited by winds (Ibid.). This created a landscape with fertile loess soils in the valley bottom while hills were left with a sandy loam layer. The taxonomic soil group is this region is classified as an *anthrosol* due to the historical and ongoing agricultural practices in this area. Anthrosols are able to provide the most ecosystem services compared to other soil groups (FAO, 2015). According to Kadaster (2018), the soil classification term in Dutch is a *leek-woudeerdgrond* (Figure 5.9). This classification describes a soil that is moderate to high in calcium and has a dominant sandy clay to sandy loam texture (Figure 5.11).

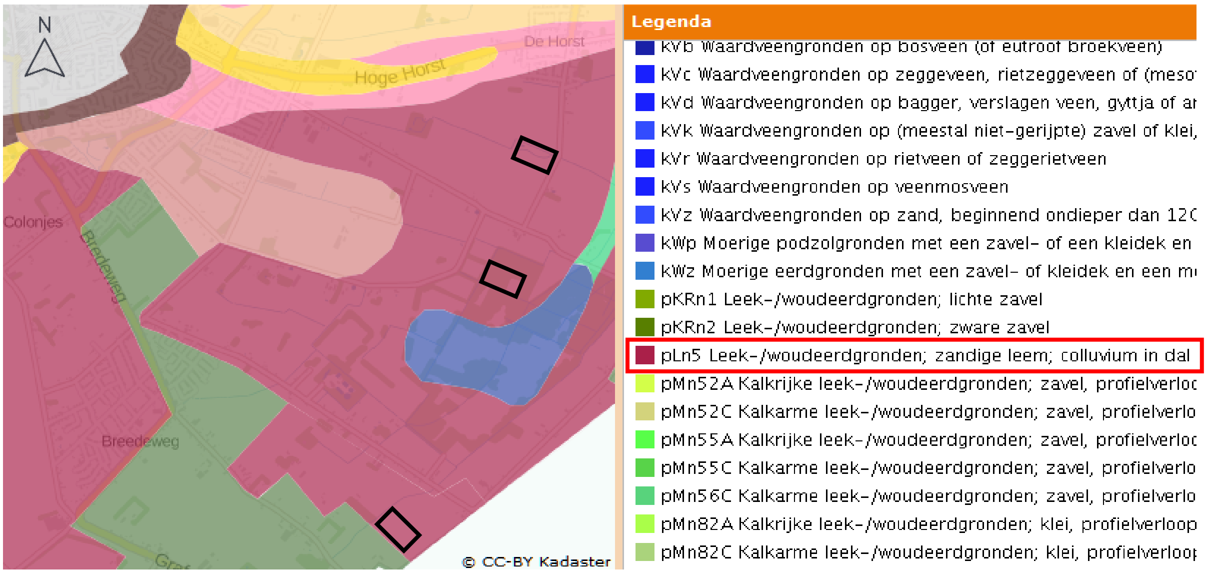


Figure 5.9: Map showing the soil types present in Groesbeek, the main soil type in research sites, boxed in black, are sandy loam soils (in Dutch: leek- woudeerdgronden). (Kadaster, 2018)

Due to the surrounding hills (Figure 5.2), the valley experiences the effect of seepage, also known as *kwel* in Dutch. As shown in Figure 5.10, this is where groundwater levels can be very high and induce muddy or water pools on the surface of the soil. Groundwater level can fluctuate between -100cm to +5cm above ground level (Biesheuvel, 2017). This is caused by infiltrated rainwater (from the hills) flowing, by gravitational forces, into lower groundwater layers. Within these layers, the vertical clay bulkheads and the impermeable clay layer prevents water to flow elsewhere, therefore, sub-surface groundwater rises. To counteract this phenomenon, the water table is regulated and lowered through drainage canals, in order to make room for agricultural land. The seepage water passes through calcareous substances, making the water slightly alkaline with a pH of 7.5 (Bakker, 2016).

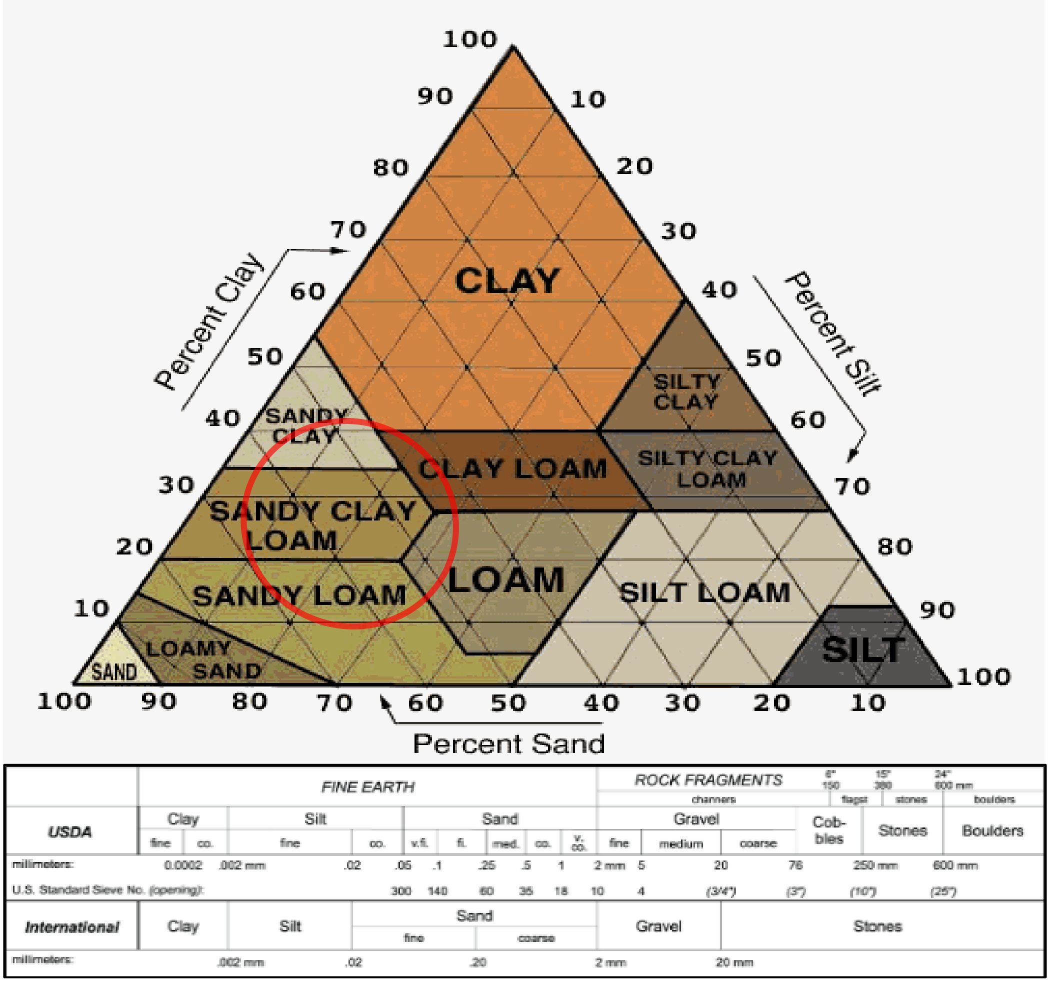


Figure 5.11: Soil texture pyramid with a red circle showing the dominant soil texture for the study area ("LAB 5 - SOIL," n.d.; USDA, n.d.)

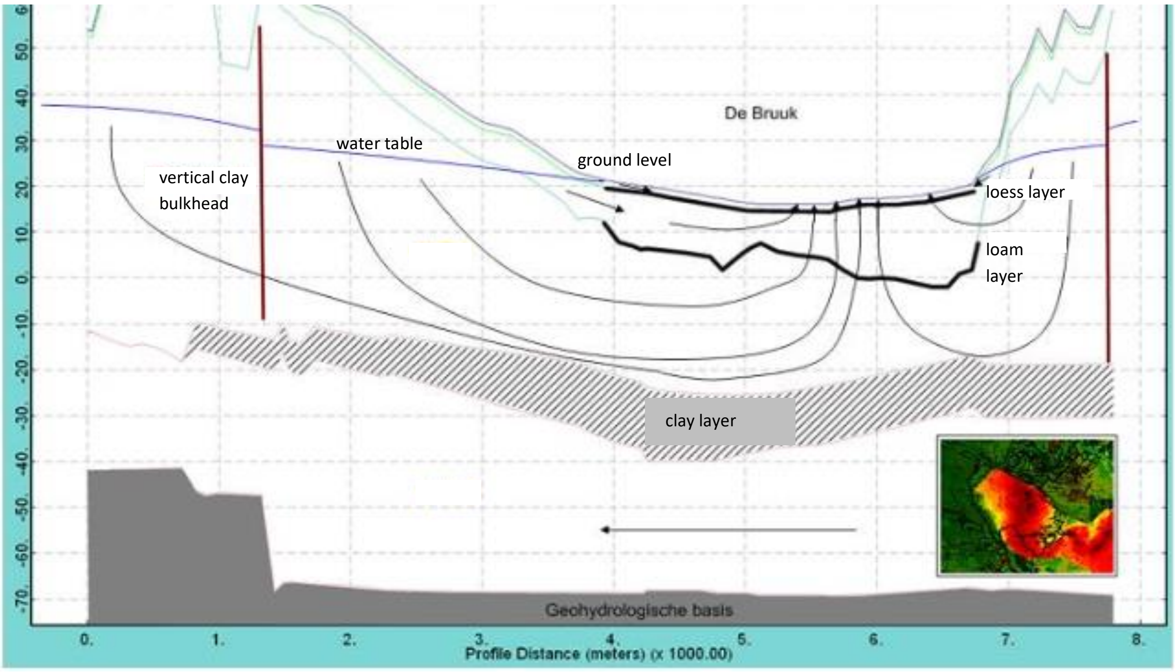


Figure 5.10: A cross-section illustrating groundwater flows for De Bruuk area and the process of seepage (adapted from DLG, 2016)

5.3 Climatic conditions

5.3.1 Temperature

Groesbeek has a temperate climate, where average temperatures can range from approximately -0.5°C to around 25°C across the year (Figure 5.12). Temperate-based perennial crops can grow in a temperature range (typically) between 3°C and 32°C (pink area in Figure 5.12) (Soilinfo-App.org, 2018). Some plants, especially woody plants, can grow outside this general range, depending on their ability to withstand varying temperatures throughout the year. Plant hardiness zone maps have been developed by the USDA in order to guide the selection of suitable plants according to their 'hardiness'; i.e. ability to withstand winter temperatures. Figure 5.13 shows that the hardiness zones for Europe and Groesbeek lies on the edge between zone 7 and 8. This means that outdoor plants can experience temperatures as cold as -17.7°C. These extreme cold temperatures are important to take into account when cultivating anything outdoors, which may become more frequent in light of climate change (EASAC, 2018).

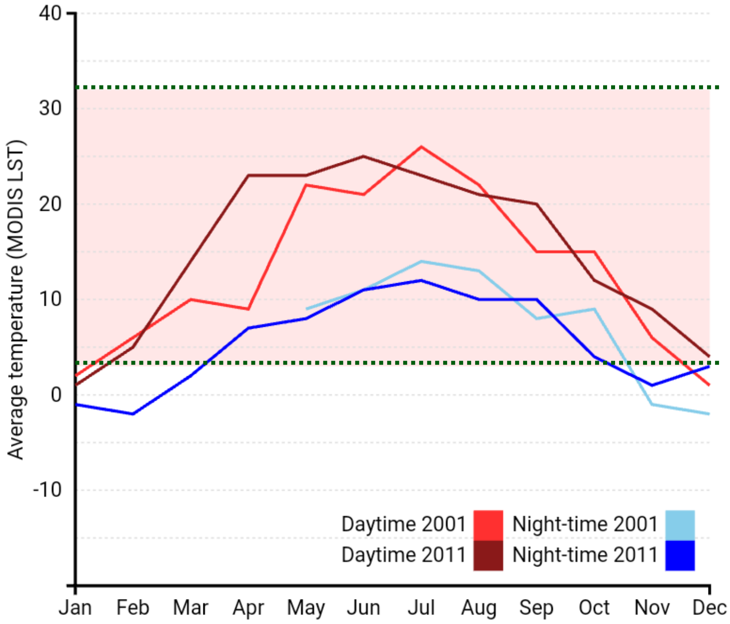


Figure 5.12: Average temperatures per month for Groesbeek with the pink area displaying temperature range most suitable for perennial crops (Soilinfo-App.org, 2018)

The average minimum and maximum temperatures during the Dutch summer time are 12.5 °C and 23.0 °C and for the winter are -0.5 °C and 5.5 °C (Figure 5.15) (KNMI, n.d.). Due to these temperate conditions, the official growing season is 183 days, beginning in April 1st and ending on September 30th (KNMI, 2015). The effects of climate change can prolong the growing season by an increase in average yearly temperatures. Besides this, more diseases and pests can spread and migrate from the warmer south to the north (van Minnen et al., 2012). An increase in average yearly temperatures can also cause higher evapotranspiration rates, leading to a higher likelihood of drought periods (PBL, 2012). KNMI (2015) and PBL (2012), predict an increasing average water shortage of 140 mm per year in the first half of this century, which can increase to an average of 220 mm of water shortage by 2050 (Figure 5.14). It has also been predicted that in extreme years, water shortage can reach up to an average of 440 mm in one year (*Van Beek et al. in* PBL, 2012). Besides a shortage of water availability for plant growth, periods of water surplus are also expected (KNMI, 2015).

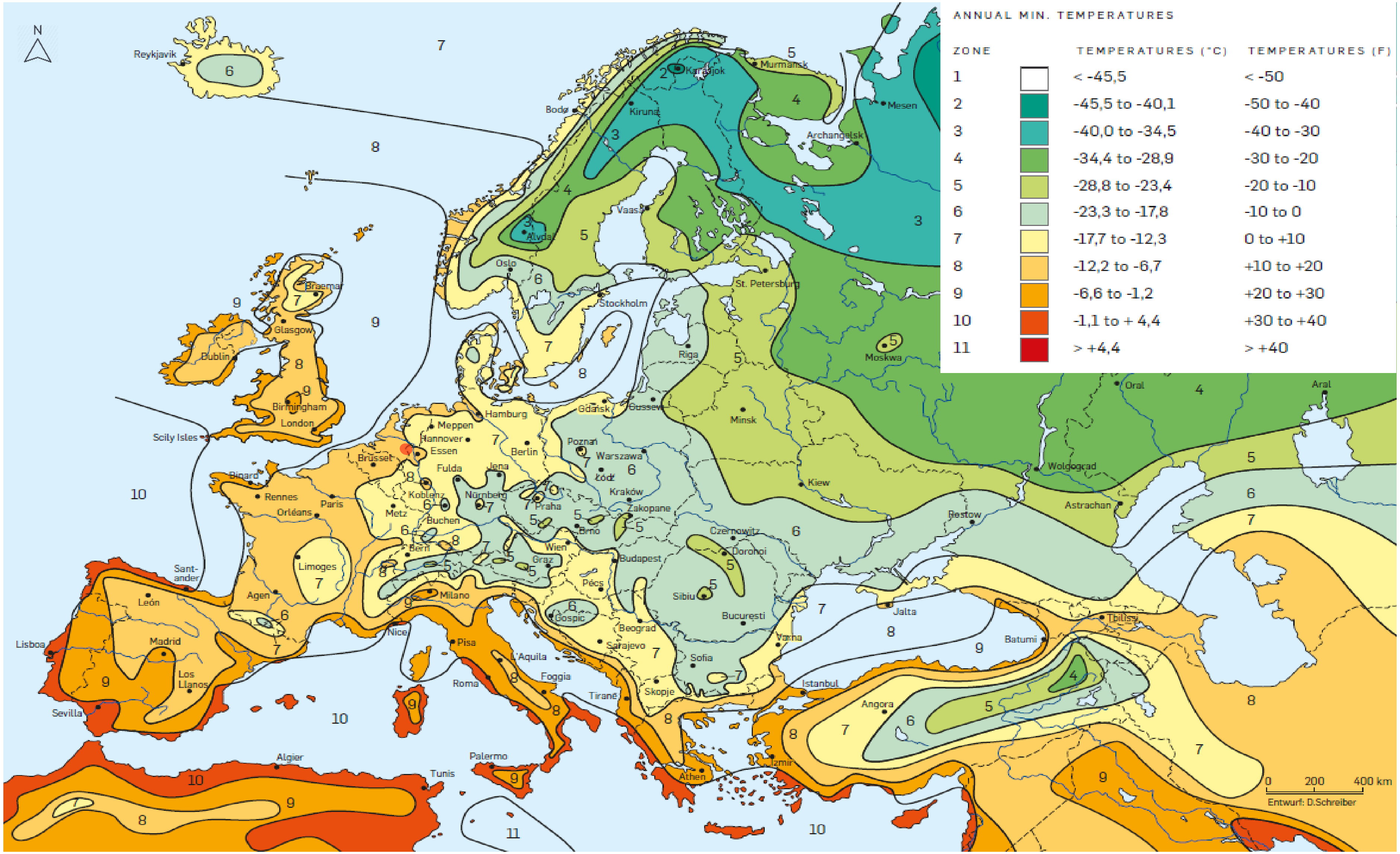


Figure 5.13: Hardiness zone map for Europe with the study area marked by a red circle (Bärtels & der Gehölze, 2014)

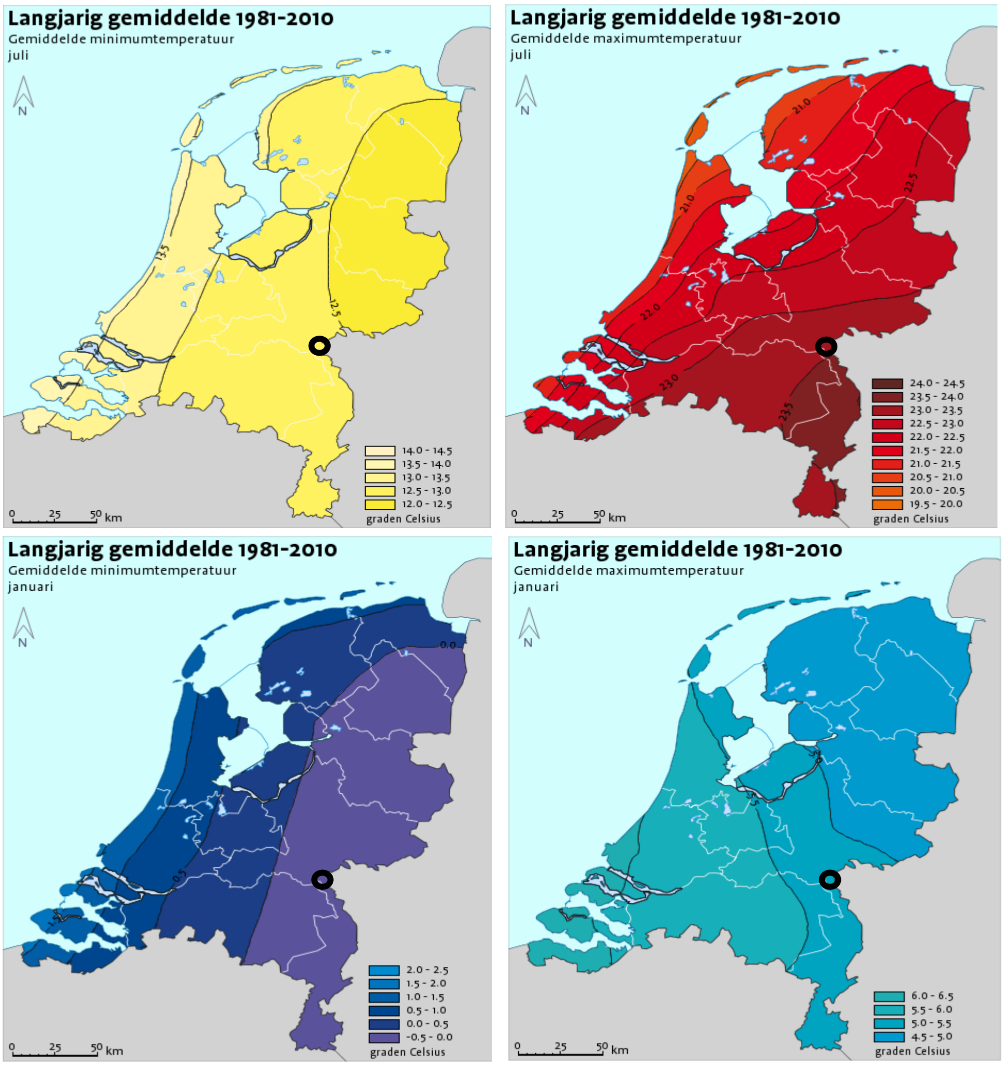


Figure 5.15: Average minimum and maximum temperatures for the month January and June, with the study area circled in black (KNMI, 2018)

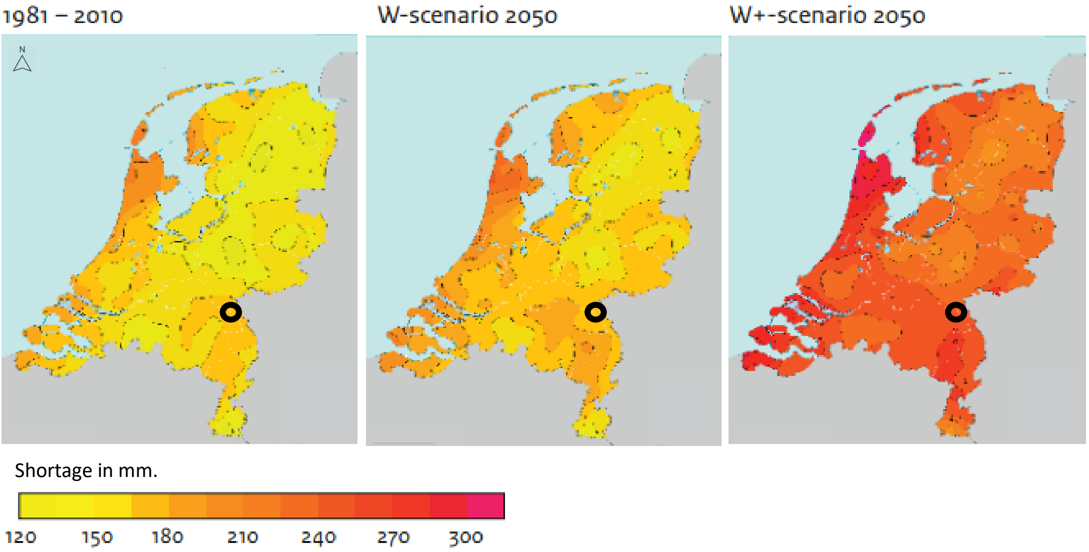


Figure 5.14: Observed and projected yearly water shortage during the growing season (April – September) for 1981-2010, the conservative 2050 projection (W- scenario 2050) and the extreme 2050 projection (W+- scenario 2050) for the Netherlands with the study area circled in black (PBL, 2012; pg. 42)

5.3.2 Rainfall

The average rainfall in the Netherlands is 50-60 mm per month (Soilinfo-App.org, 2018). However, during the growing season there can be days that are too wet (causing waterlogging) or too dry (causing periods of drought) (KNMI, 2015). On an average yearly basis, the Netherlands receives 880 mm of rainfall (Figure 5.17). Since 1910, there has been an increase in rainfall by 27%, leading to an increase in the number of extremely wet days (≥10 mm of rain) from 18 to 25 days (CBS *et al.*, 2016; Visser, 2005). Climate change projections predict a further change in the average annual rainfall with more frequent and prolonged, wetter periods (CBS *et al.*, 2016).

The local landscape of Groesbeek, which is slightly elevated and surrounded by lateral moraines, can enforce or subdue the amount of localised rainfall reaching the Groesbeek valley. According to the nearest KNMI weather station in Heumen (within 9 km west of De Bruuk), the average yearly rainfall is approximately 856 mm (2007 - 2017) (Biesheuvel, 2017). This is slightly less than the national average. There is more often a water surplus than shortage in Groesbeek, which is shown in Figure 5.16 (red bars), where the average amount of water available ranges between 35 mm and 105 mm throughout the year. The impacts of climate change may cause greater variations in the overall water availability in Groesbeek due to a greater unpredictability in weather events (van Minnen et al., 2012).

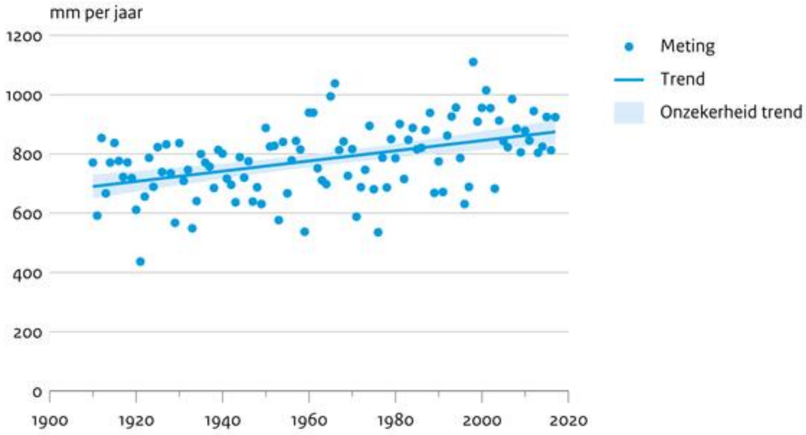


Figure 5.17: A graph illustrating the average rainfall measured per year, from 1901 till 2015 for the Netherlands (CBS et al., 2016)

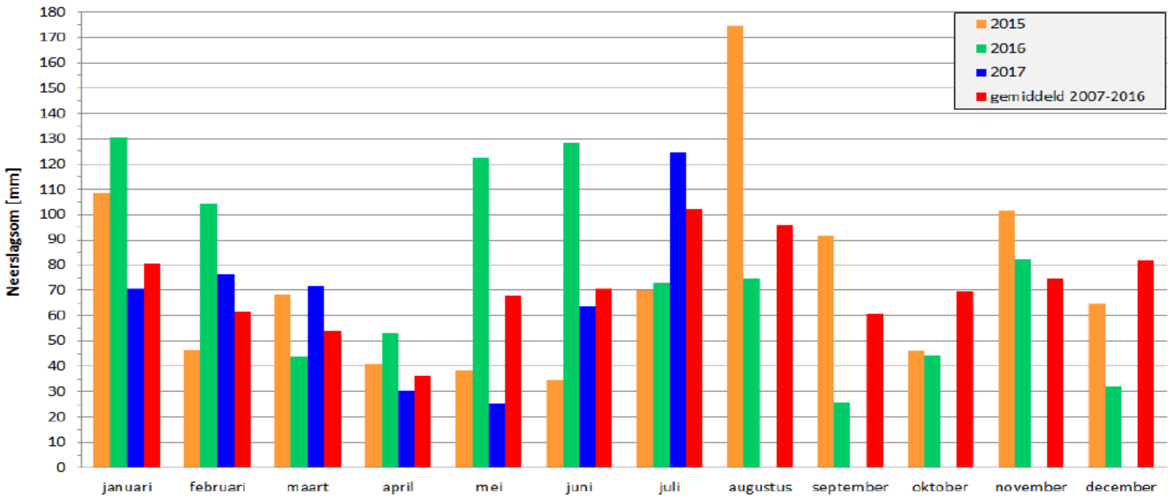


Figure 5.16: A graph showing the water balance (rainfall minus evaporation) for the region of Groesbeek, for the years 2015 (orange), 2016 (green), 2017 (blue) and the average between 2007 and 2016 (Biesheuvel, 2017)

5.3.3 Sunlight

Sunlight is also a determining factor for any agroecosystem. Compared to the southern hemisphere, the northern hemisphere typically receives less sunlight (due to the curvature of the Earth in relation to the angle at which sun rays hit the Earths' surface area). The average annual sunlight in the Netherlands is 1500 hours (Figure 5.18 & Figure 5.19). The amount of sunlight hours, in combination with other (pedo-) climatic factors such as temperature, rainfall and geography, shapes development of forest biomes (Figure 5.20). Temperate forest ecosystems typically flourish within the northern hemisphere.

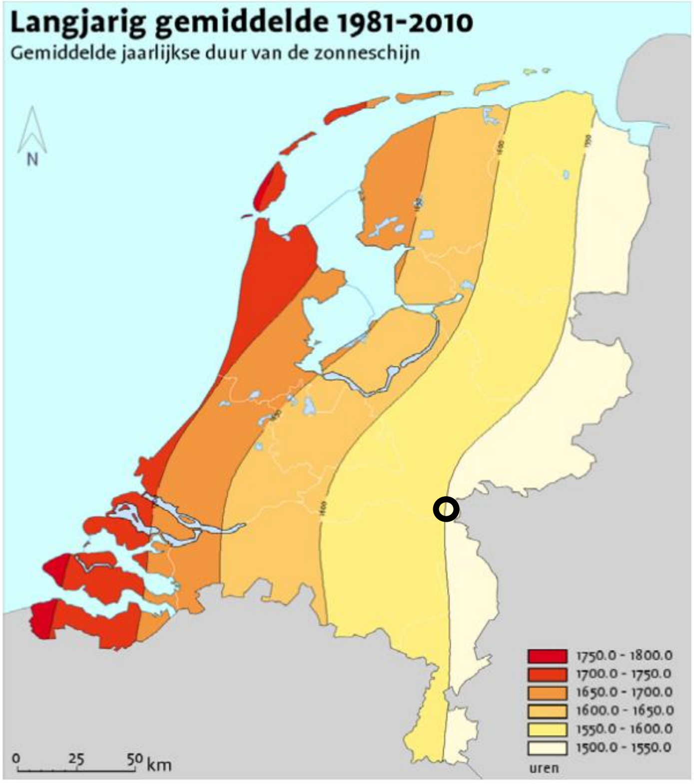


Figure 5.18: Yearly average amount of sunlight hours from 1981 – 2010 (Sluiter, 2012)

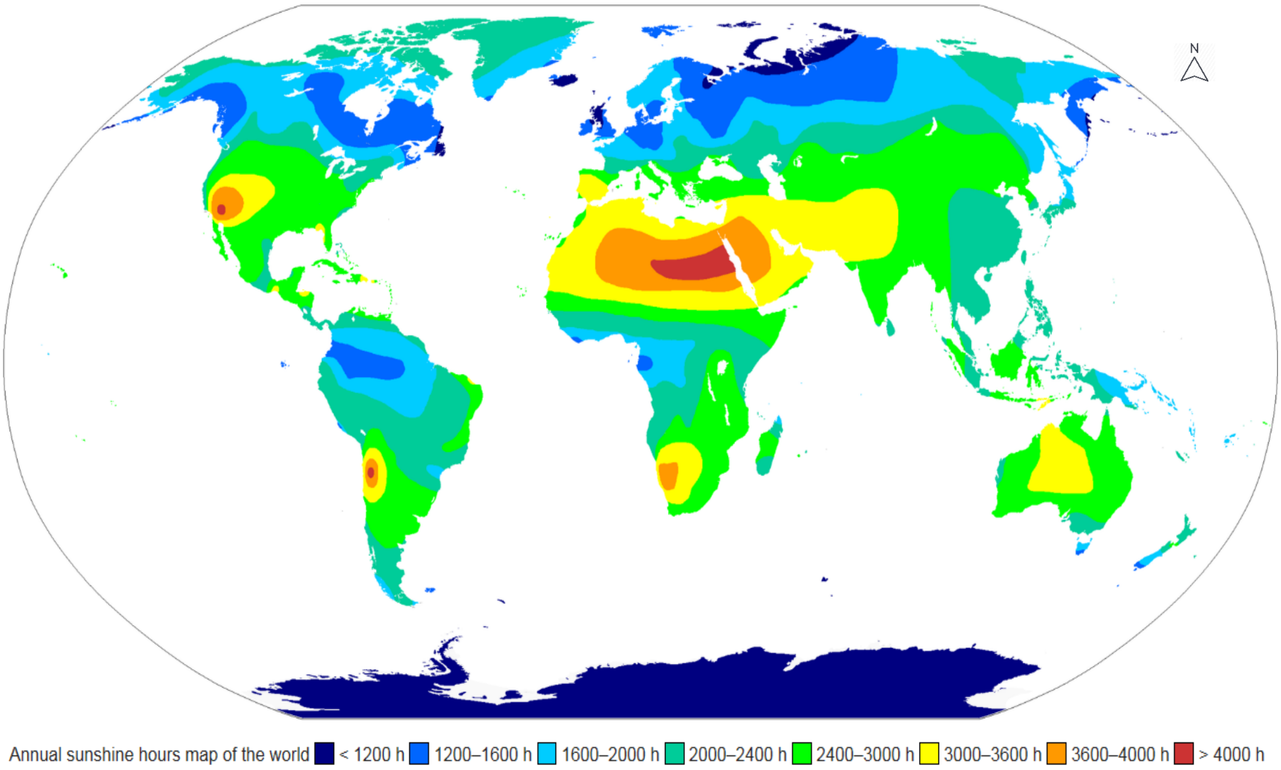
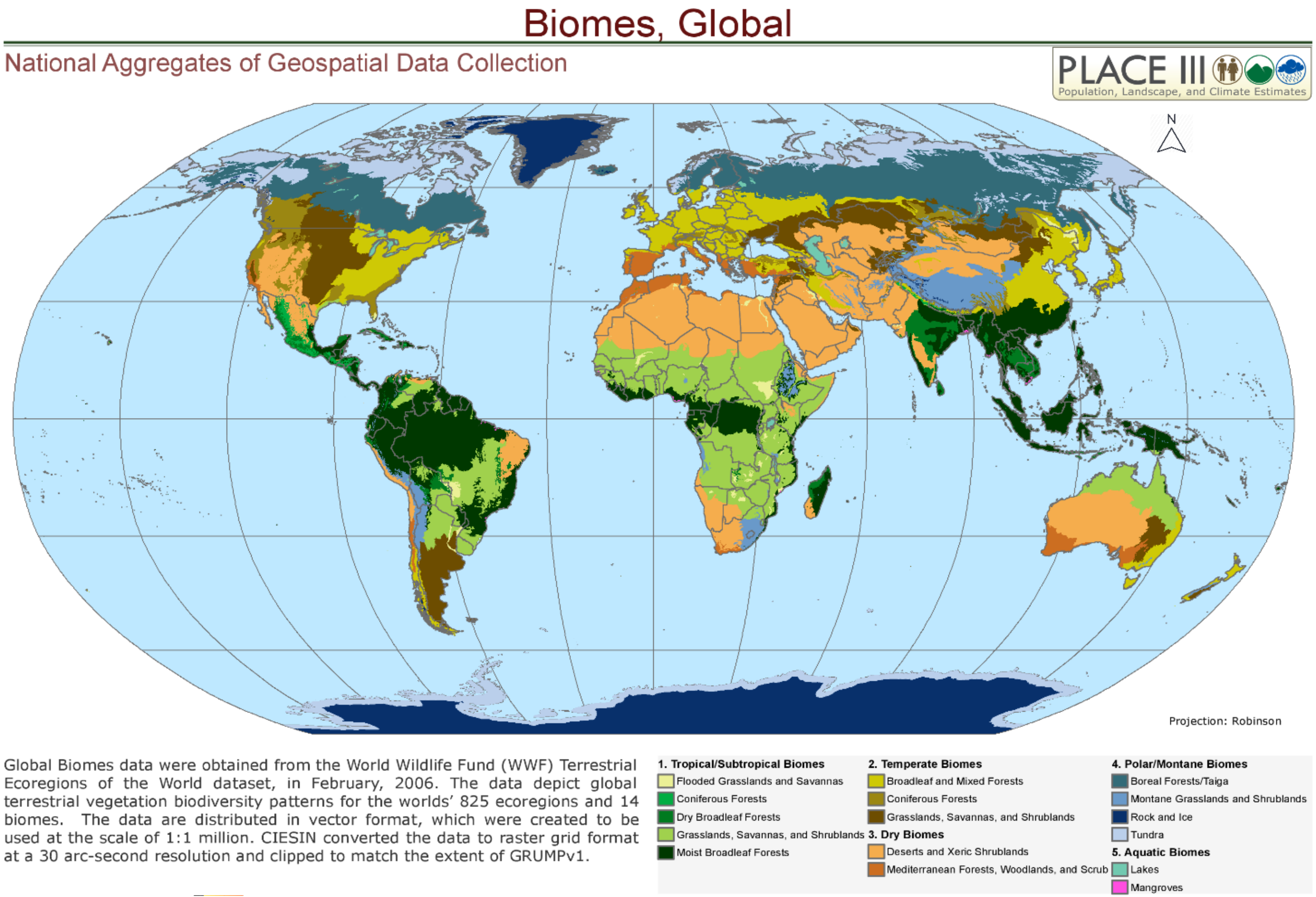


Figure 5.19: A world map showing annual sunlight hours (Landsberg, H. E. in Pinna, M., 1978)



Biomes, Global

National Aggregates of Geospatial Data Collection

Global Biomes data were obtained from the World Wildlife Fund (WWF) Terrestrial Ecoregions of the World dataset, in February, 2006. The data depict global terrestrial vegetation biodiversity patterns for the worlds' 825 ecoregions and 14 biomes. The data are distributed in vector format, which were created to be used at the scale of 1:1 million. CIESIN converted the data to raster grid format at a 30 arc-second resolution and clipped to match the extent of GRUMPv1.

Figure 5.20: A world map showing various ecological biomes; tropical/subtropical, temperate, dry, polar/montane and aquatic biomes (CIESIN, 2012).

5.3.4 Climate Change

Climate change is predicted to cause more extreme weather conditions such as intense rainfall, heatwaves, large fluctuations in temperatures, etc. (PBL, 2012; van Minnen, Ligtvoet, & PBL, 2012; Visser, 2005). Table 5.1 gives an overview of such potential climate change effects, with a focus on Dutch agriculture. Mitigating and adapting to such climate change effects requires agricultural systems that sequester more greenhouse gases than the system requires, is more resilient to extreme weather events and enhances biodiversity (Abbas et al., 2017; Burgess et al., 2015; FAO, 2014).

Table 5.1: The potential effects of climate change on agriculture in the Netherlands (Blom et al., 2008 in van Minnen et al., 2012, p. 79)

Climate factor		**Effects**	**Positive/ negative**
Change in temperature patterns	*Rising temperatures*	Increase in biomass production	+
		Increase in disease and plagues	-
		Arrival of new plant species, including weeds	?
		Temporal difference between plant development and pollination by insects	-
		A decrease in energy costs for greenhouse horticulture.	+
		A higher energy cost for cattle production due to the need for barns to be kept cool.	-
		More difficulty in storing potatoes	-
		Longer growing season, greater harvest	+
	More frequent heatwaves	Damage to crops or even crop losses	-
	Late frost	Death by frost to flower(bulb)s	-
Change in rainfall patterns	*Wetter periods*	Crop losses due to more fungi and insect plagues	-
		Seeding and harvest issues	-
		Leaching/loss of nutrients (EU Water Framework Directive)	-
		Lower quality of crops due to water saturated soils	-
	More extreme occurrence of rain- and hail storms	Crops losses due to extreme rain and/or hail	-
	Drought	Losses in production due to (extreme) drought	-
		Losses in production and lowering of quality due to salinization	-
		Quality improvement	?
Other climate variables	*Humidity*	More fungi	-
	Change in wind patterns	More insects	-
Increase in CO2		Increase in production	+
Sea level rise and soil subsidence	*Flooding*	See ‘wetter periods/humidity’	-
	Increase in salinization	Losses in production for some crops and opportunities for other crops	-/+

6 Results

6.1 Topsoil and subsoil results

Eleven soil indicators were chosen to assess soil health at each land management system. These indicators were a mix of physical, chemical and biological indicators. Statistically significant differences were found in all three soil indicator types. For the topsoil layer, results for seven soil indicators showed statistically significant differences (p-value=0.05), these were: bulk density, soil moisture, pH, organic matter, organic carbon and earthworm abundance. In the subsoil layer, four soil indicators showed statistically significant differences, namely in: bulk density, soil moisture, pH and soil resistance. All results were summarized in Table 6.1 and followed a colour-coded results scheme; where green represented results within the *optimum* range, light-green were results that fell within the *tolerable* range and red represented *sub-optimal* results which crossed a threshold. In both the topsoil and subsoil layers, site FF (food forest Ketelbroek) had the highest account of results in the *optimum* and *tolerable* range compared to CF (conventional farm). An overview of these results is also visualized in Figure 6.1 and 6.2 (Appendix 11.6.17). These radar graphs show all sites to have scored well in the topsoil (closest to 1) with slight differences in organic matter, organic carbon and earthworm abundance between FF and CF. In the subsoil, there were greater differences in bulk density and soil resistance between sites FF and CF (Figure 6.2).

Table 6.1 A summary of average topsoil and subsoil results for all soil indicators.

		Topsoil (0-5cm)			Subsoil (30-35cm)			
Soil indicator type		**CF**	**FF**	**DB**	**CF**	**FF**	**DB**	**Soil indicator**
Physical	*Soil texture*	(Sandy) loam	Loam	Light clay	(Sandy) loam	(Sandy) loam	Heavy clay	*Soil texture*
	Soil colour (Munsell)	10Y 4/3	2.5Y 3/2	10Y 2/1	10Y 4/3	10Y 4/3	10Y 4/2	*Soil colour (Munsell)*
	Soil temperature (°C)	15.84	9.86	9.04	10.74	8.12	8.42	*Soil temperature (°C)*
	Aggregate stability	**0.76**	**0.74**	0.67	**0.71**	**0.65**	0.53	*Aggregate stability*
	Bulk density (g/cm^3)**	**1.22_{DB}**	**1.12_{DB}**	$0.67_{CF, FF}$	**1.55**	**1.30**	1.13	Bulk density (g/cm^3)***
	Soil moisture (%)***	**26.36**	**39.37**	69.2	**21.61**	**29.01**	50.04	Soil moisture (%)***
	Soil resistance (kPa) *** [0-30cm]	**131.20**	**105.90**	46.23	**390.20**	**271.40**	130.20	Soil resistance (kPa) *** [30-80cm]
Chemical	pH***	**7.27**	**6.02**	4.15	**$7.05_{DB, FF}$**	**5.83_{CF}**	6.10_{CF}	pH**
	Organic matter content (%)**	**3.58_{DB}**	**6.70_{DB}**	$19.75_{CF, FF}$	**5.14**	**4.12**	6.76	*Organic matter content (%)*
	Organic carbon (%)**	**1.79_{DB}**	**3.35_{DB}**	$9.88_{CF, FF}$	**2.57**	**2.06**	3.38	*Organic carbon (%)*
Biological	Earthworm abundance (per m^2)***	**236**	**584**	261	**Identical to topsoil**	**Identical to topsoil**	Identical to topsoil	Earthworm abundance (per m^2)***

Legend

CF : Conventional field
DB : forest nature reserve "De Bruuk"
FF : Food forest Ketelbroek
*** Significantly different between all sites (p-value=0.05)
** Significantly different in relation to subscripted site(s) $_{CF, DB, FF}$ (p-value=0.05)

Optimum
Tolerable
Sub-optimal

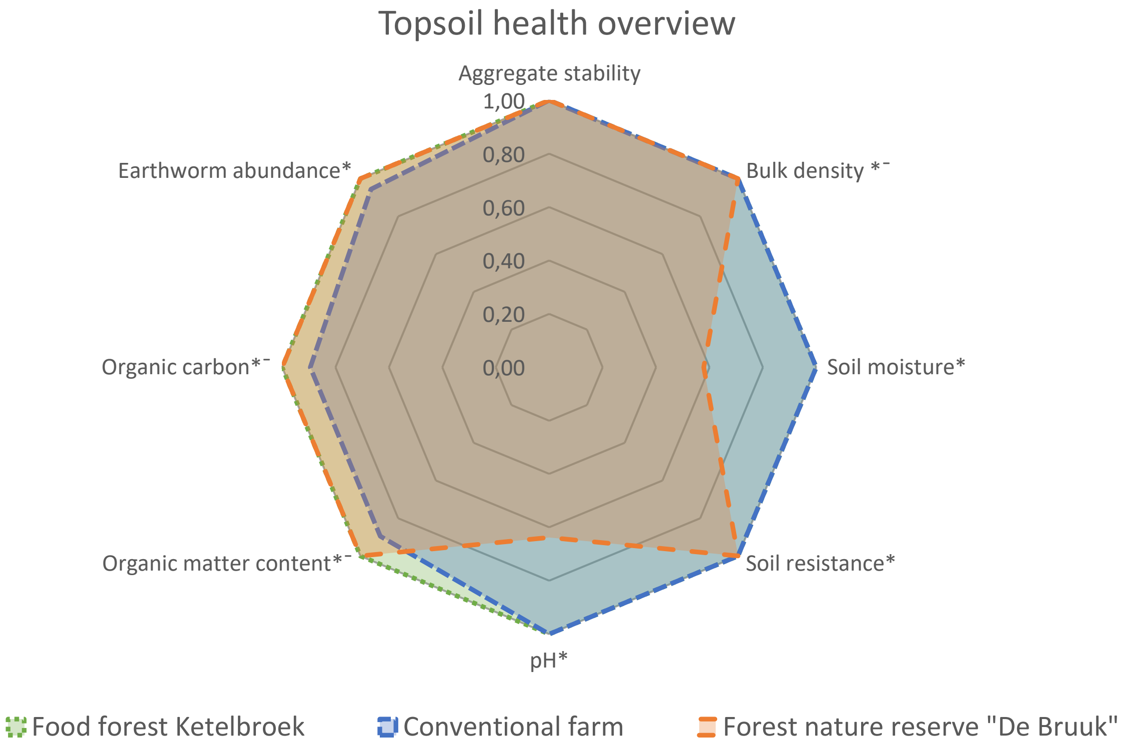


Figure 6.1: A radar graph providing a visual overview for soil health (0=sub-optimal, 1=optimal) in the topsoil (0-5cm depth) for each study site according to the following soil indicators: aggregate stability, bulk density, soil moisture, soil compaction, pH, organic matter, organic carbon and earthworm abundance. * denotes results being statistically significant different between each site and *- denotes statistically significant different between some but not all sites.

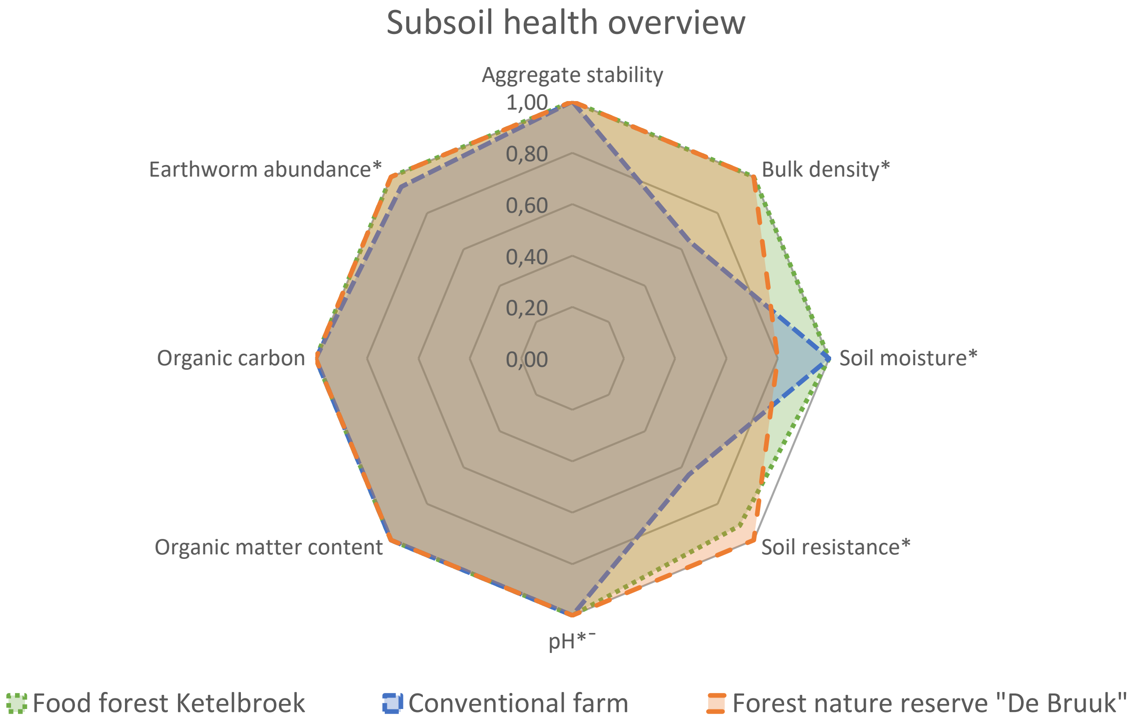


Figure 6.2: A radar graph providing a visual overview for soil health (0=sub-optimal, 1=optimal) in the subsoil (30-35cm depth) for each study site according to the following soil indicators: aggregate stability, bulk density, soil moisture, soil compaction, pH, organic matter, organic carbon and earthworm abundance. * denotes results being statistically significant different between each site and *- denotes statistically significant different between some but not all sites.

CF: Conventional Farm
FF: Food Forest Ketelbroek
DB: Forest nature reserve “De Bruuk”

6.1.1 Physical soil properties

The dominant soil texture found was (sandy) loam for both CF and FF in the top- and subsoil. At DB, the soil contained more clay; with a light clay texture in the topsoil and heavy clay in the subsoil. The colour of the soils all fell within the hue of 10YR, ranging between colour value 2 to 4 with chrome colours 1 to 3. The exception lies for the topsoil of FF, which had a very dark greyish brown colour in the topsoil (2.5Y 3/2) and a brown soil colour (10Y 4.3) in the subsoil layer. In the case of CF, soil colour remained homogeneously brown (10Y 4/3) between the top and subsoil layers. As for DB, the topsoil was black (10Y 2/1) and the subsoil was predominantly dark grey (10Y 4/2). Soil temperatures varied between 8 and 16°C across sites. These results are the averages for each site, for detailed results per sample plot, see Appendix 11.6.1, 11.6.7 & 11.6.8.

The aggregate stability index reflects the stability of the soil and indicates its ability to resist disruptive forces such as water-induced soil erosion. A relatively stable soil is one which has a stability index of 0.5 or higher (Table 4.3). Results indicated all sites as relatively stable. CF had the highest index value across both soil layers with 0.76 in the top- and 0.71 in the subsoil. This is followed by FF with 0.74 in the top- and 0.65 in the subsoil. DB scored 0.67 in the top- and 0.53 in the subsoil. These results were not statistically significant different from one another (Figure 6.3-top figures, Appendix 11.6.2 & 11.6.3).

Soil bulk density reflects how (un)compacted soil is. It is intertwined with many inherent soil processes such as organic matter development, soil mineral composition and soil arrangements (USDA, 1998). All sites showed relatively uncompacted soils (Figure 6.3-middle figures). All results, apart from the subsoil CF result, remain below the threshold of 1.32 g/cm³. All topsoil results fell below the threshold, with soil results for DB (0.67 g/cm³) being the least dense of all, followed by FF (1.12 g/cm³) and lastly by CF (1.22 g/cm³) (Figure 6.3-middle figures). Topsoil results for DB in relation to CF and FF showed statistically significant differences yet results between FF and CF were not significantly different (Appendix 11.6.5). All subsoil results also fell below the threshold, with DB having the lowest density (1.13 g/cm³), followed by FF (1.30 g/cm³) and then CF (1.55 g/cm³). These subsoil results were statistically significant different between each site.

Soil moisture is a vital medium for transferring nutrients and minerals. Soil moisture varied across all sites. Results for CF and FF were within the ideal soil moisture range of 20-40% for both the top- and subsoil. In the topsoil, FF had a higher moisture content than CF; 39.37% and 26.36% respectively. In the subsoil, this was 29.01% and 21.61% respectively. Moisture content came out higher in the subsoil at FF than the topsoil at CF. Overall, DB had a higher moisture content in the top-, 69.20%, and subsoil, 50.04%. All data were significantly different between sites across both soil layers (Appendix 11.6.6).

In addition to bulk density measurements, soil resistance was measured to investigate soil compaction at greater depths (0-80cm). Figure 6.4 indicated most measurements to have averaged below the threshold of 250 kPa, apart from subsoil results at CF and FF. Across both soil layers, DB measured with the lowest average of 46.23 kPa in the top- and 130.20 kPa in the subsoil. This is followed by FF with 105.90 kPa in the top- and 271.4 kPa in the subsoil, the latter surpassing the threshold. CF remained below the threshold with 131.20 kPa in the topsoil yet surpassed the threshold in the subsoil with 390.20 kPa. The scatterplot Figure 6.4) showed at which depth compaction occurred. Measured soil resistance (per plot) at FF indicated signs of compacted soil at depths from 20cm onwards and clustered around a depth of 44cm; where the trend line intercepts with the threshold. For DB, major signs of compacted soil were from a depth of 70cm onwards. For CF, indications of compacted soils started at a depth of 20cm and clustered around 46cm. Overall, CF measurements indicated a higher presence of compacted soils in the subsoil layers compared to FF and DB. All data were significantly different between sites across both soil layers (Appendix 11.6.10).

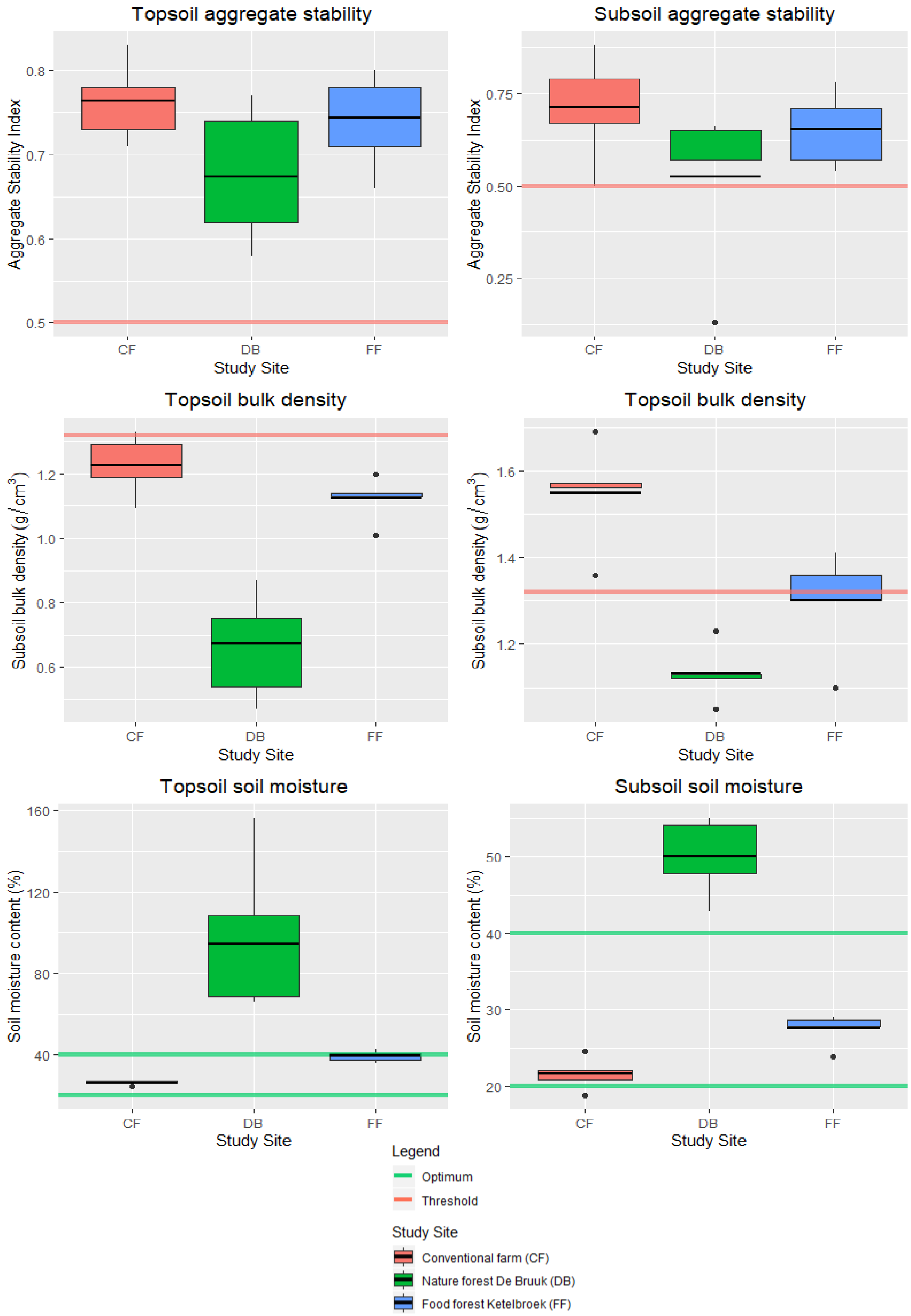


Figure 6.3: Boxplot results for physical soil properties; aggregate stability, bulk density and soil moisture content for topsoil and subsoil layers at each study site: conventional farm (CF), forest nature reserve "De Bruuk" (DB) and food forest Ketelbroek (FF).

CF: Conventional Farm
FF: Food Forest Ketelbroek
DB: Forest nature reserve "De Bruuk"

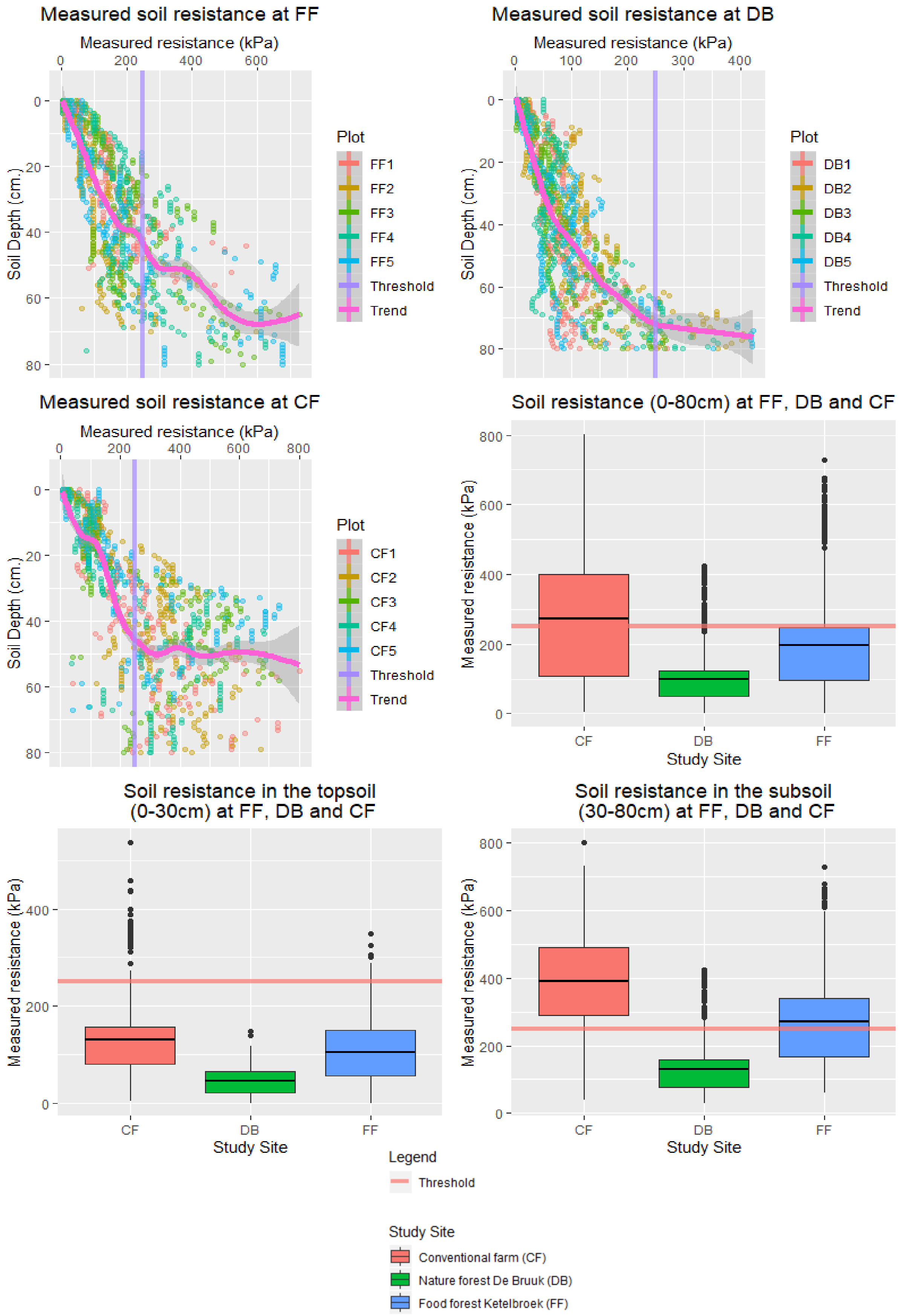


Figure 6.4: Scatter plots and boxplots showing measured soil resistance (kPa) across soil depths of 0 to 80cm at each study site: conventional farm (CF), forest nature reserve "De Bruuk" (DB) and food forest Ketelbroek (FF).

CF: Conventional Farm
FF: Food Forest Ketelbroek
DB: Forest nature reserve "De Bruuk"

6.1.2 Chemical soil properties

The acidity of the soil (pH) influences soil processes and plant nutrient availability. Optimum pH levels for optimal growing conditions and soil functioning range from 5.5 to 7 for loess soils (Table 4.3). Site FF was within the optimum range for both the top- and subsoil (Table 6.1). In the topsoil, the pH level at site CF surpassed the upper threshold and DB remained below the lower threshold (Figure 6.5-top figures). Statistically significant differences existed between each site for the topsoil layer (Appendix 11.6.12). CF remained outside the optimum range throughout the soil layers. In the subsoil, pH at DB was within the optimum range. There was only a statistically significant difference for CF in relation to DB and FF. There was no significant difference between DB and FF.

Organic matter plays a key role in supporting soil processes: reinforcing soil structure and supplying nutrients to plants and soil fauna. Across all soil layers, all sites remained above the optimal threshold of 4% (Table 4.3), except for CF in the topsoil (Figure 6.5). The forest DB had the highest amount of SOM in both the top- and subsoil with 19.75% and 6.76% respectively (Table 6.1). This was followed by FF with 6.70% in the topsoil and 4.12% in the subsoil. CF had the lowest measured SOM value in the topsoil with 3.58% (below the medium range/lower limit) and had the second highest SOM value in the subsoil with 5.14%. For the topsoil, DB results showed a statistically significant difference in relation to CF and FF (Appendix 11.6.14). There was no statistically significant difference between CF and FF. For the subsoil, no significant differences existed between sites.

Organic carbon is an inherent component of soil organic matter. Besides the important function of organic matter, soil carbon acts as a temporary pool for carbon. Carbon can accumulate in the soil and subsequently be used and recycled by soil- and plant life. During this process, carbon can oxidize into the atmosphere. The forest DB had the highest SOC in both the topsoil and subsoil, 9.88% and 3.38% respectively (Table 6.1). In the topsoil, FF has the second highest SOC with 3.36%, followed by CF with 1.78%. For the topsoil, DB had a statistically significant difference in relation to CF and FF (Appendix 11.6.14). No significant difference exists between CF and FF. In the subsoil, CF has the second highest SOC with 2.54% and then FF with 2.04%. No statistically significant differences were found between sites for the subsoil.

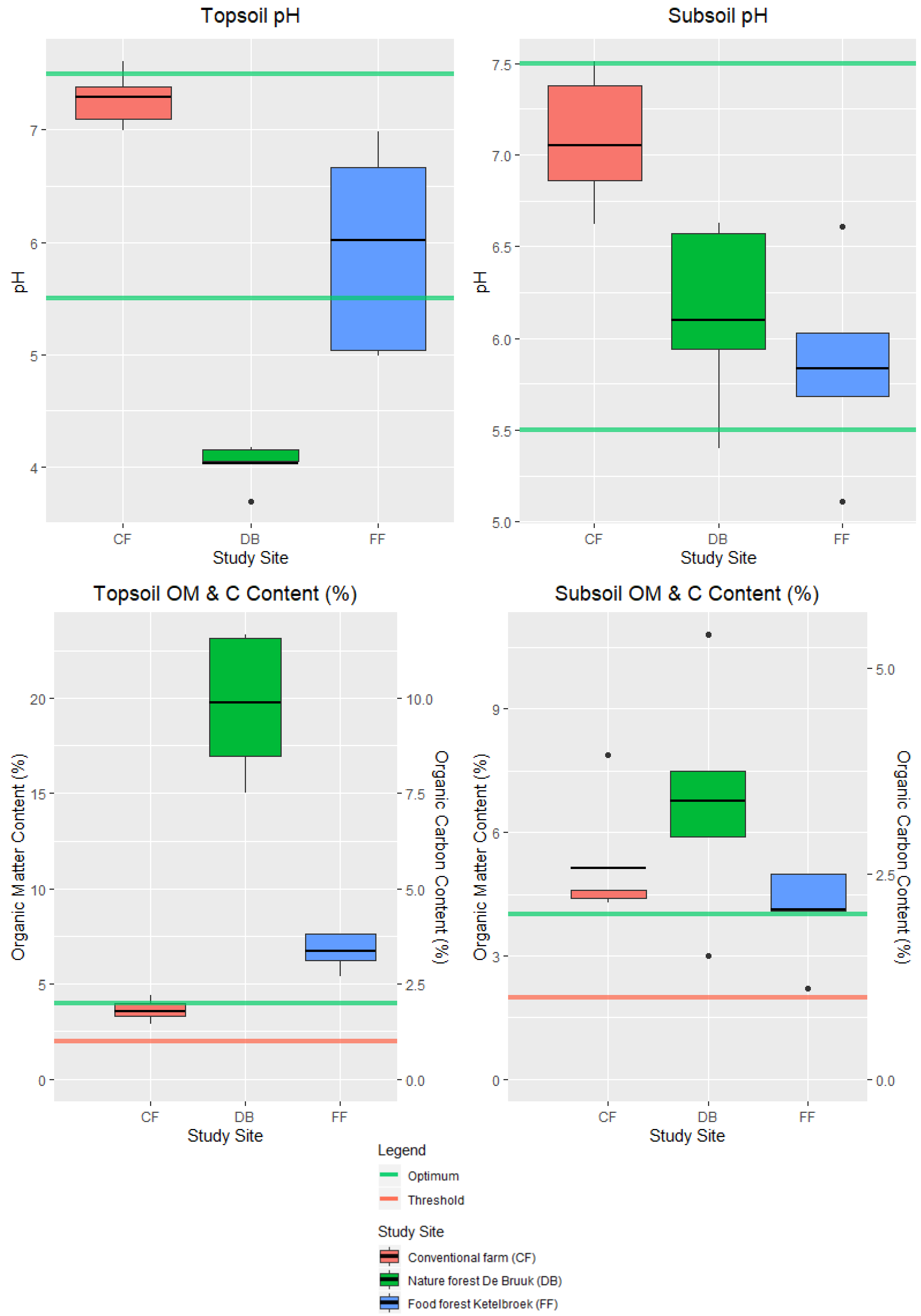


Figure 6.5: Boxplot results for chemical soil properties; pH, organic matter content and organic carbon content at each study site: conventional farm (CF), forest nature reserve "De Bruuk" (DB) and food forest Ketelbroek (FF).

CF: Conventional Farm
FF: Food Forest Ketelbroek
DB: Forest nature reserve “De Bruuk”

6.1.3 Biological soil properties

Earthworm abundance and species type is a typical indicator used to assess the functioning of the soil. They play a crucial role in aggregating soil (by building organic matter), increasing infiltration and stimulating microbial activity (Edwards, 2019). The minimal threshold for the number of earthworms per m^2 is 250 (Table 4.3). Figure 6.6 showed that FF had the highest number of earthworms with an average count of 584. FF is the only site to have averaged above the optimal minimum threshold (Table 6.1). Site DB had the second highest earthworm abundance with 261, followed by an average count of 236 at site CF. The result for FF was statistically significant different from that of CF (Appendix 11.6.15). There was no statistically significant difference between CF and DB or between FF and DB.

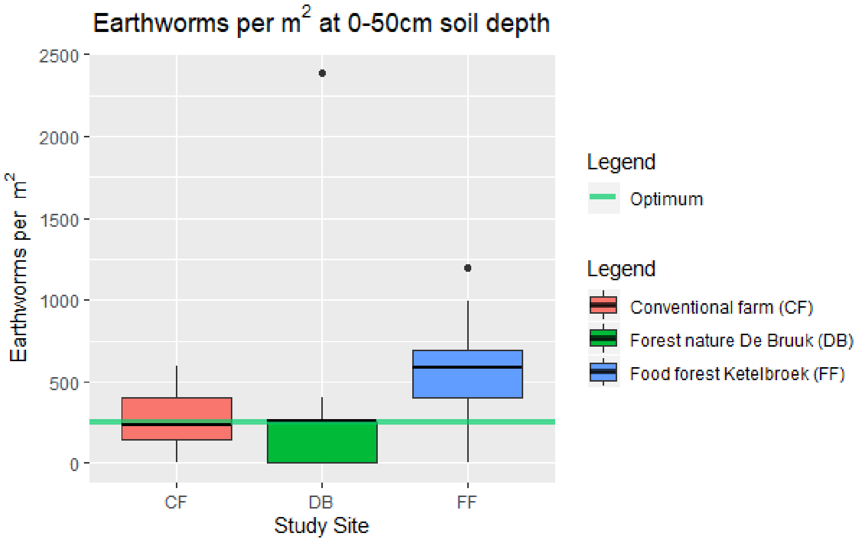


Figure 6.6: A boxplot for earthworm abundance results at each study site: conventional farm (CF), forest nature reserve "De Bruuk" (DB) and food forest Ketelbroek (FF) (data adopted and adapted from Baas, 2018).

Figure 6.7 illustrates the percentages of species types found per site. More endogeic species, such as *Aporrectodea rosea*, were found at CF than at DB or FF. DB and FF appear to have had similar ratios between epigeic and endogeic earthworm types. Epigeic species primarily feed on leaf litter and live in the upper soil layers. Endogeic species live and feed in the soil, often in deeper layers. Species such as *Aporrectodea caliginosa* (endogeic) and *Lumbricus rubellus* (epigeic) were found at all sites. At site FF, *Lumbricus castaneus* (epigeic) was also identified. At DB, two rare endogeic species were identified: *Eiseniella tetraedra* and *Octolasion cyaneum*, which favour wet soil conditions (Natural England, 2014).

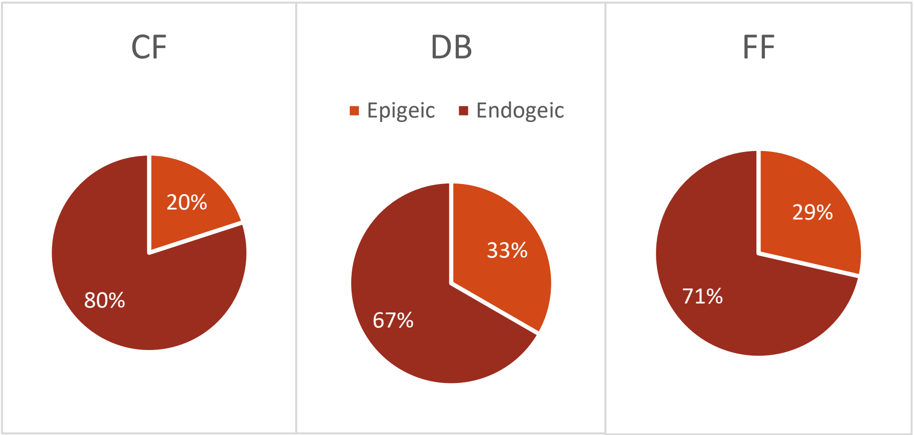


Figure 6.7: Earthworm species type at each study site: conventional farm (CF), forest nature reserve "De Bruuk" (DB) and food forest Ketelbroek (FF) (data adopted and adapted from Baas, 2018).

CF: Conventional Farm
FF: Food Forest Ketelbroek
DB: Forest nature reserve "De Bruuk"

6.1.4 Temporal trends

Organic matter and carbon content

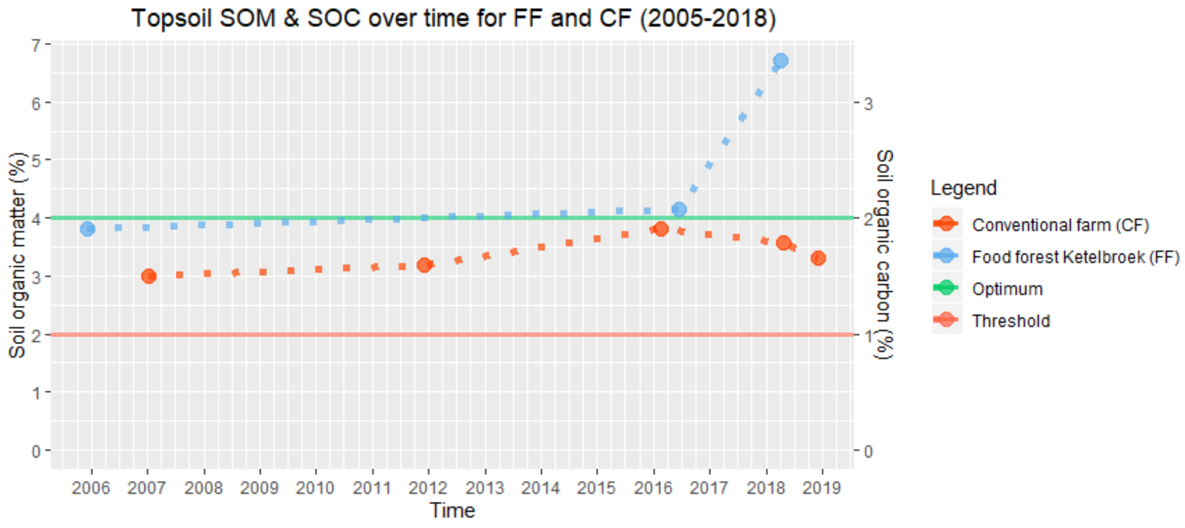


Figure 6.8: SOM and SOC measurements over time (2005 - 2018) for food forest Ketelbroek (FF) and the conventional farm (CF)

Based on historical data, SOM and SOC trends were observed between 2005 and 2018 (Appendix 11.6.16). Figure 6.8 showed how in 2005 (December), SOM and SOC at FF was at 3.8% and 1.9% respectively. This increased to 6.71% (for SOM) and 3.35% (for SOC) in 2018 (April). This is an increase of almost 3% (for SOM) and 1.5% (for SOC) over a period of approximately 12 years. At CF, SOM levels increased slightly from 3% 2007 (January) to 3.57% in 2018 (April). This is an increase of 0.57% over a period of 11 years. SOM and SOC levels for CF remain slightly under the optimal minimum, whereas levels at FF climbed into the optimal range around 2016.

7 Discussion

This chapter provides a discussion of the results, methods and concepts used in this study. With kind permission, relevant soil data is also referenced from Baas (2018) and Westhoff (2019) to further enrich this soil assessment study.

7.1 Soil data

This sub-chapter discusses the findings of this study per soil indicator type; physical, chemical and biological. The limitations of these methods and ways of improvement are also discussed.

7.1.1 Physical soil properties

Soil texture and type

As mentioned in Chapter 4.2, soil texture is an important soil property with inherent effects on soil processes. Soil texture results varied between and within each site, such as silty-, sandy- and clay loam within FF (Appendix 11.6.1). Classifying soil textures for loamy soils was challenging as the composition of such a soil can be a mixture of sand, silt and clay. Distinguishing soil texture between silt and clay was difficult and may have led to an overestimation of silty or clayey loam soils. Therefore, the generalization of soil texture per field remains an approximation.

Through a cross-comparison with Baas' (2018) soil study results, Baas indicated all sites to be more sandy, especially for DB. In this study, soil texture results at DB were generally classified as more clayey soils than sandy (loam). Through a literature study on the soils at DB, it was found that complex clay and sand layers were formed during previous glacial activity (DLG, 2016). It is therefore possible that sandy- and clay loam soils are present at DB and for the greater region of the study area (Groesbeek).

These sample results showed how heterogeneous soil textures were within and between sampling sites. Furthermore, this also reflects the complexity of making any soil assessment with a benchmark that is dependent on soil texture (such as bulk density, organic matter and water holding capacity). To take such inherent variation into account, benchmarks can be set with wider ranges or provide thresholds/optimum ranges per soil texture. More accurate methods for a soil texture analysis include particle size analysis (ISRIC, 2002) or rapid texture analysis (Moebius-Clune et al., 2017).

Much more soil information can also be consulted from Baas' soil study. In particular, soil profiles taken at each site indicate large differences in soil formation (Figure 7.1). The soil profile at DB is largely dark brown with large aggregated clumps. Signs of aggregation indicate a positive soil structure formation process (with the exception for heavy clay soils). The brown colouration of the soil indicates a relatively humus-rich soil, i.e. high in organic matter.

The soil profile for CF is much paler in colour, with a greyish-brown in the top layer; indicating a relatively humus-poor soil, most likely due to high groundwater levels or poor drainage capacity (within the soil). The white layer underneath the top layer indicates either a limestone layer or an illuvial layer; a soil layer where organic matter and nutrients have leached downwards. The bottom part of the soil profile at CF is a loose, sandy layer with gravel.

Figure 7.1: Soil profile per site: forest reserve "De Bruuk" (DB), conventional farm (CF) and food forest Ketelbroek (FF) (Baas, 2018).

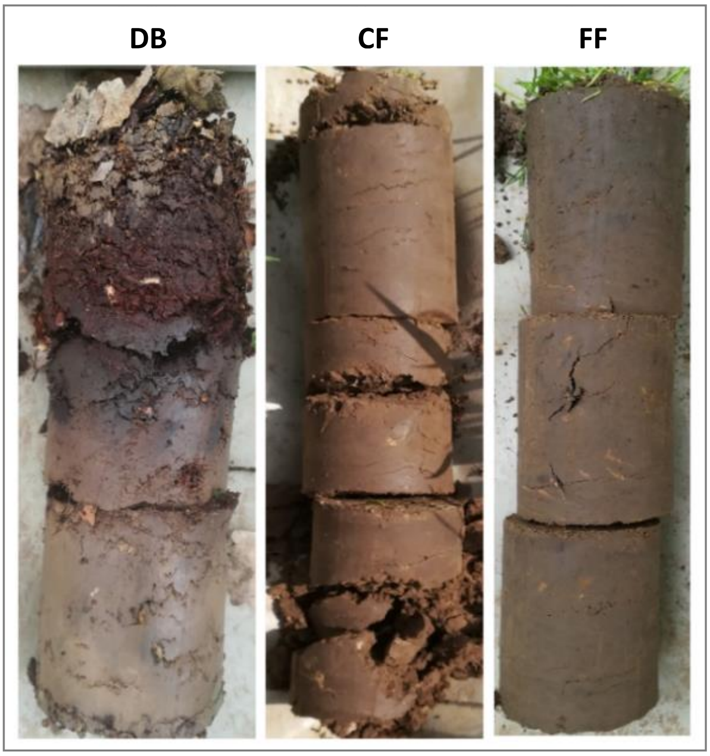


Figure 7.2: Soil cores (0-15cm) for each site: forest reserve "De Bruuk" (DB), conventional farm (CF) and food forest Ketelbroek (FF) (Baas,

The soil profile at FF may indicate an intermediate stage between DB and CF. The topsoil horizon is browner compared to CF with a semi-loose structure and some aggregated soil clumps. The orange layer in the middle of the profile may indicate where the ground water fluctuates or an illuvial layer. The bottom layer is similar to that of CF; a loose, white-coloured soil with some gravel and potentially some weathered clay. Overall, these soil profiles are different, and much can be interpreted from them. For example, Baas also classified the humus formation: agro-hydro-mull ("akkerhydromull" in Dutch) at CF, stream-hydro-mull-modor ("beekhydromull & beekhydromullmodor") at FF and forest-hydro-modor ("boshydormodor") at DB (Figure 7.2). The difference between a mull and a modor humus profile is the presence of a leaf litter layer (O horizon); a mull is without one and a modor with one. The main decomposers of organic material in a mull profile are earthworms and bacteria, whereas fungi also play a role in modor profiles (Baas, 2018). Identification of the humus formation can be considered a cost-effective indicator for a soil health assessment with any perennial-incorporated agroecosystem. Monitoring the development of a humus profile may be a useful tool to track soil developments at a food forest. Humus classification systems typically relate to forest soils, however new classification names have recently been developed to make identification at agroecosystems possible (Zanella et al., 2017; Zanella et al., 2018).

CF: Conventional Farm
FF: Food Forest Ketelbroek
DB: Forest nature reserve "De Bruuk"

Aggregate stability

Results indicated CF with the highest aggregate stability score. This indicated how stable to soil is to water-induced soil erosion. During field work at CF, it was observed that the soil had a very crumbly and fine structure. Certain integrated farming practices could contribute to this stable soil structure, such as the use of (winter) cover crops and green manure, but this remains to be explored. Also, signs of cracking on the soil surface was observed in some areas of the field. This suggests that the soil at CF was experiencing water-stressful conditions. How this influences the stability of the soil and to what extent this influenced the outcome would require further testing. For example, a soil slaking test is an easy additional test that can be done to further assess aggregate stability (Slier et al., 2018b).

Bulk density & soil resistance

Sampling method

Measuring bulk density with a core sample remains a relatively simple and popular method. This method may give slightly higher results due to the risk of compaction when sampling, especially for clay soils (Slier et al., 2018b). However, this can be accounted for when soil moisture is also measured.

Measuring soil resistance with a penetrologger is a relatively simple and quick method. However, it is also an expensive and highly specialised tool. This makes this method less accessible to those who aim to assess or monitor their field on a restricted budget.

Data interpretation

Comparing bulk density rates between a forest soil rich in organic material with an agricultural soil should be seen as anecdotal due to inherent differences in the soil and the function of each site. Despite this, using DB as a conceptual reference point can be important when following the trend of bulk density for any food forest.

This study determined a bulk density range and threshold for sandy loam textured soils from

Figure 4.3. Bulk density ranges were relatively large due to the presence of sandy-, silty- and clay loam soil. For more specific bulk density thresholds, Slier et al. (2018) provided a summary per textural class (Table 7.1). For future reference, these thresholds could be incorporated when interpreting soils with different soil textures.

Table 7.1: Bulk density thresholds per textural class (Arshad et al. in Slier et al., 2018)

Soil textural class	Minimum bulk density for root restrictions (g cm^{-3})
Coarse, medium and fine sands; loamy sands	1.80
Very fine sand, loamy very fine sand	1.77
Sandy loams	1.75
Loam, sandy clay loam	1.65
Sandy clay	1.60
Silt, silt loam	1.55
Silty clay loam	1.50
Silty clay	1.45
Clay	1.40

It is also known that “bulk density tends to increase with depth” (Slier et al., 2018b, p. 28), however, literature gives little indication of the extent of this, in particular for the subsoil. Therefore, the optimal minimum of 1.32 g/cm^3 remained for both the top- and subsoil layer. In reality, a higher range could be applicable for the subsoil.

Compaction at the subsoil was present at both CF and FF. This result can be explained from the use of (heavy) farming machinery and the practice of ploughing at CF. For FF, this is not the case since 2009. However, prior to 2009, the use of farming machinery and ploughing did occur. The legacy of these practices is most likely the cause of subsoil compaction measured at FF. It would be interesting to monitor how soil resistance changes over time at FF to see if (and perhaps to what extent) subsoil compaction can be remediated.

Soil moisture

Comparing soil moisture levels at CF, FF and DB may be incomparable as groundwater levels differ too largely between the two. Groundwater levels at DB are naturally high, causing seasonal swamp conditions. This phenomenon also induces the build-up organic matter which decomposes at a lower rate than well-drained soils. At DB, the organic horizon layer of the soil is a rich humus layer with a legacy of built-up organic matter, i.e. peat. Due to this geo-hydro-morphological context, soil moisture levels are naturally very high compared to FF and CF (which have drainage canals to lower the water table). In this context, comparing an organic soil with mineral soils may be incomparable or unfit. For this study's purposes, comparing FF and CF with a forest are for reference purposes only. Also, a larger range for soil moisture should be taken for peat soils.

7.1.2 Chemical soil properties

pH

When pH levels are sub-optimal, plant nutrient availability can be compromised. When pH levels are lower than 4.5, "nutrients such as calcium, magnesium, phosphorus, potassium and molybdenum become unavailable" (Moebius-Clune et al., 2017, p. 56). When pH levels are higher than 7.5, nutrients such as phosphorus, iron, zinc and copper become unavailable (Ibid.) Although pH levels at DB were acidic (4.15 in the topsoil), Moebius-Clune et al. (2017) stated that crops can tolerate acidic soils with high(er) levels of soil organic matter (SOM). SOM is very high at DB (19.75% in the topsoil). pH (in the topsoil) is one of two indicators which were classified as sub-optimal for DB. Although results showed a low pH at "De Bruuk", this is deemed insignificant due to the ecological stage it is in; a post-climax forest with high SOM levels. SOM is inherently acidic by nature. pH in the subsoil was optimal in the subsoil. Therefore, taking this into consideration and the high level of SOM in the topsoil, there is no threat of nutrient unavailability. This exemplifies the interrelationships between soil properties and how assessing soil health with solely a reductionist approach can lead to inaccurate interpretations.

The relatively high pH levels at CF (7.17 in the top- and 7.05 in the subsoil) can be attributed to the addition of limestone to the field several months before sampling took place (before 15 December 2017). Liming the soil ("landbouwkalk" in Dutch) is a common agricultural practice to amend acidic soils. Baas measured pH levels between 4.7 and 5.5 in May 2018 (two months after field measurements were taken for this study). Although these acidic pH levels were measured using a less precise method (pH paper strip method), these observations suggest an otherwise acidic soil at the arable farm.

Soil organic matter and content

Sampling method

Sampling at all sites was a technical challenge as they are different in their form and function. FF is a highly heterogeneous field with several hundreds of plant species. There lies an uncertainty as to the accuracy of SOM and SOC (or any other soil property) results representative for this system. At the same time, arriving at precise and accurate results would be time consuming and labour intensive. To account for the heterogeneity, one sample was taken per identified stratum, i.e. micro-habitat. To improve the accuracy of this method, three or more samples should be taken per stratum when time and funding allows. Although sampling was easier at CF, as it was homogenous with only one stratum, finding accurate results (and comparable) required considerations from a range of factors. Sampling for SOM at CF (or any arable farm) can be heavily influenced by the season, stage of crop growth and agricultural practices such as the application of soil amendments or tillage time and frequency). Taking note of these conditions and factors are important for any agricultural soil study. Sampling the topsoil at DB was also a challenge as it was difficult to distinguish the humus layer (O horizon) from the topsoil (A-horizon). This may have resulted in topsoil results with relatively high SOM values if a large amount of humus was included in the sample. Despite this potential inaccuracy, results indicate a high level of SOM, which is typical for an aging forest. These results can be considered precise for the top layer when explicitly mentioning the inclusion of the O horizon.

Laboratory method

The loss on ignition (LOI) method is one of the most common methods to estimate total content of organic matter and organic carbon in the soil. Despite this popular method, there remains no universal standard protocol. For this study, an adaptation was made based on the standard procedure described by Bakker (2010), Heiri, Lotter, & Lemcke (2001) and Slier *et al.* (2018). No corrections were made for the losses of weight for the following phenomena: $CaCO_3$ decomposition (loss of CO_2), structural water released from crystal lattices (clay) and NaCl volatilization. Taking this into account, SOM results may be overestimated for soil samples with a high clay content (such as for the "De Bruuk") and those containing high concentrations of limestone ($CaCO_3$). This is the case for CF. SOM values may therefore be overestimated for CF. Also, due to the presence of calcareous soils in this region, SOM results may be positively biased.

To further decrease variation and standard deviation per sample/batch (when using the LOI method), it is recommended to increase the sample mass to ≥20g. (instead of 5g.), tray-turning at half-time (when in the furnace) and to apply a clay correction factor from 0.01 to 0.09 for structural water loss at ignition temperatures from 350 to 650°C (Hoogsteen, et al., 2015). Considerations can also be made from the Cornell Framework for assessing soil health, which proposes the following equation (to derive SOM from the LOI method): % OM = (% LOI * 0.7) - 0.23 (Moebius-Clune et al., 2017, p. 47).

Investigating different structures and functions of SOM is also worth exploring as the LOI method only shows the total concentration of SOM. SOM consists of plant residues, living microbial biomass, detritus and humus. There are many intermediate stages of SOM, generally, SOM can be sub-divided into active organic matter (including microorganisms) and stable organic matter (i.e. humus) (FAO, 2005). Compared to stable organic matter, active organic matter is a more sensitive soil attribute to sudden changes happening in the soil, such as tillage (Gregorich et al., 1994). This makes it a more precise indicator for soil health when studying or monitoring the effects of soil management, land management practices or land-use change. Examples of such (proxy-)indicators are permanganate-oxidizable carbon, hot water-extractable carbon and water-soluble carbon (Bünemann et al., 2018).

Data interpretation

According to Hijbeek (2017), Dutch agricultural soils have an average SOM value of 3.5%. This makes the result for CF (3.58% in the topsoil, 5.14% in the subsoil) stand out as being just above national average for the topsoil and having a relatively high SOM value for the subsoil. On the other hand, these SOM values are relatively low in comparison to those at FF and DB. Based on a pilot study, Rutgers, Mulder, & Schouten (2008) developed biological soil quality benchmarks based on ten Dutch land use and soil type combinations, including arable land on clay, - on sand and dairy farming on loess. The reference values (for the topsoil) for SOM were 2.2%, 6.9% and 5.3% respectively. If results were to be made comparable, only FF would be higher than the ideal reference value of 6.1% (when based on similar soil types, the average was taken for sand and loess). (In this case, DB is considered incomparable as the soil type (clay) and functionality (conservation area, not agricultural) are different). Comparing SOM results from this study to any of these reference values remains a difficult and highly interpretive task.

Soil organic carbon stocks

Further calculations indicate a soil organic carbon stock of 11t C/ha at CF, 19 t C/ha at FF and 33 t C/ha at DB in the top 5cm soil layer (Table 7.2). In the subsoil layer (30-25cm depth), the carbon stock is 20t C/ha at CF, 13 t C/ha at FF and 19t C/ha at DB. These calculations were made based on bulk density and soil organic carbon results using the following simplified equation (Edwards, 2019):

$$SOC\ stock\ (t\ C/ha) = Carbon\ content\ (\%) \times bulk\ density\ \left(g/cm^3\right) \times soil\ depth\ (cm)$$

Based on an in-depth study on SOM in the Netherlands, Conijn and Lesschen (2015) quantified the average carbon stock per soil type and land use (Appendix 11.6.18). For *eerdgronden* (matching the soil type to the study area), the average carbon stock for the top 5cm is 11.8 t C/ha for cropland, 14.7 t C/ha for grassland and 16 t/ha for nature. This shows how the topsoil carbon stock at FF (19 t C/ha) is significantly higher and above the national average for every land-use system (cropland, grassland and nature). The carbon stock at CF is close to the national average for cropland in the topsoil (0-5cm) and significantly higher in the subsoil (30-35cm). Average SOC stocks below 30cm have not been quantified by Conijn and Lesschen (2015), although these figures suggest a high SOC storage in the subsoil at CF nonetheless. Further research is needed to investigate these SOC stocks across soil layers. For example, studies can investigate SOC stocks at greater soil depths, e.g. 0-100cm. Remote sensing techniques can currently estimate SOM and SOC stocks in the first few mm. of the soil, therefore, in-field soil sampling is advised as a more precise method to calculate SOC stocks when (up to date) soil data is lacking. These results suggest food forestry can play a potentially large role in storing carbon in the soil.

Table 7.2: Carbon stock per study site (CF, FF and DB) and average carbon stock potential per land-use type (cropland, grassland and nature) on eerdgronden (adapted from Conijn & Lesschen, 2015)

	Conventional farm (CF)	Food forest Ketelbroek (FF)	Nature forest "De Bruuk" (DB)	Cropland	Grassland	Nature
Topsoil SOC stock (t C/ha for 0-5cm in 2018)	11	19	33	12	15	16
Subsoil SOC stock* (t C/ha for 30-35cm in 2018)	20*	13	19	ND	ND	ND

**Subsoil results are positively biased due to $CaCO_3$ being included in SOC calculations, especially for CF*
ND represents no data available

In summary, reaching valid statements and conclusions based on SOM data, or any other data from this study, remains a challenge as it is highly dependent on where the reference point is placed; absolute per soil type, relative to one another or otherwise. Also, there are no explicit SOM nor SOC thresholds or benchmarks for subsoil layers (≥30cm depth). Hijbeek (2017) described various thresholds by reviewing how "Jones et al. (2012) report that 3.4% SOM (= 2% SOC) is widely used as threshold [...], but also acknowledge that there is much debate on the quantitative evidence for this level. [...] Zwart et al. (2013a) [mentioned] a much lower value of 1.5% OM [...] as possible critical level in the Netherlands. Van Camp et al. (2004) concluded that it is not possible to define one single threshold[...]" (Hijbeek, 2017, p. 9). In this study, the optimum minimum was set at 4% which was based on the "value of 2% SOC for agricultural soils often [being] considered [the] limit below which the soil becomes unstable" (*Morari et al. in* Stolte et al., 2016, p. 64). Establishing a universal threshold value for SOM or where the critical minimum lies remains difficult due to inherent dependencies on soil type, climate, land management practices and land-use goals. These factors should be considered for any future soil assessment study.

7.1.3 Biological soil properties

Earthworm abundance

Earthworm results were adopted from Baas' study due to time- and resource limitations. Baas adapted the standardised method of ISO/DIS 23611-1 to reduce the impact of soil disturbance during soil sampling, time and labour work. Sampling and species identification were carried out on-site, which is recommendable for future studies. The sample number is 16 per site and a statistically significant difference existed between FF and CF. It is assumed that these results are valid due to the high sample number. However, further statistical analysis is advised to check for validity and reliability of this data.

Biological indicators are increasingly being mentioned as essential for any soil assessment (Bünemann et al., 2018). This is because soil biota play an important role in the soil food web and "are considered the most sensitive indicators of soil quality due to their high responsiveness to changes in environmental conditions" (Bünemann et al., 2018, p. 116). Studying which soil biota, in what way and its practical feasibility remains an on-going exploration. For further soil studies, it is recommended to include more biological indicators such as examining nematodes, litter decomposition or measuring *in situ* soil respiration (Bünemann et al., 2018; Thoumazeau et al., 2019).

7.1.4 Temporal trends

Organic matter and carbon content

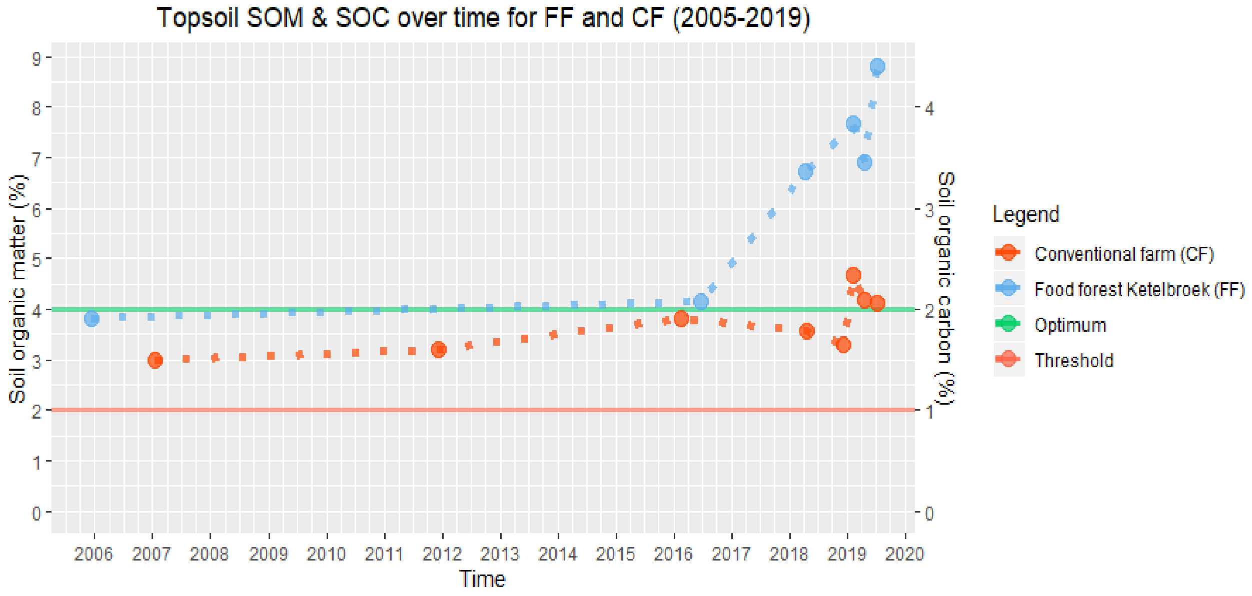


Figure 7.3: SOM and SOC measurements over time (2005 - 2019) for food forest Ketelbroek (FF) and the conventional farm (CF)

Building on more recent data collected in 2019 by Westhoff (2019-unpublished), further SOM & SOC developments can be observed (Appendix 11.6.16). Figure 7.3 displays a significant rise in SOM and SOC for FF, from 3.80% in the winter of 2005 to 8.82% in the summer of 2019. This shows an increase of 5% in 13 years. Although the food forest was planted in 2009, it can be said that organic matter levels have risen by more than double in the last 10 years. There are also incremental increases in SOM (and SOC) for CF, rising from 3.00% in 2007 (January) to 4.13% in 2019 (June). This is an increase of 1.13% over a period of 12 years. Data from Westhoff (2019-unpublished) also shows seasonal differences; SOM and SOC drop during spring (April) but in the summer (June) SOM and SOC increases at FF (6.92% to 8.82%) yet slightly decreases at CF (4.18% to 4.13%). The large increase of SOM at FF between spring and summer of 2019 may be explained from the turnover of aboveground and belowground biomass to SOM from previous years. The rate at which this happens is a question to explore in future studies. Monitoring SOM and SOC in the top- and subsoil can provide insights as to how this trend changes over time. This data also reflects inter-seasonal variation. To account for this. sampling for SOM and SOC should therefore remain consistent seasonal wise; in this case, ideally early spring time.

The data used to produce Figure 6.8 & Figure 7.3 was compiled from five different sources: BLGG, Eurofins, Bakker, Rebisz and Westhoff (Appendix 11.6.15). It is assumed all data are representative observations of each site. Data from BLGG and Eurofins are assumed to be significant and representative due to a high sample size (n=40 at 0-25cm depth) (Appendix 11.1). Data from Bakker (2016), Rebisz (2018) and Westhoff (2019) are statistically significant (Appendix 11.6.15). SOM values from Bakker (2016) are taken from samples KFF3, KFF4 and 1KN5. KA1 and KA2 were excluded as these samples were taken in the agroforestry part, outside the scope of this report. Further statistical analysis is needed to know how representative these data results are. Further SOM & SOC may be triangulated and monitored using publicly available remote sensing databases such as the Dutch Soil Information System (BIS) and the Dutch Mapping of Public Provisioning of Services (PDOK).

7.1.5 Sampling design

Applying a sampling design to any bio-diverse planting system remains a challenge, especially when the aim is to produce valid statements characterizing a land-use system. There were many other possible sampling design possible, such as simple random sampling, aligned systematic sampling, unaligned systematic sampling and cluster sampling design (McRoberts, Tomppo, & Czaplewski, n.d.). An ACT food forest working group suggested two sampling designs for food forest EcoVredeGaard (EVG) (Figure 4.4) namely a systematic and a random-stratified sampling design (Slier et al., 2018b). The latter is a commonly strategy used in environmental assessments. This approach is also adopted for this research project. It should be noted that other sampling techniques are possible for follow-up studies at Ketelbroek or at other food forests, which are often dependent on what is being measured.

7.2 Concepts and frameworks

Several concept and frameworks were drawn upon, adapted and placed into the context of a Dutch temperate agro-ecosystem. Such concepts and frameworks are, to some degree, simplified constructs of reality (Watt & Berg, 2002). Soil health is the main concept used with several (proxy-) indicators used to operationally define this concept. To what extent these operational definitions reflect the meaning of this concept remains, to some extent, uncertain. This measurement validity will always have some form of uncertainty as there remains much to be understood about (soil) ecology and its complex web of interactions. Despite this slice of uncertainty, much can still be understood about reality when concepts, frameworks and indicators are explicitly defined. This provides a basis for critical evaluation. This study remained explorative in understanding the practice of food forestry through the soil, where attention was given to defining the many concepts used in this study. Secondly, most soil measurements taken during this study were seen as one-time observations of reality. Reality can be better understood when trends are observed through monitoring efforts. Thirdly, how data is interpreted is also worth reflecting upon. The results were interpreted by myself to the best of my abilities and understanding. Unbiased work cannot be completely disregarded as standards were set (ex. benchmark system) and interpretations were made. This can, and to some extent has been, minimised through critical reflection and evaluation by me, supervisors and peers throughout the process of this study.

7.2.1 Classifying farming systems

In this report, the arable farm was termed a conventional farming system. Through further reflection, the ‘conventionality’ of this farm became questionable due to the integrated approach of closing several processes described by the farmer. Comparing several conventional Dutch (arable) farms is likely to show a variety of farming systems. This may be interesting to explore in a follow-up study, where the impacts of a food forest is compared with several types of arable farms. On another note, the dominant discourse divides organic against conventional agriculture with little nuance in between. This report adopts the same terminology yet remains critical of such oversimplified terms by recognising the diversity in existing arable farming systems across the Netherlands. This divisive discourse is also applicable to the Dutch language and culture: “gangbaar” versus “biologisch”. For further studies, it is recommended to look beyond such terms and thoroughly describe each farming system and its practices at a farm-level approach, in collaboration with the farmer.

7.2.2 Soil health and soil quality

Soil health and soil quality are used interchangeably in this study. Why both terms are used and not one or the other is a normative reason; soil health is more closely associated to the value of human health, whereas soil quality is often associated with chemical and physical attributes of the soil. Soil health evokes (and implies) a sense of liveliness which is more than soil quality is defined generically. Through a review of these concepts, Laishram et al. (2012) distinguishes soil quality as being related to soil functioning/processes, whereas soil health denotes the soil as a finite non-renewable and dynamic living resource. These differences are combined and considered true for both terms in this study. Recognising the soil as a living resource has also brought greater attention and interest into the dynamics of soil ecology. Abiotic and biotic aspects of the soil are often inter-dependent, as mentioned between soil texture in relation to bulk density or organic matter. Soil organisms also play a crucial role in the process of decomposition (break-down of organic compounds) and mineralization (bioavailability of nutrients to plant and soil fauna). This has translated into the development and incorporation of biological soil indicators for many soil assessments (Bünemann et al., 2018). Several integrative and innovative soil health assessments include the Cornell Framework - A Comprehensive Assessment of Soil Health ((Moebius-Clune et al., 2017), the soil quality assessment framework for agricultural soils in the Netherlands (Hanegraaf et al., 2019), the Biofunctool® (Thoumazeau, Bessou, Renevier, Trap, et al., 2019) and iSQAPER - Interactive Soil Quality Assessment in Europe and China for Agricultural Productivity and Environmental Resilience. Many biological soil indicators remain unstandardized and innovative. Overall, soil ecology remains a complex yet interesting field of study where much remains to be understood on the dynamics of biotic and abiotic interactions in the soil.

7.2.3 Soil quality index: ranges and thresholds

This thesis based its optimal ranges and threshold from literature studies. Soil texture is a highly variable property and defining ranges and thresholds was a difficult task. This benchmark system should not be considered as rigid, but rather as a (generalised) reference system. Reflecting on the limitations of a soil quality benchmark has led to the consideration of alternative forms of referential systems, such as creating an upper and lower quantile range based on results from within the sample group (Rutgers et al., 2008). Secondly, this study assumes these ranges and thresholds to be significant for the topsoil layer, although the literature was not always explicit at which soil depths these reference values are applicable to. This poses questions on whether different ranges are necessary between topsoil and subsoil layers, for example when assessing bulk density at different soil layers or SOM ranges across soil layers. This remains to be explored.

7.2.4 Soil threats

Identifying soil threats has placed emphasis on the value of this natural resource base and the urgency to address (European) soils at risk of degradation (Berge et al., 2017). There remains no consensus on the number of soil threats and the order of importance due the difficulty in assessing soil threats. How widespread and severe these threats are, and their potential risk are often context specific and dependent on defining which actors are affected by these soil threats. Quantitative data on soil threats is limited, scattered and lacking in uniformity across EU countries. Despite this, efforts were made to create a soil threat susceptibility map for EU soil (Figure 7.4).

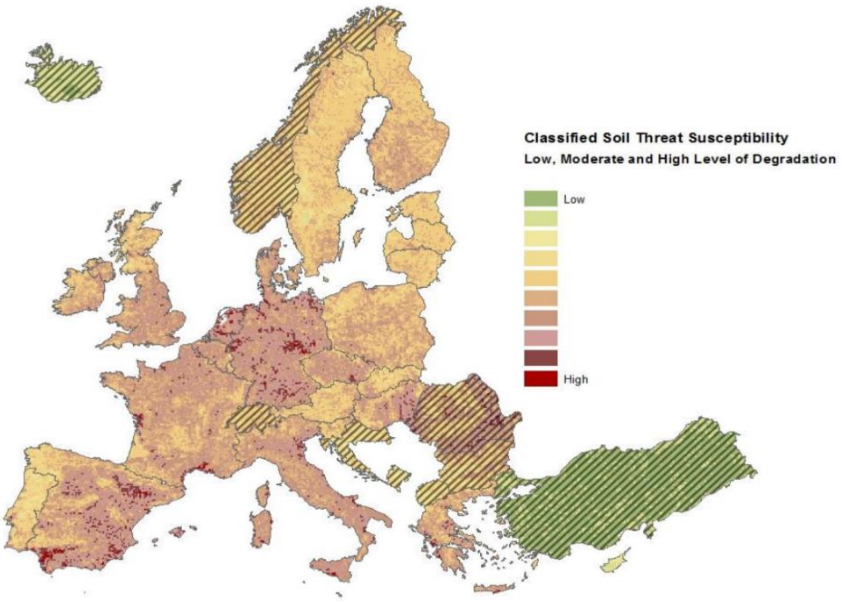


Figure 7.4: A map showing how susceptible soils are to a level of degradation, shaded areas represent missing data. (Stolte et al., 2016)

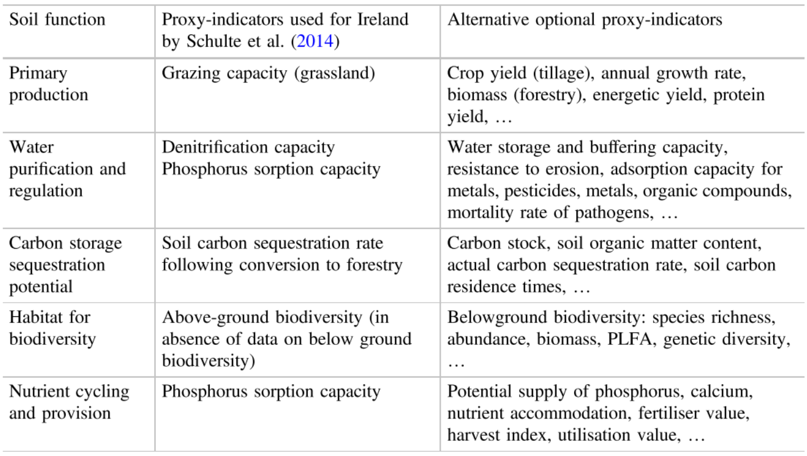
Several parts of the Netherlands are highly susceptible to soil threats. According to an EU wide assessment on land degradation, the Netherlands is at risk of: wind erosion, peat erosion, soil sealing, soil salinization, soil contamination and (subsoil) compaction (Stolte et al., 2016). Soil compaction is a prominent threat to Dutch soils, as approximately 50% of the most productive and fertile soils have compacted subsoils (Ibid.).

This study also showed subsoil compaction at CF and FF, most likely caused from the practice of ploughing and the use of heavy machinery. Compaction can severely lead to land degradation if practices causing (subsoil) compaction are not changed. For example, soil compaction can lead to a reduction in crop yields and soil functioning as soil-pore space for air, water and nutrients becomes limited. There are mechanical and biological methods that can reduce or prevent soil compaction. Mechanical methods include decreasing tyre pressure, soil loosening and restricting axles loads to "a limit of 6 t on a single axle or 8–10 t on a tandem axle" (Batey, 2009, p. 342), Biological methods include adopting no-tillage and planting species with taproots or wide-spreading root systems such as "*Ailanthus altissinza, Gleditsia triacanthos, Pinus taeda, Robinia pseudoacacia, Ulmus americana, U. parvifolia*" (Kozlowski, 1999, p. 609) (Kayombo & Lal, 1993)(Kayombo & Lal, 1993)(Kayombo & Lal, 1993)(Kayombo & Lal, 1993)(Kayombo & Lal, 1993)(Kayombo & Lal, 1993). The development of perennial rooting systems can enhance soil structure through increased aeration in the soil and from the effects of many (direct and indirect) soil processes related to plant roots (Flores Fernández et al., 2017; Kozlowski, 1999). Spoor, Tijink, & Weisskopf stress that "the prime aim of [...] mechanical measures must [...] be to improve conditions with minimal loss of soil support, leaving the natural and biological processes to complete the remediation [process]" (Spoor et al., 2003, p. 180). Monitoring subsoil resistance at FF can indicate to what extent the practice of food forestry can remediate a compacted subsoil.

7.2.5 Soil processes and (ecosystem) functions

Going in-depth into soil processes and ecosystem functions remained outside of the scope of this report. It is however, worth mentioning that the assessment of ecosystem functioning (or its services) also serves as the starting point where then, soil indicators are included and connected to a function. An example of connecting soil indicators to soil-based ecosystem services is shown in

Table 7.3, developed from an Irish case study by Schulte et al. (2018). Another approach is connecting soil groups (based on WRB- world reference base) to ecosystem functions (FAO, 2015). These approaches may also be relevant when assessing ecosystem functions, particularly in agricultural landscapes.



Soil function	Proxy-indicators used for Ireland by Schulte et al. (2014)	Alternative optional proxy-indicators
Primary production	Grazing capacity (grassland)	Crop yield (tillage), annual growth rate, biomass (forestry), energetic yield, protein yield, …
Water purification and regulation	Denitrification capacity Phosphorus sorption capacity	Water storage and buffering capacity, resistance to erosion, adsorption capacity for metals, pesticides, metals, organic compounds, mortality rate of pathogens, …
Carbon storage sequestration potential	Soil carbon sequestration rate following conversion to forestry	Carbon stock, soil organic matter content, actual carbon sequestration rate, soil carbon residence times, …
Habitat for biodiversity	Above-ground biodiversity (in absence of data on below ground biodiversity)	Belowground biodiversity: species richness, abundance, biomass, PLFA, genetic diversity, …
Nutrient cycling and provision	Phosphorus sorption capacity	Potential supply of phosphorus, calcium, nutrient accommodation, fertiliser value, harvest index, utilisation value, …

Table 7.3 Proxy-indicators per soil-based ecosystem function (Schulte et al., 2018, p. 205)

7.2.6 Linking frameworks: a soil compass

The soil compass framework was developed to link soil health (attributed to several soil quality indicators) to soil threats, soil processes and soil-based ecosystem functions (Figure 7.6). This is a qualitative framework to provide a visual overview of the status of soil, land and/or ecosystem in question. A simplified version is shown in Figure 7.5, where orange circles represent soil threats (darker orange signifies specific soil threat) in relation to soil processes (in blue), which in turn affect ecosystem functioning (in green). This compass follows a traffic light system from green – orange – red. Green represents a fully functioning ecosystem, orange a semi-functioning ecosystem and red a poor-functioning ecosystem. What defines a fully-, semi- or poor functioning ecosystem is dependent on the context; soil type, climate,

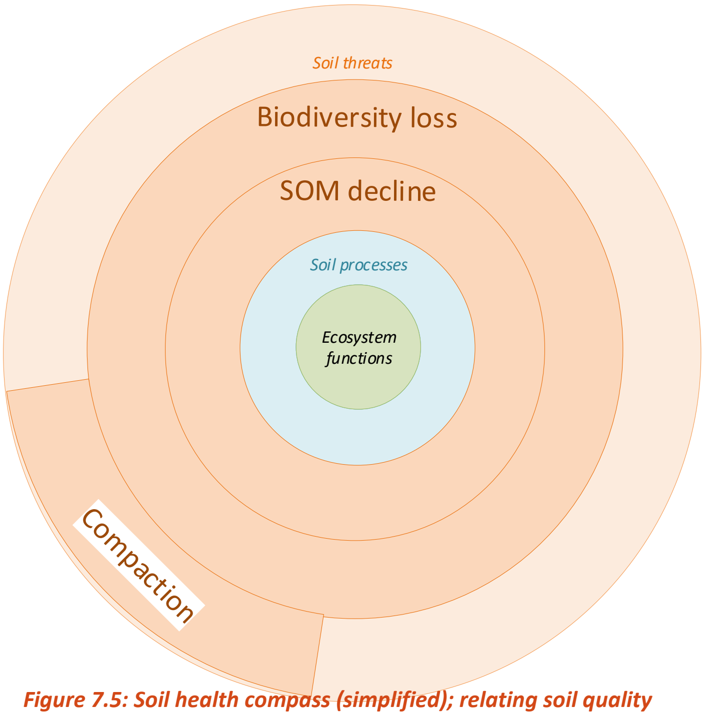


Figure 7.5: Soil health compass (simplified); relating soil quality indicators to soil threats, soil processes and ecosystem functions. The orange circles represent soil threats, which affect soil processes (in blue) and these affect ecosystem functions (in green).

CF: Conventional Farm
FF: Food Forest Ketelbroek
DB: Forest nature reserve "De Bruuk"

land-use type, land management practices, etc.

Figure 7.6 shows the extensive version of the soil health compass with soil processes and ecosystem functions sub-categorised and soil quality indicators connected to soil threats. If more quantitative data were available for food forest Ketelbroek, for example on the productivity (e.g. in t/ha/year) and overall biomass production, then this could serve as an elaborate visualisation tool to qualitatively compare the status of soil health and ecosystem functioning between agroecosystems.

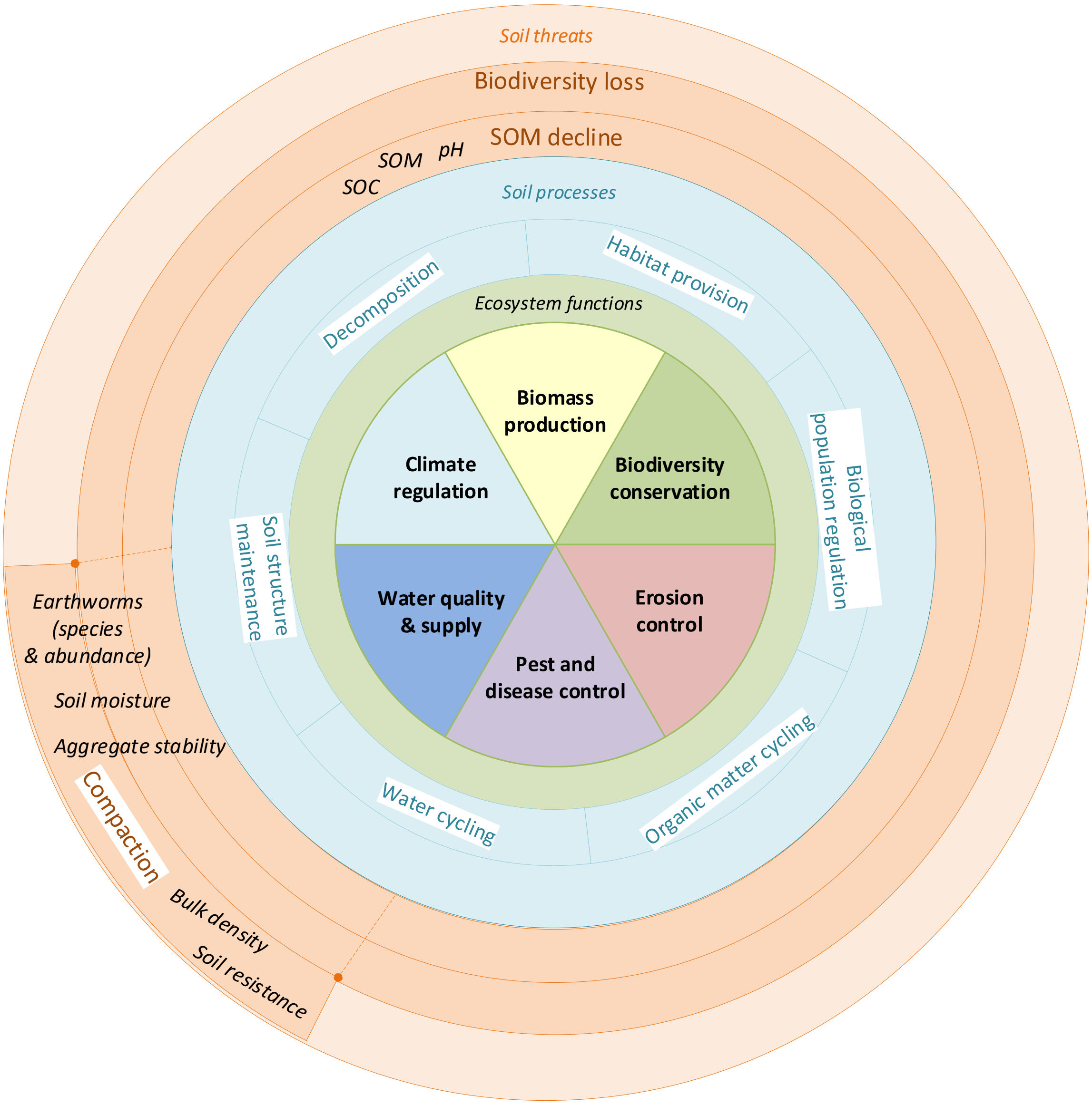


Figure 7.6: Soil health compass (extensive); relating soil quality indicators to soil threats, soil processes and ecosystem functions. The orange circles represent soil threats, which affect soil processes (in blue) and these affect ecosystem functions (in green circle with a different colour per ecosystem function). Soil quality indicators (in black in the orange circles) are related to soil threats.

To illustrate the soil compass in context, simplified soil compasses were shown per study site (Figure 7.70). Forest "De Bruuk" (DB) was shown with green-coloured soil threats as an optimum reference point, meaning there were no soil threats and thus, a functioning (green) ecosystem. At the conventional farm (CF), soil compaction was a threat (in red) and SOM decline was sub-optimal but not a threat (light green). This was qualitatively assessed as a semi-functioning ecosystem (orange). At food forest Ketelbroek (FF), biodiversity loss and SOM decline were not a threat (green) but compaction was a threat (in red). This was qualitatively assessed as a semi-functioning ecosystem (orange) because of the existing threat from soil compaction. The colours were assigned according to soil threats identified from the results from this study (Appendix 11.7). These soil compasses visualize which soil threats exist. Making further judgements on the impacts on ecosystem functioning remains a qualitative assessment.

Figure 7.7: Soil health compasses for DB (forest "De Bruuk"), CF (conventional farm) and FF (food forest Ketelbroek); connecting soil health results to soil threats, soil processes and ecosystem services. Soil threats operate with a traffic light system: green = no threat, light green = sub-optimal with no significant threat, orange = partial threat, red = threat.

Assigning colours to the soil health compass was a qualitative way to interpret soil data and, in this case, dependent on a benchmark system. Soil results for DB deviated from how it was presented in the soil compass due to this land-use system being a designated nature area with a different soil type. Hence, soil threats inferred from the results (high soil moisture and a low pH) were deemed insignificant as this benchmark is relevant for agroecosystems on loess soils. Hence, DB-B version was adopted and used as a reference point (Figure 7.8). This simplified example shows how soil assessments, in all its complexity and confounding variables, can be processed and interpreted through a soil compass.

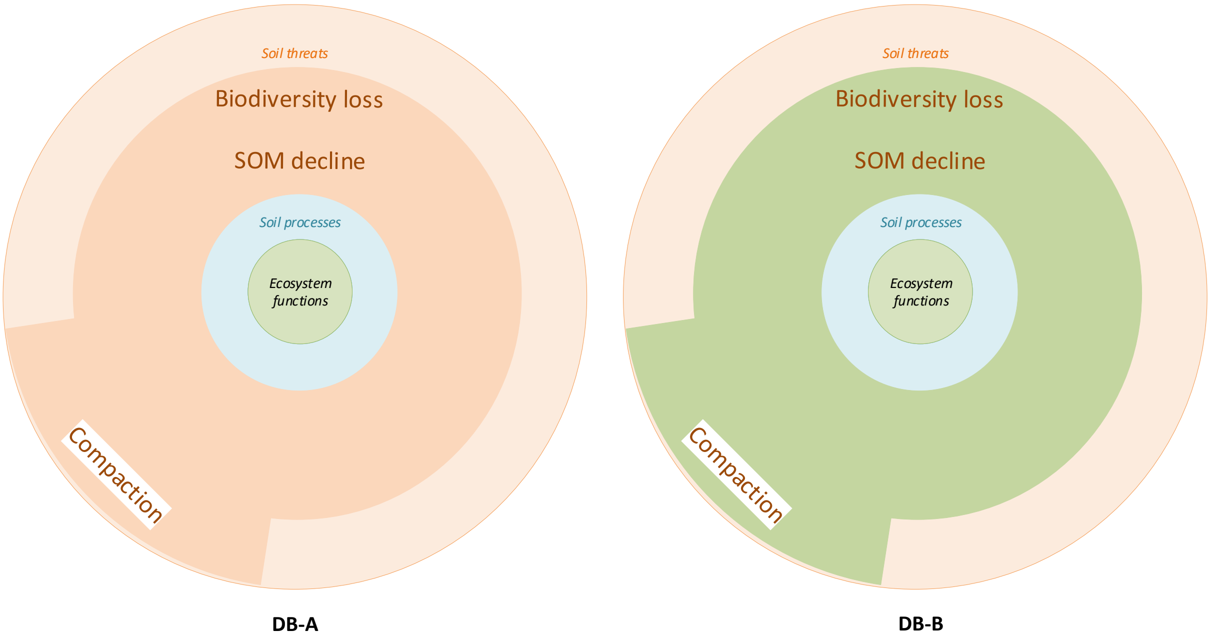


Figure 7.8: Soil health compass for DB-A (according to the benchmarks set in this study) and DB-B (taking into account peat soil type and nature/forest land use system)

CF: Conventional Farm
FF: Food Forest Ketelbroek
DB: Forest nature reserve “De Bruuk”

7.2.7 Food forestry: concept and practice

Like agroforestry, food forestry systems can take shape in many diverse forms and provide a multitude of functions and ecosystem services. The flexibility, adaptability and variability in space and over time can be resilient characteristics in addressing current societal challenges such as climate change, biodiversity loss, food security, food sovereignty, and human wellbeing and prosperity. *Stichting Voedselbosbouw Nederland* visualizes some ecosystem functions in relation to a variety of land-use types (Figure 7.9).

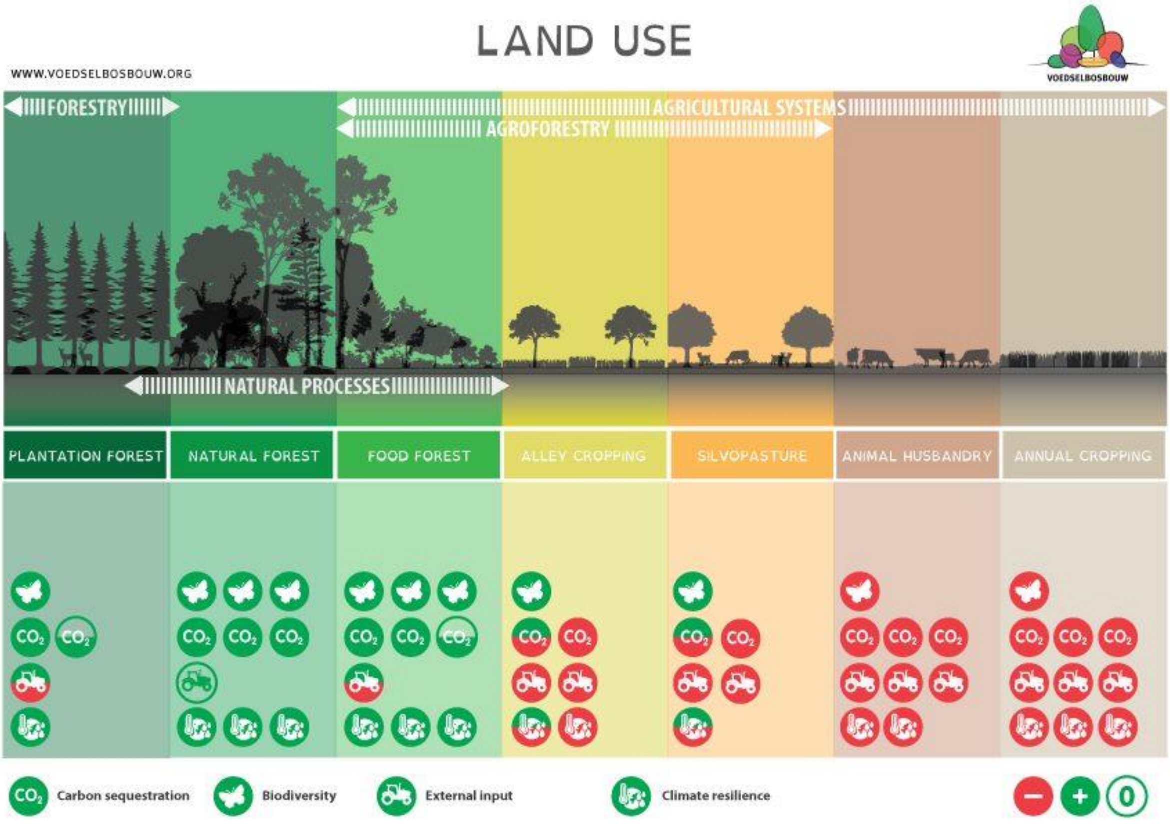


Figure 7.9: A qualitative valuation of ecosystem functions and services per land use type (Stichting Voedselbosbouw Nederland, 2019)

What distinguishes a food forest from any other agroforestry system is a discussion in itself. In the Netherlands, a food forest can be sub-categorised as a form of agroforestry system which most closely mimics a natural forest ecosystem. Designing a food forest which mimics a forest ecosystem often implies a higher level of complexity in both form and composition over time and space compared to other agroforestry systems. Another subtle difference is the extent of ecological succession that is allowed for. In the context of temperate regions, most ecological states (when undisturbed) succeed into a forest ecosystem. The principles of food forestry work alongside this ecological progression and sometimes influences the speed of succession (often accelerating the processes) towards a (near) climax stage. Most other agroforestry and arable farming systems are maintained at a desired state (or worked towards a particular stage), often before reaching an ecological climax. Such forms of maintenance can involve large amounts of energy and resources to prevent such ecological evolvement (Conforti & Giampietro, 1997; Pimentel et al., 1973; Smith et al., 2008). This can lead to a greater discussion as to which agroforestry system is more or less sustainable or regenerative. Food

CF: Conventional Farm
FF: Food Forest Ketelbroek
DB: Forest nature reserve “De Bruuk”

forestry has potential as a regenerative form of agriculture and land restoration capabilities(Park et al., 2018). Food forests seem to be more 'natural' than other forms of agroforestry systems and thus be implied to be more 'sustainable', but this claim remains to be substantiated per context. This study suggests that food forestry can be a more sustainable form of land management practice than conventional arable farming systems for sandy loam soils in a temperate climate, but far more research is needed to validate this. Perhaps food forestry practice at Ketelbroek is a *Cinderella* agroforestry system (Nair, Viswanath, & Lubina, 2017). This is a term used to highlight location specific agroforestry systems with unrecognized potentials. If this is to be further investigated, it is highly recommended to increase the sample size for both arable farms and food forests. Finding more (established) temperate food forest remains an obstacle.

Inferences made from extensive knowledge on the effects of forest ecosystems (conceptually) point towards agroforestry systems, including food forestry, as potentially land restorative and regenerative practices with several case studies indicating this (Dollinger & Jose, 2018; Elevitch et al., 2018; Lovell et al., 2018; Park et al., 2018; Udawatta, Rankoth, & Jose, 2019). To what extent (temperate) food forestry practices can realise such potential depends on the form and its functional capacity. Determining the functional capacity of a land is, on one aspect, shaped by ecological boundaries such as climate and soil type. Another determining aspect is how society gives value to land and assigns functionality to it based on what is of value by society (at that moment in time). Efforts are made to take both aspects into account, such as the functional land management framework which "allows for the quantification of both the supply of, and demand for, agricultural ecosystem services" (Schulte et al., 2014, p. 46).

The effects and impacts of a food forest are, therefore, context specific and dependent on environmental factors (i.e. soil type and climate), human-induced pressures (i.e. climate change, soil threats, land use change, land management practices, etc.) and socio-economic factors (i.e. food culture, cultural values, market state, policies and politics, accounting of environmental services, etc.). The nuance lies with which context it is taken in; at which state the land is before and after the development of a food forest and in which environmental and socio-economic context a comparison is made.

8 Conclusions

Soil health results indicate that all sites score optimally or near-optimal in most cases. This suggests all systems have a well-functioning soil ecosystem (Figure 7.7). Within the context of comparing agroecosystems, this study indicates soil health to be better at food forest Ketelbroek than the conventional arable farm (as visualized in Figure 6.1 and 6.2). Topsoil results all scored within the optimum range at food forest Ketelbroek. In comparison to this, the conventional arable farm had slightly lower organic matter levels, organic carbon and earthworm abundance; which scored in the *tolerable range*. The conventional farm scored better than the food forest in terms of aggregate stability in the top- and subsoil and organic matter levels and carbon content in the subsoil. However, these results showed no statistically significant difference between each site. The land management practices at the arable farm seems to maintain a relatively stable soil condition, albeit with the aid of external inputs. Relating the amount of external inputs to the generated outputs and the effects on soil health are for future studies to investigate.

Signs of subsoil compaction are present at both food forest Ketelbroek and the conventional farm. These were the only sub-optimal results for both sites. This is most likely caused by the use of (heavy) farming machinery and the practice of ploughing. Although these practices are no longer adopted at food forest Ketelbroek since 2009, the legacy of these practices in the previous farming system have remained. Monitoring subsoil resistance at both sites with knowledge of farming techniques used can further investigate the trend of soil compaction at both sites.

Organic matter and organic carbon levels have also increased significantly over time at food forest Ketelbroek, which doubled in the last decade at the food forest, from approximately 4.0% in 2009 to 8.8% in 2019. This also suggests that food forestry can have a significant carbon storage capacity.

When incorporating forest “De Bruuk” within the analysis (and using the benchmark set for agroecosystems on loess soil), the forest “De Bruuk” scores better in almost all soil quality aspects in comparison to food forest Ketelbroek and the conventional arable farm, for both the top- and subsoil. Although results showed a high soil moisture and low pH at “De Bruuk”, these can be deemed insignificant due to the ecological stage it is in; a post-climax forest with high OM levels in the topsoil. Comparing a young food forest with a post-climax forest should be taken anecdotally and serves more as a conceptual reference point.

The soil compass was used to visualize all findings in relation to three key soil threats: SOM decline, compaction and biodiversity loss (Figure 7.7). The forest “De Bruuk” was used as a reference point and the assumption was made that it can alleviate and prevent all three soil threats. The soil health compass visualises food forest Ketelbroek with no soil threats apart from (subsoil) compaction. The conventional farm is also threatened by (subsoil) compaction, the threat of biodiversity loss and SOM decline are not a significant threat yet not optimal either. This suggests that food forestry as a land management approach (at food forest Ketelbroek) may mitigate soil threats such as SOM decline, compaction and biodiversity loss. Further studies are needed to substantiate these indications, which can be carried out by monitoring SOM and subsoil resistance over time. Overall, this study suggests that food forestry can be a sustainable form of land management practice for sandy loam soils in a temperate climate, but far more research is needed to validate this. Perhaps food forestry practice at Ketelbroek is a *Cinderella* agroforestry system: a location specific system with unrecognised potential (Nair et al., 2017).

9 Recommendations

Further studies are needed to explore whether and to what extent the practise of food forestry (at Ketelbroek or elsewhere) supports the functionality at soil, farm and ecosystem level. Monitoring short and long-term changes (in soil quality) is necessary to evaluate the impacts, ideally in combination with integrative soil assessments. Soil health can be assessed in numerous ways. Therefore, integrative soil quality assessments and the inclusion of more biological soil quality indicators are highly recommended. Examples of biological indicators are examining nematodes, litter decomposition and measuring *in situ* soil respiration (Bünemann et al., 2018). Works such as the fieldwork manual for a food forest monitoring and evaluation study (Slier et al., 2018a) and the comprehensive assessment of soil health-The Cornell Framework (Moebius-Clune et al., 2017) are examples to refer to.

When assessing and monitoring soil health, data triangulation is also advised to (1) validate the measurements of a soil property and/or (2) compare how measurements deviate from data obtained from the field and from remote sensing technologies. Ideally, a triangulation is advised where field data is compared with historical soil literature/previous field data and geospatial soil data where possible. Examples of existing (and public) geospatial databases include the Dutch Soil Information System (BIS) and the Dutch Mapping of Public Provisioning of Services (PDOK) which collect and display all national geo-datasets. For global references, it may be of interest to compare data with global remote sensing data such as SoilGrids.org, a "system for automated soil mapping based on global compilation of soil profile data and publicly available remote sensing data" (ISRIC, 2019). Soil apps are also emerging as useful databases, such as SoilInfo and SQAPP. Exploring and incorporating remote sensing technologies has a high potential for data collection and monitoring efforts.

Comparing soil results in the top- and sub-layers and between different farming systems may also be of interest to explore. Connecting soil health (and its indicators) to soil processes and soil ecosystem functions also remains important to bridge, as this connects reality to functionality and to the potential of soil, land and ecosystems. Connecting these concepts and frameworks can ultimately bridge to overarching frameworks such as the Sustainable Development Goals. Making these connections can stimulate policies and politics to encourage existing and novel practices which are sustainable forms of agricultural intensification, regenerative and climate resilient.

Much remains to be explored with regard to understanding food forest Ketelbroek and food forestry as a practice. A brief list of recommended research topics outside the scope of this study include:

- Compare soils between food forest and silvoarable agroforestry system within Ketelbroek and between comparable sites
    a. Examine the role of soil microbes in soil processes and how this change over time, e.g. explore the dominance of fungal and/or bacteria within the soil
    b. Explore flora and fauna abundance, monitor planted and migratory plants
    c. Explore water storage capacity
    d. Examine soil properties during or post weather-induced stresses such as extreme hot and cold temperatures, intense rainfall
    e. Explore (existing and climate change-induced) effects of soil-borne pests and/or diseases
- Explore carbon storage capacities across different forms of (temperate) agroforestry systems

- Explore water quality and quantity entering and leaving the wetland nature area at food forest Ketelbroek to investigate hydrological dynamics at and around the food forest.
- Explore total productive capacities (in terms of dry bulk weight and nutritional value) at food forest Ketelbroek and other temperate food forests
- Explore various forms of economic (feasibility) strategies for food forestry start-ups in the context of the Netherlands

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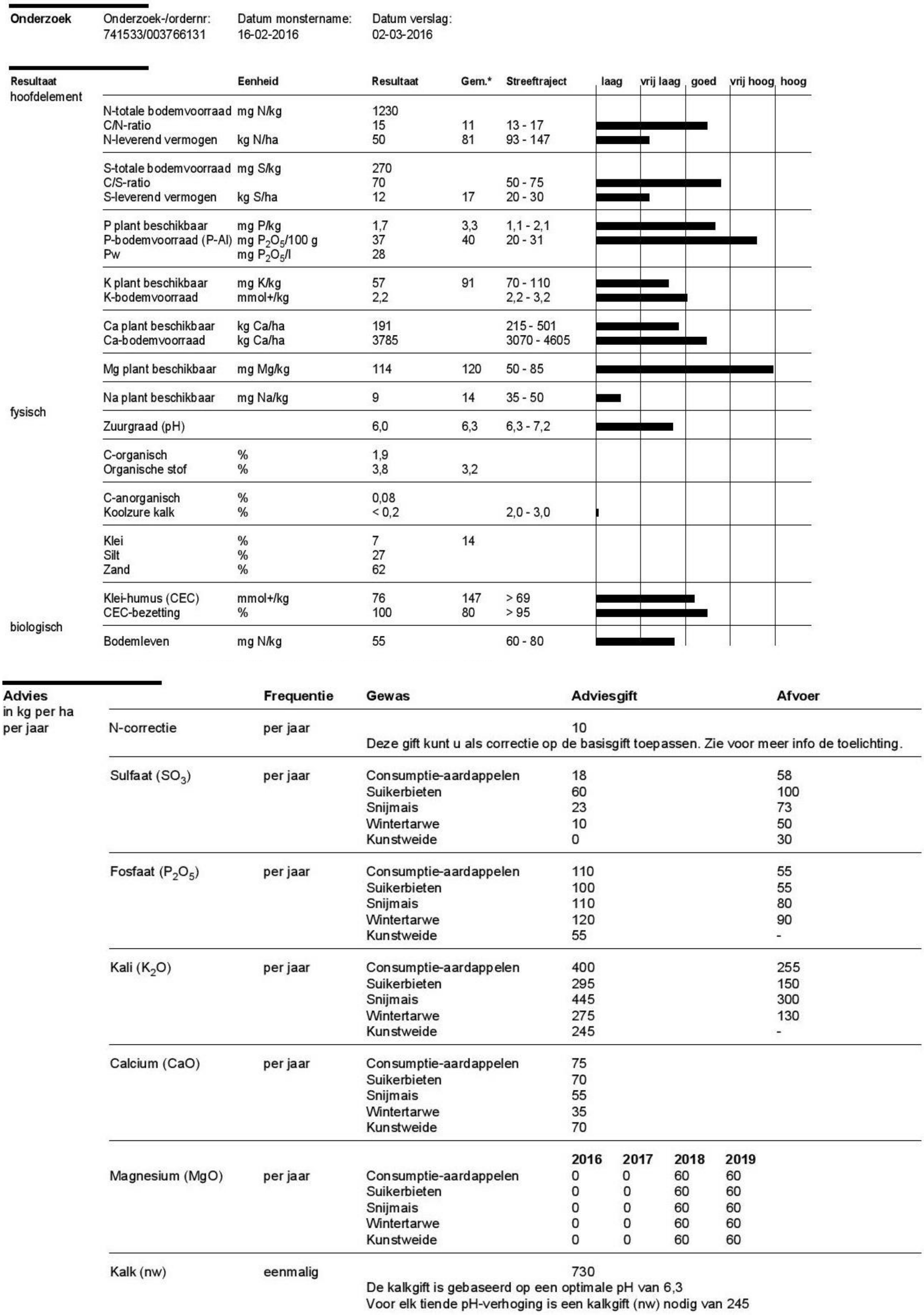
11 Appendix

11.1 Complete soil assessment on arable field, taken in 2016 (H. Coenen, 2018. pers.comm., 18th April)



Onderzoek	Onderzoek-/ordernr:	Datum monstername:	Datum verslag:
	741533/003766131	16-02-2016	02-03-2016

Resultaat		**Eenheid**	**Resultaat**	**Gem.***	**Streeftraject**	**laag**	**vrij laag**	**goed**	**vrij hoog**	**hoog**
hoofdelement	N-totale bodemvoorraad	mg N/kg	1230							
	C/N-ratio		15	11	13 - 17					
	N-leverend vermogen	kg N/ha	50	81	93 - 147					
	S-totale bodemvoorraad	mg S/kg	270							
	C/S-ratio		70		50 - 75					
	S-leverend vermogen	kg S/ha	12	17	20 - 30					
	P plant beschikbaar	mg P/kg	1,7	3,3	1,1 - 2,1					
	P-bodemvoorraad (P-Al)	mg P_2O_5/100 g	37	40	20 - 31					
	Pw	mg P_2O_5/l	28							
	K plant beschikbaar	mg K/kg	57	91	70 - 110					
	K-bodemvoorraad	mmol+/kg	2,2		2,2 - 3,2					
	Ca plant beschikbaar	kg Ca/ha	191		215 - 501					
	Ca-bodemvoorraad	kg Ca/ha	3785		3070 - 4605					
	Mg plant beschikbaar	mg Mg/kg	114	120	50 - 85					
	Na plant beschikbaar	mg Na/kg	9	14	35 - 50					
fysisch	Zuurgraad (pH)		6,0	6,3	6,3 - 7,2					
	C-organisch	%	1,9							
	Organische stof	%	3,8	3,2						
	C-anorganisch	%	0,08							
	Koolzure kalk	%	< 0,2		2,0 - 3,0					
	Klei	%	7	14						
	Silt	%	27							
	Zand	%	62							
	Klei-humus (CEC)	mmol+/kg	76	147	> 69					
	CEC-bezetting	%	100	80	> 95					
biologisch	Bodemleven	mg N/kg	55		60 - 80					

Advies in kg per ha per jaar		**Frequentie**	**Gewas**	**Adviesgift**	**Afvoer**
	N-correctie	per jaar		10	
			Deze gift kunt u als correctie op de basisgift toepassen. Zie voor meer info de toelichting.		
	Sulfaat (SO_3)	per jaar	Consumptie-aardappelen	18	58
			Suikerbieten	60	100
			Snijmais	23	73
			Wintertarwe	10	50
			Kunstweide	0	30
	Fosfaat (P_2O_5)	per jaar	Consumptie-aardappelen	110	55
			Suikerbieten	100	55
			Snijmais	110	80
			Wintertarwe	120	90
			Kunstweide	55	-
	Kali (K_2O)	per jaar	Consumptie-aardappelen	400	255
			Suikerbieten	295	150
			Snijmais	445	300
			Wintertarwe	275	130
			Kunstweide	245	-
	Calcium (CaO)	per jaar	Consumptie-aardappelen	75	
			Suikerbieten	70	
			Snijmais	55	
			Wintertarwe	35	
			Kunstweide	70	

			2016	**2017**	**2018**	**2019**
Magnesium (MgO)	per jaar	Consumptie-aardappelen	0	0	60	60
		Suikerbieten	0	0	60	60
		Snijmais	0	0	60	60
		Wintertarwe	0	0	60	60
		Kunstweide	0	0	60	60

Kalk (nw)	eenmalig		730

De kalkgift is gebaseerd op een optimale pH van 6,3
Voor elk tiende pH-verhoging is een kalkgift (nw) nodig van 245

perc duits

Toelichting

De resultaten en/of het advies van dit bemestingsonderzoek kunt u t/m 2019 gebruiken. Laat het perceel daarna opnieuw bemonsteren. Dan krijgt u een betrouwbaar bemestingsadvies gebaseerd op de actuele bodemtoestand.

gebruiksnorm

De adviezen die vermeld worden, zijn gebaseerd op het halen van een landbouwkundig optimale opbrengst op perceelsniveau. Vanuit de wetgeving zijn er gebruiksnormen. Gebruiksnormen gelden op bedrijfsniveau. Als de som van de landbouwkundige adviesgiften hoger is dan de gebruiksnorm, verlaag dan de gift bij de minst behoeftige gewassen. Overleg dit met uw adviseur.
De adviesgift voor fosfaat en kali is als volgt opgebouwd:

- is de gevonden toestand lager dan het streefniveau, dan geldt: adviesgift = reparatiegift + economische gift of afvoer indien deze hoger is.
- is de gevonden toestand gelijk aan het streefniveau, dan geldt: adviesgift = economische gift of afvoer indien deze hoger is.
- is de gevonden toestand hoger dan het streefniveau, dan geldt: adviesgift = economische gift.

De aangegeven afvoer is gebaseerd op de hieronder vermelde gemiddelde opbrengst die is geoogst. Is de werkelijke opbrengst bijvoorbeeld 10% hoger of lager, dan ligt de afvoer ook 10% hoger of lager. Indien achter een gewas geen afvoer staat vermeld, dan zijn gemiddelde afvoerwaarden niet voorhanden.

Gewas	Opbrengst (ton/ha)	Afvoer van oogstrest
Consumptie-aardappelen	50,0	Nee
Suikerbieten	75,0	Nee
Snijmais	50,0	Nee
Wintertarwe	9,5	Ja
Kunstweide	-	-

Indien de stroresten (graan) worden ondergewerkt, dan is de afvoer circa de helft lager.

Stikstof:
De N-levering is lager dan gemiddeld op deze grondsoort. Er wordt daarom geadviseerd om het basisadvies dat geldt voor het gewas te verhogen; deze aanpassing is als N-correctie aangegeven. De N-correctie gaat uit van een groeiseizoen van circa 5 maanden. Als het groeiseizoen korter is, bijv. 4 maanden; dan 4/5 deel van de genoemde N-correctie gebruiken voor verhoging van de N-gift.
Neem voor een toegespitst stikstofadvies een N-mineraalmonster!

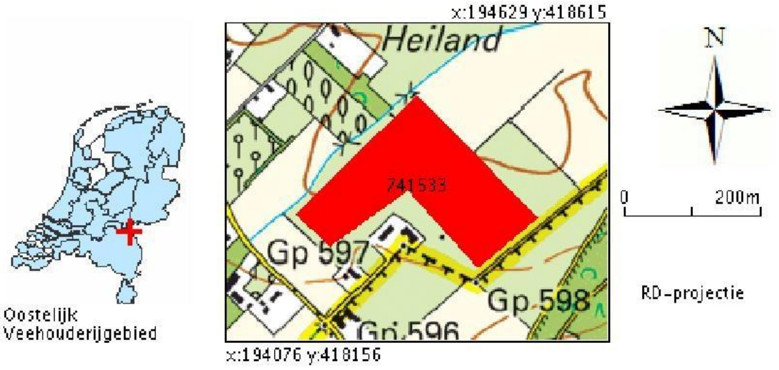
Zwavel:
Bij de adviesgift voor zwavel is rekening gehouden met capillaire opstijging, depositie, S-leverend vermogen (SLV) en onttrekking door het gewas.
Granen: Het zwavelleverend vermogen (SLV) is met name in het voorjaar zeer gering omdat de mineralisatie van S pas in de 2^e helft van het groeiseizoen goed op gang komt. Dit kan bij granen problemen opleveren. Granen hebben met name in het voorjaar een zwavelbehoefte. Ondanks een voldoende toevoer op seizoensbasis kan er dus een gebrek ontstaan in het voorjaar. Aanbevolen wordt om een startgift te geven van 35 kg sulfaat.

Fosfaat:
Op pagina 1 van dit verslag staat de berekende Pw vermeld. Dit getal kunt u gebruiken bij het aanvragen van Flexibele Gebruiksnormen Fosfaat.
Het advies is gebaseerd op de direct beschikbare fosfaat (P-PAE) en op de voorraad fosfaat (P-Al).

Kali:
Kunstweide: De adviesgift geldt voor twee maaisneden. Als u meer of minder dan twee sneden maait, pas de gift dan aan met 80 kg K_2O per snede per ha.

Calcium:
Het calciumadvies is gebaseerd op de hoeveelheid calcium aan het klei-humuscomplex (CEC), voor de plant beschikbare calcium in de bodem (Ca-beschikbaar) en op gewaseigenschappen (o.a. type gewas en gevoeligheid voor Ca-gebrek).
Om de bodemtoestand te handhaven en/of omdat voor bepaalde gewassen de gevoeligheid voor Ca dusdanig is, kan er - ondanks een grote hoeveelheid Ca-beschikbaar - toch nog een Ca-advies gegeven zijn.
De adviesgift moet u nog corrigeren voor de hoeveelheid calcium in meststoffen zoals KAS, (tripel)superfosfaat en kalkmeststoffen.

GIS-info



Hoekpunten perceel: 194352 418511, 194176 418338, 194226 418290, 194339 418372, 194441 418259, 194528 418332, 194352 418511

Org.stofbalans In de gekleurde balk staat de informatie over organische stof (kg/ha) die u moet weten om het organische stofgehalte niet te laten dalen.

Jaarlijks afbraakpercentage van de totale voorraad organische stof: 2,9

- 🟥 Voorraad organische stof die over 1 jaar in de bemonsterde laag nog aanwezig zal zijn als er geen (effectieve) organische stof wordt aangevoerd.
- 🟧 Totaal benodigde aanvoer van effectieve organische stof om percentage organische stof op peil te houden.
- 🟩 Aanvoer via gewasresten (gemiddeld binnen opgegeven bouwplan of gewassen).
- 🟥 Nog aan te vullen via bijv. dierlijke mest, groenbemesters en/of compost.

Gewas(rest)	Aanvoer effectieve organische stof
Consumptie-aardappelen	875
Suikerbieten	1275
Snijmais	660
Wintertarwe	1640
Kunstweide	1600

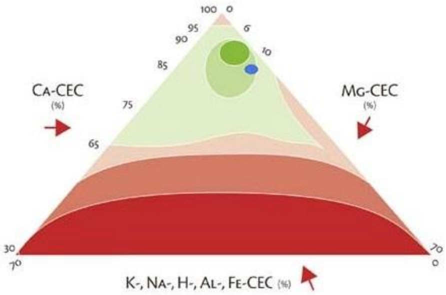
Gemiddelde aanvoer/jaar	1210

Bij granen gaan we uit van afvoer van stro.

Om het organische stofgehalte met 0,1% te verhogen dient u een extra hoeveelheid effectieve organische stof aan te voeren van: 2975 kg per ha.

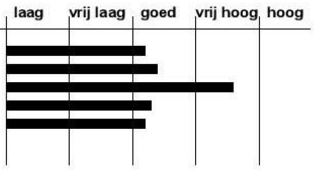
Fysisch De beoordeling van de structuur wordt gedaan op basis van de verhouding tussen calcium, magnesium en overige kationen aan het klei-humuscomplex. Uiteraard is de werkelijke structuur ook afhankelijk van weersomstandigheden en vochttoestand van de bodem tijdens berijden en bewerken en de zwaarte van machines. De beoordeling is een basis voor de realisatie van een goede bodemstructuur.

Weergave onderlinge verhouding van de CEC-bezetting.



- 🟩 optimale structuur
- 🟩 goede structuur
- 🟩 matige structuur
- 🟧 zeer matige structuur
- 🟥 slechte structuur
- 🟥 zeer slechte structuur
- ● huidige situatie van dit perceel

	Eenheid	Resultaat	Streeftraject
Klei-humus (CEC)	mmol+/kg	76	> 69
Ca-bezetting	%	84	80 - 90
Mg-bezetting	%	13	6,0 - 10
K-bezetting	%	2,9	2,0 - 5,0
Na-bezetting	%	1,1	1,0 - 1,5
H-bezetting	%	< 0,1	< 1,0
Al-bezetting	%	< 0,1	< 1,0



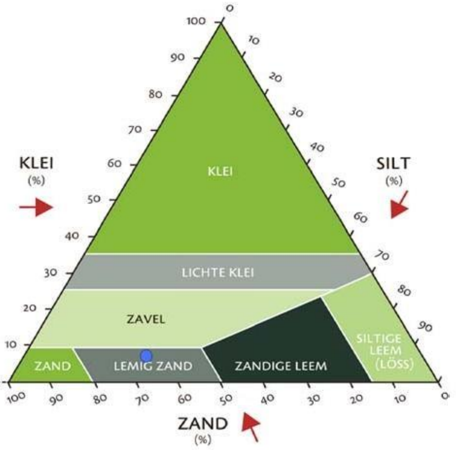
in kg per ha per jaar

	Frequentie	Adviesgift
Calcium (CaO)	eenmalig	65
Magnesium (MgO)	eenmalig	0

De geadviseerde hoeveelheid calcium (CaO) is om een optimale bezetting aan het complex te realiseren. Let op: mogelijk krijgt u ook een calciumgift voor uw gewas en/of een kalkgift geadviseerd. U hoeft niet meerdere keren calcium te geven. Calcium uit stikstof-, fosfaat- en kalkmeststoffen (zie kalkgift) dient u hierop in mindering te brengen.

perc duits

Fysisch Weergave van de textuurdriehoek.



Naast klei (lutum), worden ook de silt- en zandfracties weergegeven. Klei is kleiner dan 2 micrometer (µm), siltdeeltjes zijn 2-50 µm en zanddeeltjes groter dan 50 µm. De onderlinge verdeling van bodemdeeltjes wordt onder andere gebruikt om het verslempingsrisico van een bodem in te schatten. Bij verslemping wordt de bodem dichtgesmeerd met kleinere deeltjes (klei en silt). Een heel eenzijdige verdeling (bijvoorbeeld hoofdzakelijk zand- of kleideeltjes) levert het minste risico van slemp op. Bij een bepaalde verhouding aan bodemdeeltjes met 10-20% klei is het risico op slemp het grootst.

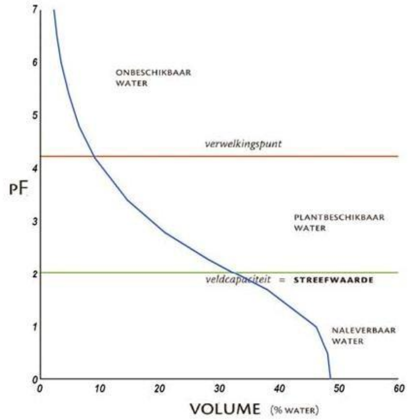
Indicatie van % afslibbaar = % klei + (0,3 * % silt) = 15

	Eenheid	Waardering	Streeftraject	laag	vrij laag	goed	zeer goed
Verkruimelbaarheid	rapportcijfer	9,3	6,0 - 8,0	■	■	■	■
Verslemping	rapportcijfer	6,3	6,0 - 8,0	■	■	■	

De verkruimelbaarheid is goed te noemen. Echter is dit ook afhankelijk van de soort teelt.

Gezien het resultaat is de kans op verslemping klein.

Weergave van de waterretentiecurve.



De hoeveelheid plant beschikbaar water in de bemonsterde laag is 59 mm. Dit is wat u maximaal zou moeten beregenen. Alles wat u meer geeft spoelt af van het perceel of zakt naar diepere lagen. Gewassen hebben moeite om voldoende water op te nemen als het vochtgehalte van het perceel onder pF 2,7 daalt. Wanneer u het vochtgehalte kan bepalen, begin dan met beregenen als het vochtgehalte van dit perceel op 22,2 % vocht zit en geef dan 27 mm.

Het actuele vochtgehalte kan bepaald worden door een vochtsensor of verzamel grond van een tiental plekken in het perceel. Meet het gewicht van de vochtige grond en het gewicht van de grond na 24 uur drogen. Het verschil tussen de twee is een indicatie van het vochtgehalte van het perceel.

perc duits

Fosfaat

Op de voorkant van het verslag staan de resultaten voor fosfaat op de gebruikelijke manier gepresenteerd: een getal en een waarderingsbalkje. De cijfers zijn ook verwerkt in een 'bodemprofiel' (zie figuur). Hierin geven we de fosfaatvoorraad en de beschikbare hoeveelheid P met kleuren aan. De pijl symboliseert de nalevering vanuit de voorraad. De dikte van de pijl toont hoeveel nalevering van fosfaat fosfaat per groeiseizoen mogelijk is.

P-buffering is 22
Dit valt binnen het streeftraject van 17 - 27
De P-bodemvoorraad zal de plant beschikbare P op peil kunnen houden.

Gemiddelde

Op de voorzijde van dit verslag zijn regiogemiddelden weergegeven. Hiermee kunt u uw resultaten vergelijken met overeenkomstige percelen uit uw regio. Indien we onvoldoende gegevens hebben - als gevolg van te weinig geanalyseerde grondmonsters - zijn landelijke gemiddelden berekend.

Het gemiddelde is berekend voor de situatie:

Regio:	Landelijk
Grondsoort:	Löss
Teeltgroep:	Akker-/tuinbouw

De meest opvallende afwijkende resultaten (max. 5) ten opzichte van het gemiddelde én streeftraject zijn weergegeven in onderstaande tabel:

	Resultaat	Gem.	Streeftraject
N-leverend vermogen	50	81	93 - 147
K plant beschikbaar	57	91	70 - 110
Na plant beschikbaar	9	14	35 - 50
Klei-humus (CEC)	76	147	> 69

Contact & info

Bemonsterde laag: 0 - 25 cm
Grondsoort: Lemig zand
Monster genomen door: Eurofins Agro, Sander Schuurman
Contactpersoon monstername: Patrick Bens: 0652002106
Bemonsteringsmethode: W-patroon, min. 40 steken; volgens Eurofins Agro standaard MIN 1000 Q
Specificatie oppervlakte: Groot perceel, 3-5 ha

Na verzending van dit verslag wordt, indien de aard en de onderzoeksmethode van het monster dit toelaat, het monster nog twee weken bij Eurofins Agro voor u bewaard. Binnen deze tijd kunt u eventueel reclameren en/of aanvullend onderzoek aanvragen.

Methode

N-totale bodemvoorraad	Q	Em: NIRS (TSC®)	C-organisch	Q	Em: NIRS (TSC®)
C/N-ratio		afgeleide waarde	Organische stof		afgeleide waarde
N-leverend vermogen		afgeleide waarde	C-anorganisch		Em: NIRS (TSC®)
S-totale bodemvoorraad	Q	Em: NIRS (TSC®)	Koolzure kalk		afgeleide waarde
C/S-ratio		afgeleide waarde	Klei		Em: NIRS (TSC®)
S-leverend vermogen		afgeleide waarde	Silt		Em: NIRS (TSC®)
P plant beschikbaar	Q	Em: CCL3(PAE®)	Zand		Em: NIRS (TSC®)
P-bodemvoorraad (P-Al)	Q	PAL1: Gw NEN 5793	Klei-humus (CEC)		Em: NIRS (TSC®)
Pw		afgeleide waarde	Ca-bezetting		Em: NIRS (TSC®)
K plant beschikbaar	Q	Em: CCL3(PAE®)	Mg-bezetting		Em: NIRS (TSC®)
K-bodemvoorraad		Em: NIRS (TSC®)	K-bezetting		Em: NIRS (TSC®)
Ca plant beschikbaar		afgeleide waarde	Na-bezetting		Em: NIRS (TSC®)
Ca-bodemvoorraad		afgeleide waarde	H-bezetting		afgeleide waarde
Mg plant beschikbaar	Q	Em: CCL3(PAE®)	Al-bezetting		afgeleide waarde
Na plant beschikbaar	Q	Em: CCL3(PAE®)	CEC-bezetting		afgeleide waarde
Zuurgraad (pH)		Em: NIRS (TSC®)	Bodemleven		Em: NIRS (TSC®)

Q Methode geaccrediteerd door RvA
Em: Eigen methode, Gw: Gelijkwaardig aan, Cf: Conform
P-bodemvoorraad (P-Al) Deze analyse is in duplo uitgevoerd.

De resultaten zijn weergegeven in droge grond.
Alle verrichtingen zijn binnen de gestelde houdbaarheidstermijn tussen monstername en analyse uitgevoerd.

11.2 A table listing all sample coordinates and corresponding codes

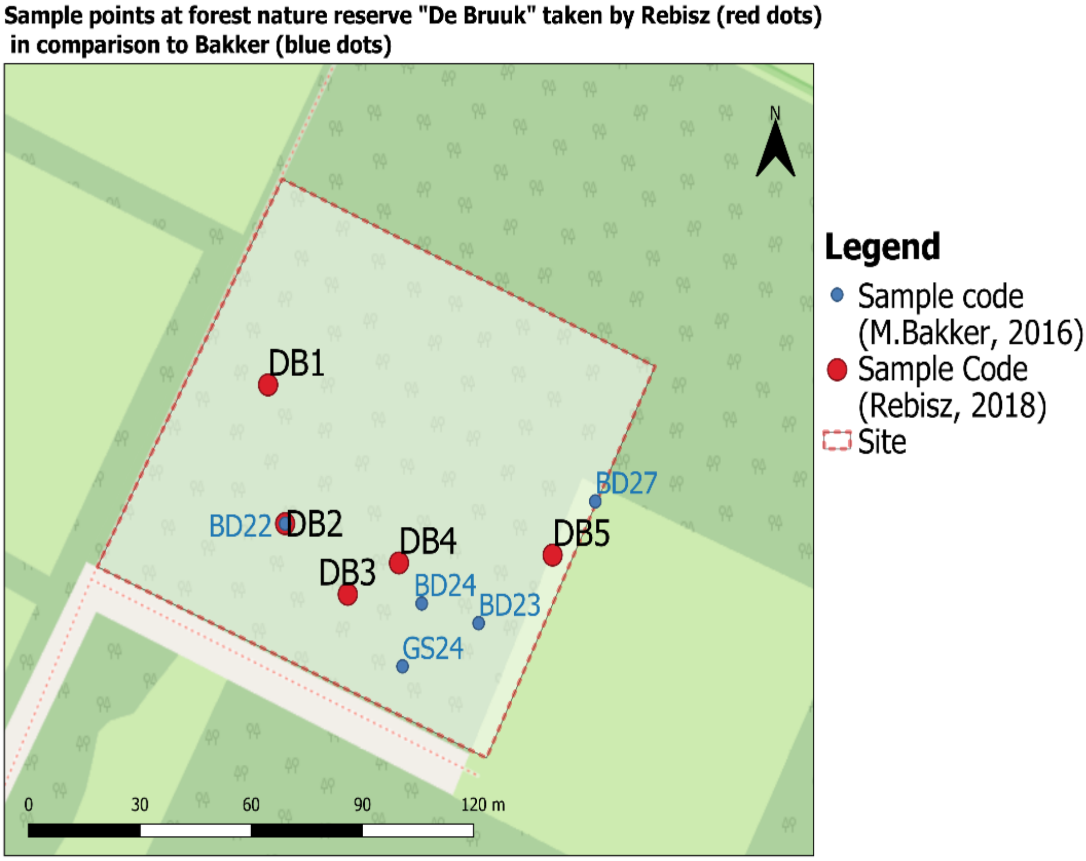
Table 11.1:A list of all the sample locations and Bakker's soil sampling locations in relation to old and new coding (Bakker, 2016)

Rebisz sample code	Longitude (N)	Latitude (E)	Bakker's sample code
FF1	51°46'7.73"N	5°57'58.95"E	BD10
FF2	51°46'8.33"N	5°58'0.92"E	BD2
FF3	51°46'8.92"N	5°58'3.84"E	GS3
FF4	51°46'8.60"N	5°57'57.27"E	GS4
FF5	51°46'9.79"N	5°57'58.40"E	BD6
AF6	51°46'7.21"	5°58'3.45"	/
DB1	51°45'51.7"N	5°57'51.8"E	N/A (new point)
DB2	51°45'51.7"N	5°57'51.8"E	BD22
DB3	51°45'50.43"N	5°57'51.36"E	Originally: GS24 51°45'49.30"N, 5°57'52.70"E
DB4	51°45'49.30"N	5°57'52.70"E	BD24
DB5	51°45'50.4"N	5°57'55.8"E	BD27
CF1	51°45'12.7"N	5°57'25.6"E	/
CF2	51°45'11.3"N	5°57'25.5"E	/
CF3	51°45'11.2"N	5°57'26.7"E	/
CF4	51°45'11.4"N	5°57'27.8"E	/
CF5	51°45'10.5"N	5°57'30.2"E	/

Table 11.2: Coordinates for all soil compaction measurement locations

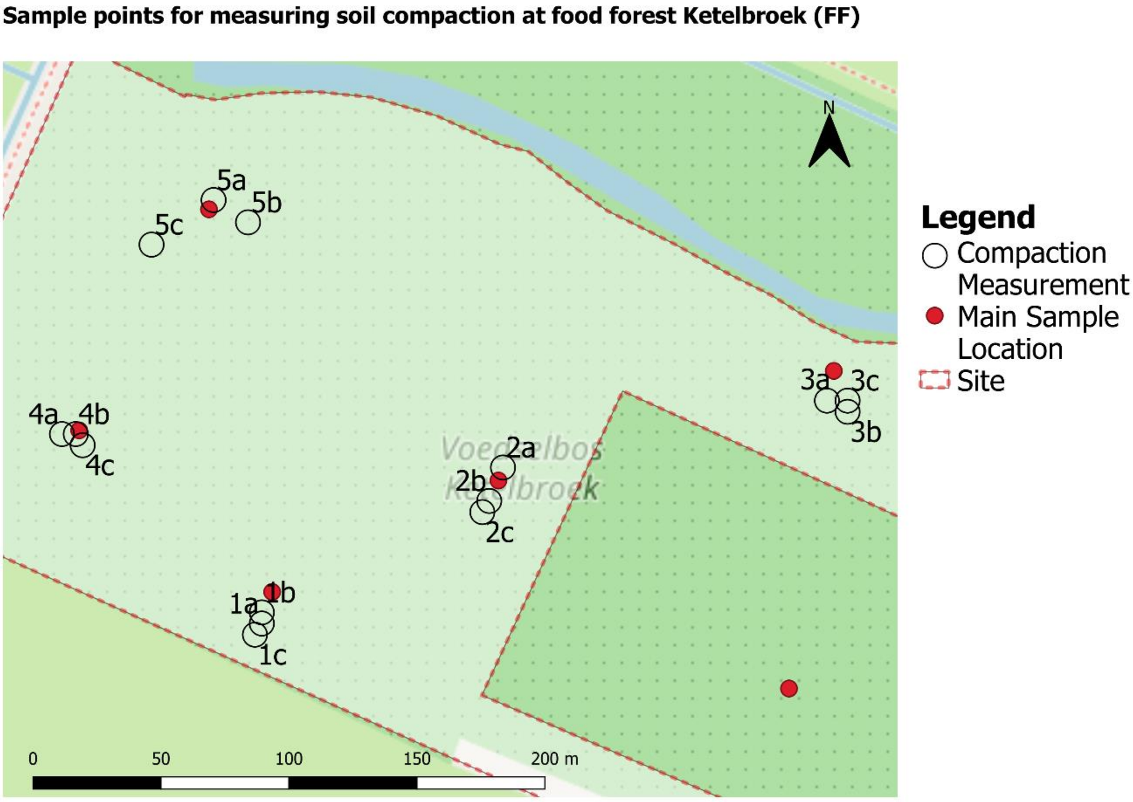
Site Code	Latitude	Longitude	Sample #
FF1a	N51 46.126	E005 57.981	1a
FF1b	N51 46.127	E005 57.981	1b
FF1c	N51 46.125	E005 57.980	1c
FF2a	N51 46.140	E005 58.016	2a
FF2b	N51 46.137	E005 58.014	2b
FF2c	N51 46.136	E005 58.013	2c
FF3a	N51 46.146	E005 58.063	3a
FF3b	N51 46.145	E005 58.066	3b
FF3c	N51 46.146	E005 58.066	3c
FF4a	N51 46.143	E005 57.952	4a
FF4b	N51 46.143	E005 57.954	4b
FF4c	N51 46.142	E005 57.955	4c
FF5a	N51 46.164	E005 57.974	5a
FF5b	N51 46.162	E005 57.979	5b
FF5c	N51 46.160	E005 57.965	5c

DB1a	N51 45.858	E005 57.850	1a
DB1b	N51 45.852	E005 57.862	1b
DB1c	N51 45.855	E005 57.853	1c
DB2a	N51 45.837	E005 57.867	2a
DB2b	N51 45.849	E005 57.865	2b
DB2c	N51 45.844	E005 57.866	2c
DB3a	N51 45.831	E005 57.892	3a
DB3b	N51 45.833	E005 57.882	3b
DB3c	N51 45.837	E005 57.884	3c
DB4a	N51 45.835	E005 57.894	4a
DB4b	N51 45.840	E005 57.894	4b
DB4c	N51 45.834	E005 57.891	4c
DB5a	N51 45.842	E005 57.930	5a
DB5b	N51 45.839	E005 57.928	5b
DB5c	N51 45.838	E005 57.933	5c
CF1a	N51 45.212	E005 57.431	1a
CF1b	N51 45.211	E005 57.431	1b
CF1c	N51 45.212	E005 57.432	1c
CF2a	N51 45.188	E005 57.423	2a
CF2b	N51 45.188	E005 57.422	2b
CF2c	N51 45.187	E005 57.422	2c
CF3a	N51 45.186	E005 57.445	3a
CF3b	N51 45.187	E005 57.446	3b
CF3c	N51 45.188	E005 57.446	3c
CF4a	N51 45.188	E005 57.459	4a
CF4b	N51 45.187	E005 57.461	4b
CF4c	N51 45.188	E005 57.461	4c
CF5a	N51 45.173	E005 57.507	5a
CF5b	N51 45.174	E005 57.507	5b
CF5c	N51 45.174	E005 57.509	5c



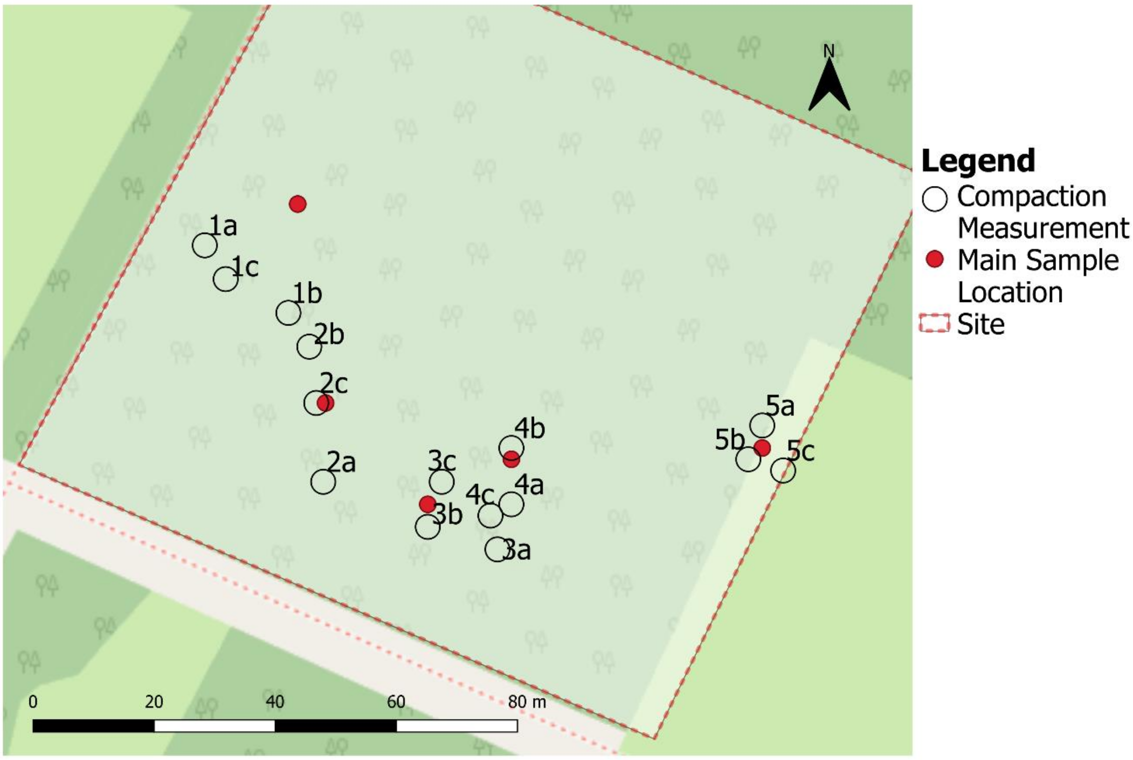
Sample points at forest nature reserve "De Bruuk" taken by Rebisz (red dots) in comparison to Bakker (blue dots)

Figure A: A map showing sample points numbered according to Bakker's (2016) sampling locations and Rebisz’s (2018) at nature reserve "De Bruuk" (DB).

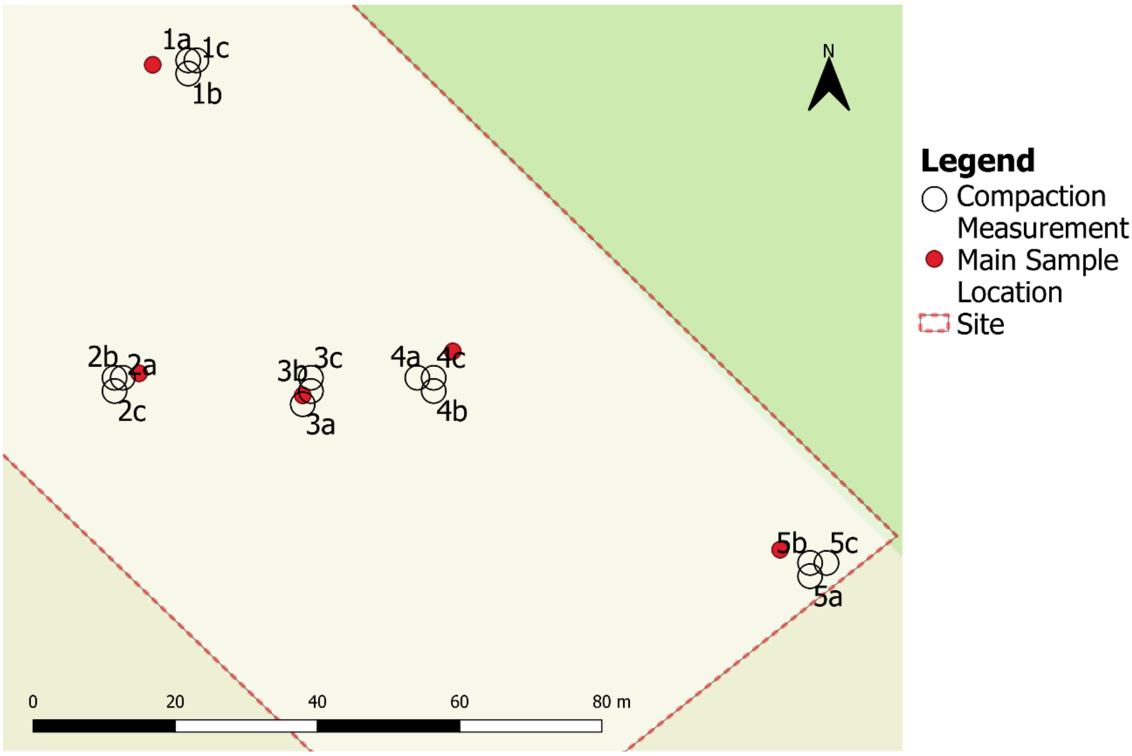


Sample points for measuring soil compaction at food forest Ketelbroek (FF)

Sample points for measuring soil compaction at forest nature reserve "De Bruuk" (DB)



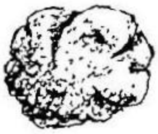
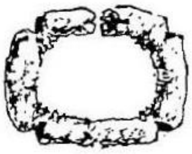
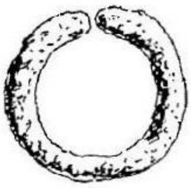
Sample points for measuring soil compaction at the conventional farm (CF)



11.3 Soil texture guide (Gooren et al. 2017, pg. 8)

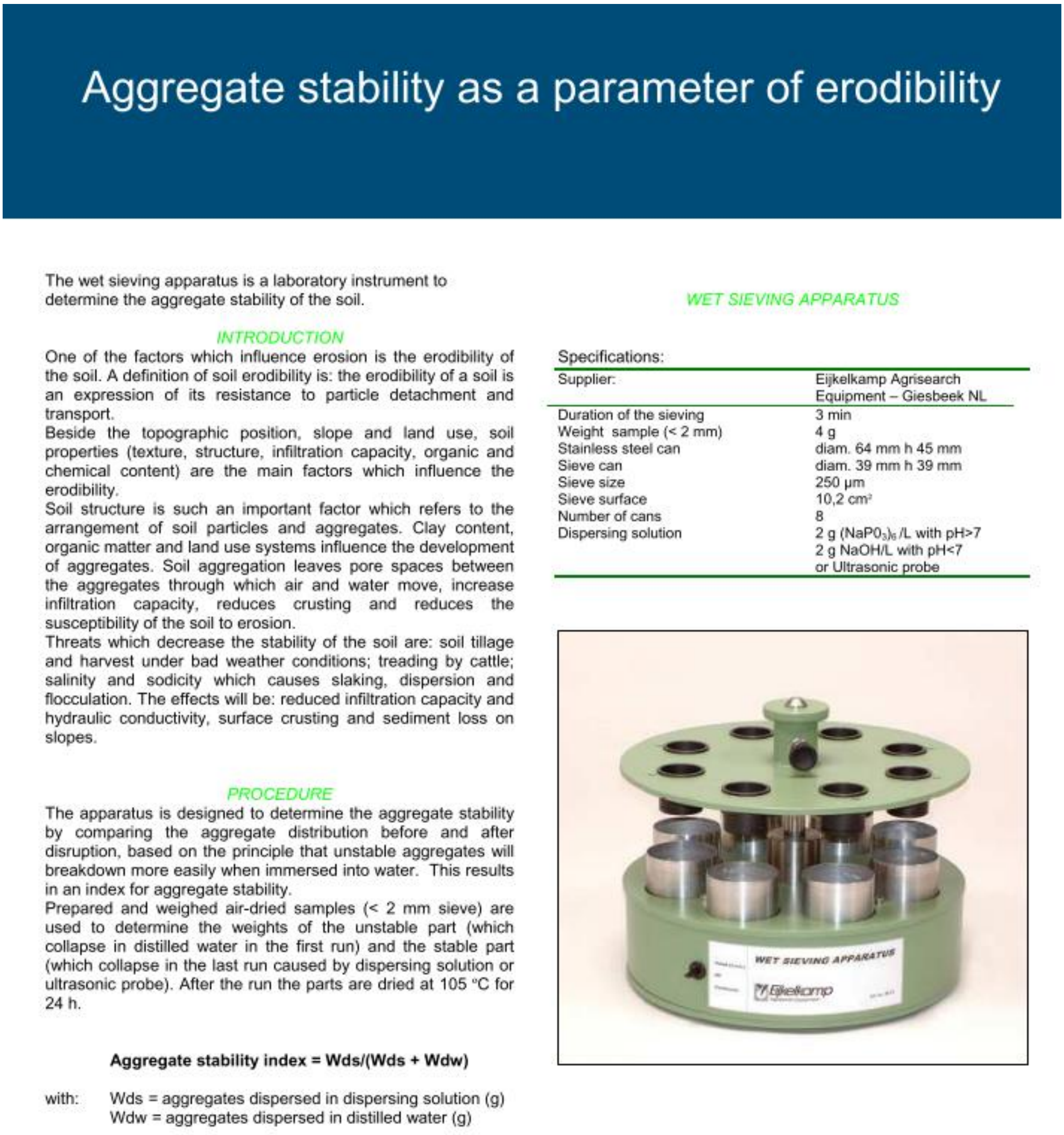
- **Texture** of the soil is one of the most important indicators. It contains a lot of information about the erodibility of a soil, possible cation exchange, pores and available water, infiltration behaviour etc. It can easily be determined with the help of the following description:
  - **Take a small handful** of fine earth from the soil as your sample.
  - Slowly **add small amounts of water**, **mix** it very well with the sample, and try to **form** a ball. Stop adding water as soon as the ball starts to stick to your hand.
  - Soil texture can roughly be estimated by using this moist sample. Try to **form** the sample into the **different shapes** shown in the graph below. If you do not have sand, start from the second picture and see how many of the shapes you can form with your sample. The last shape that you are able to form with your sample will tell you the soil texture.

> **Note:** *Texture classes 1 to 4 are sandy to silty soils, which have generally better infiltration. Texture classes 5 to 7 are clay soils which have generally poorer infiltration. Needless to say, this is a rough estimation which needs to be confirmed by laboratory analysis if you wish to extend your observation to a soil survey!*

1. The soil remains loose and single grained; it can only be heaped into a pyramid:	**Sand**	
2. The soil contains sufficient silt and clay to become somewhat cohesive; it can be shaped into a ball that easily falls apart:	**Loamy Sand**	
3. The soil can be rolled into a short, thick cylinder approximately the diameter of a pencil:	**Silt Loam**	
4. This cylinder can be rolled into a thinner cylinder about 15 cm long:	**Loam**	
5. The thinner cylinder can be bent into a U-shape:	**Clay Loam**	
6. The U-shaped cylinder can be bent to form a circle that shows cracks:	**Light Clay**	
7. The U-shaped cylinder can be bent to form a circle without showing cracks:	**Heavy clay**	

Soil colour info: http://soilsteaching.uga.edu/pedology/Munsell.pdf

11.4 Standard Procedure for Aggregate Stability Using Wet Sieving Test (adopted from WUR, n.d.)



Aggregate stability as a parameter of erodibility

The wet sieving apparatus is a laboratory instrument to determine the aggregate stability of the soil.

INTRODUCTION

One of the factors which influence erosion is the erodibility of the soil. A definition of soil erodibility is: the erodibility of a soil is an expression of its resistance to particle detachment and transport.

Beside the topographic position, slope and land use, soil properties (texture, structure, infiltration capacity, organic and chemical content) are the main factors which influence the erodibility.

Soil structure is such an important factor which refers to the arrangement of soil particles and aggregates. Clay content, organic matter and land use systems influence the development of aggregates. Soil aggregation leaves pore spaces between the aggregates through which air and water move, increase infiltration capacity, reduces crusting and reduces the susceptibility of the soil to erosion.

Threats which decrease the stability of the soil are: soil tillage and harvest under bad weather conditions; treading by cattle; salinity and sodicity which causes slaking, dispersion and flocculation. The effects will be: reduced infiltration capacity and hydraulic conductivity, surface crusting and sediment loss on slopes.

PROCEDURE

The apparatus is designed to determine the aggregate stability by comparing the aggregate distribution before and after disruption, based on the principle that unstable aggregates will breakdown more easily when immersed into water. This results in an index for aggregate stability.

Prepared and weighed air-dried samples (< 2 mm sieve) are used to determine the weights of the unstable part (which collapse in distilled water in the first run) and the stable part (which collapse in the last run caused by dispersing solution or ultrasonic probe). After the run the parts are dried at 105 °C for 24 h.

Aggregate stability index = Wds/(Wds + Wdw)

with: Wds = aggregates dispersed in dispersing solution (g)
Wdw = aggregates dispersed in distilled water (g)

WET SIEVING APPARATUS

Specifications:

Supplier:	Eijkelkamp Agrisearch Equipment – Giesbeek NL
Duration of the sieving	3 min
Weight sample (< 2 mm)	4 g
Stainless steel can	diam. 64 mm h 45 mm
Sieve can	diam. 39 mm h 39 mm
Sieve size	250 µm
Sieve surface	10,2 cm²
Number of cans	8
Dispersing solution	2 g $(NaP0_3)_6$ /L with pH>7 2 g NaOH/L with pH<7 or Ultrasonic probe

Procedure (elaborated)

1. The metal cups were filled with distilled water (a few mm. below the top). It was checked to see that no water will overflow when the rack with the soil samples is fully submerged inside the metal cups.

2. 4 g. of prepared soil (sieved at 2mm) was placed into the black inner cup, a duplicate was made for the same soil sample.

3. Step 4 was repeated for the remaining soil samples.
4. Then, the rack was submerged into the water and allowed to soak for a few seconds.
5. Once the rack was secured in the right position, wet sieving apparatus was switched on. The automatic sieving programme took 3 minutes.
6. Afterwards, the rack was raised to the higher level (no longer being in contact with water) and allowed to drain any remaining water in the black cups.
7. During this time, plastic cups were weighted to three decimal points and labelled accordingly.
8. The metal cups were then emptied individually into their corresponding plastic cup, a wash bottle with distilled water was used to collect the remaining soil aggregates into the plastic cups.
9. Then, the metal cups were rinsed and cleaned. The metal cups were filled with either $NaPo_3$ or NaOH solution, according to the pH of the soil sample (which was measured earlier). $NaPo_3$ was used when the soil pH was above 7, NaOH was used when the pH was below 7. The metal cups were placed back into the wet sieving apparatus accordingly.
10. The rack containing the black inner cups were lowered into the dispersion solution and the apparatus was turned on for another 3-minute run.
11. Afterwards, the rack was lifted again and checked if the remaining stable soil aggregates dissolved into the solution. If there were still some soil remains (apart from small stones and root hairs), the black inner cups was then lowered and submerged again, and a glass stick was used to stir the remains into the dispersion solution.
12. Once this was done, the metal cups were emptied into their corresponding plastic cups and labelled accordingly.
13. All plastic cups were placed into a drying oven at 105°C until all water had evaporated.
14. Once done, the plastic cups were weighed and recorded.

11.5 Standard Procedure for Soil Organic Matter Content (adapted from Bakker, 2016; Heiri, Lotter, & Lemcke, 2001; Slier et al., 2018)

1. Principle of the method

The organic matter of the soil samples is measured gravimetrically by dry combustion of the organic material in a furnace at 550°C. The loss in the weight gives an indication of the content of organic matter in the sample. Also, at such high temperatures, several soil components besides carbon are lost. No corrections are made for the losses of weight for the following phenomena: $CaCO_3$ decomposition (loss of CO_2), structural water released from the crystal lattice and NaCl vitalization.

2. Apparatus

a. Drying oven
b. Furnace (capable of reaching and maintaining a temperature of at least 550°C
c. Weighing scale accurate to three decimal places

3. Procedure

a. An empty crucible was first weighed to three decimal places and label accordingly. (W_0)
b. Then, 5 g. of soil was weighted and placed into the empty crucible (W_w)
c. The crucible with the soil sample was then placed into a drying oven at 105°C for 24 hours
d. After 24 hours, the weight of the crucible was measured and recorded (W_d)
e. The same crucible is then placed into the furnace. The temperature was raised gradually from room temperature to 550°C. The sample remained in the furnace at this temperature for 4 hours.
f. After 4 hours, the furnace was switched off and allowed to cool to ≤150°C.
g. The crucible with the combusted soil sample was then weighted and recorded (W_c).

4. Calculation

First, the soil moisture content was also calculated using the formula:

$$Soil\ moisture = \frac{w_w - w_d}{w_d} \times 100 = \frac{weight\ of\ wet\ soil - weight\ of\ dry\ soil}{weight\ of\ dry\ soil} \times 100$$

Expressed in percentage (%).

The soil organic matter content was calculated using the formula:

$$SOM = \frac{w_d - w_c}{w_c} \times 100$$

$$= \frac{weight\ of\ dry\ soil - weight\ of\ combusted\ soil}{weight\ of\ combusted\ soil} \times 100$$

Expressed in percentage (%)

11.6 Raw data

11.6.1 Overview of dataset: results of nine soil quality indicators

(Compaction and earthworm datasets are found in Appendix 11.6.9 & 11.6.15)

Site Code	Sample Code	Soil temp. (°C)	Soil texture	Soil colour	Soil Moisture (%)	pH	Organic Matter content (%)	Soil Organic Carbon (%)	Bulk Density (g/cm^3)	Aggregate Stability
FF1	FF1$_{0}$	9.6	loam	2.5Y 3/2	29.94	5.04	7.61	3.81	1.14	0.77
	FF1$_{30}$	8.1	sandy loam	2.5Y 4/3	22.49	5.11	4.09	2.04	1.30	0.66
FF2	FF2$_{0}$	9.7	loam	2.5Y 3/2	28.97	6.98	6.71	3.35	1.14	0.66
	FF2$_{30}$	8.3	sandy loam	2.5Y 3/3	21.82	6.61	4.96	2.48	1.34	0.57
FF3	FF3$_{0}$	10.2	silty loam	2.5Y 3/3	27.40	4.99	6.21	3.10	1.01	0.78
	FF3$_{30}$	8.2	sandy loam	2.5Y 4/2	19.25	5.68	2.15	1.08	1.41	0.71
FF4	FF4$_{0}$	10.7	sandy loam	2.5Y 3/2	26.42	6.43	7.63	3.82	1.13	0.80
	FF4$_{30}$	8.5	sandy loam	2.5Y 4/2	21.99	5.74	4.97	2.49	1.10	0.78
FF5	FF5$_{0}$	9.1	clay loam	10Y 4/2	28.41	6.66	5.39	2.69	1.20	0.71
	FF5$_{30}$	7.5	silty loam	10Y 4/3	22.31	6.03	4.30	2.15	1.36	0.54
AF6	AF6$_{0}$	8.9	light clay	10Y 4/2	25.72	6.78	6.31	3.15	1.27	0.54
	AF6$_{30}$	7.3	silty loam	2.5Y 3/3	19.16	6.12	4.09	2.04	1.45	0.25
DB1	DB1$_{0}$	9	clay loam	10Y 2/1	60.98	4.15	23.25	11.63	0.47	0.74
	DB1$_{30}$	8.6	heavy clay	10Y 4/3	35.50	6.57	2.98	1.49	1.12	0.13
DB2	DB2$_{0}$	9.1	clay loam	10Y 2/1	40.61	3.69	23.11	11.55	0.73	0.62
	DB2$_{30}$	8.6	light clay	10Y 4/2	35.12	5.96	10.79	5.40	1.05	0.65
DB3	DB3$_{0}$	8.8	light clay	10Y 2/2	42.20	4.11	17.59	8.79	0.75	0.77
	DB3$_{30}$	8.1	heavy clay	10Y 4/2	29.99	5.40	6.63	3.32	1.23	0.66
DB4	DB4$_{0}$	9.2	light clay	7.5Y 2/1	52.04	4.05	56.56	28.28	0.54	0.58
	DB4$_{30}$	8.5	heavy clay	10Y 3/3	33.46	6.63	7.49	3.75	1.13	0.62
DB5	DB5$_{0}$	9.1	light clay	10Y 2/3	39.83	4.17	14.96	7.48	0.87	0.66
	DB5$_{30}$	8.3	heavy clay	10Y 4/3	32.38	5.94	5.92	2.96	1.13	0.57

Site Code	**Sample Code**	**Soil temp. (°C)**	**Soil texture**	**Soil colour**	**Soil Moisture (%)**	**pH**	**Organic Matter content (%)**	**Soil Organic Carbon (%)**	**Bulk Density (g/cm^3)**	**Aggregate Stability**
CF1	CF1$_0$	15.6	loam	10Y 3/4	19.71	7.10	4.40	2.20	1.19	0.73
	CF1$_{30}$	11	light clay	10Y 4/4	19.69	6.87	7.88	3.94	1.36	0.88
CF2	CF2$_0$	16.1	sandy loam	10Y 3/3	21.16	7.38	3.27	1.64	1.22	0.77
	CF2$_{30}$	10.6	loam	10Y 4/4	18.08	6.86	4.29	2.15	1.57	0.72
CF3	CF3$_0$	15	loam	10Y 4/3	20.73	7.61	3.99	1.99	1.09	0.71
	CF3$_{30}$	10.6	sandy loam	10Y 4/4	17.90	7.38	4.49	2.25	1.57	0.79
CF4	CF4$_0$	15.7	sandy loam	10Y 3/4	21.38	7.37	3.26	1.63	1.29	0.83
	CF4$_{30}$	10.5	sandy loam	2.5Y 4/3	17.26	6.62	4.37	2.18	1.56	0.67
CF5	CF5$_0$	16.8	sandy loam	10Y 3/4	21.27	6.99	2.94	1.47	1.33	0.78
	CF5$_{30}$	11	sandy loam	10Y 5/2	15.82	7.51	4.65	2.32	1.69	0.50

Soil quality indicators and their respective colour-coded ranges for loess soils, where red are sub-optimal values, orange are medium ranges and green are ideal ranges (taken from , pg. 19)

Indicator	**Range**			**Source**
	Low	*Medium*	*High*	
pH	< 6.5	6.5 - 7	> 7	(Whitefield, 2002 in Limareva, 2014)
Soil moisture (%)	< 20	20 - 30	> 30	(Sparks, 2003)
Bulk density (g/cm^3)	>1.32	1.32 - 1.72	>1.72	(USDA, n.d.)
Soil compaction (kPa)	< 125	125	> 125	(Vermeulen, Verwijs, & van den Akker, 2013)
Aggregate stability (%)	< 30	30 - 50	> 50	(Ohio State University, 2018)
Soil organic matter content (%)	< 4	4 - 8	> 12	(Morari et al., 2016 in Stolte et al., 2016)
Soil organic carbon (%)	< 2	2 - 6	> 6	(EEA, 2012; Aksoy, Yigini, & Montanarella, 2016)
Earthworm abundance (per m^2)	<120	120 - 250	>250	(Pfiffner, 2014)

11.6.2 Aggregate stability: raw data

Sample code	Duplicate A/B	Weight of empty cup (g.)	Weight of dried unstable aggregates in cup (g.)	*Wdu* - Weight of unstable aggregates minus cup (g.)	*Wdu* Average	Weight of empty cup (g.)2	Weight of dried stable aggregates in cup (g.)	*Wds* - Weight of stable aggregates minus cup (g.)	*Wds* Average	**ASI - Aggregate Stability Index (Wds/Wdu+Wds)**	Average ASI (0-35cm)	Average ASI top-layer (0-5cm)	Average ASI sub-layer (30-35 cm)
FF1$_0$	A	11.447	12.246	0.799	0.722	11.409	13.608	2.199	2.414	**0.770**	0.698	0.745	0.651
	B	11.302	11.946	0.644		11.293	13.922	2.629					
FF1$_{30}$	A	11.305	12.722	1.417	1.132	11.293	13.397	2.104	2.159	**0.656**			
	B	11.363	12.210	0.847		11.291	13.505	2.214					
FF2$_0$	A	10.549	11.803	1.254	1.363	8.037	10.753	2.716	2.602	**0.656**			
	B	11.306	12.777	1.471		10.536	13.024	2.488					
FF2$_{30}$	A	10.446	12.330	1.884	1.704	10.545	12.619	2.074	2.214	**0.565**			
	B	7.987	9.511	1.524		10.537	12.891	2.354					
FF3$_0$	A	10.521	11.557	1.036	0.882	11.383	14.364	2.981	3.158	**0.782**			
	B	10.524	11.251	0.727		7.981	11.315	3.334					
FF3$_{30}$	A	10.528	11.805	1.277	1.175	11.397	14.173	2.776	2.871	**0.710**			
	B	11.405	12.477	1.072		8.045	11.011	2.966					
FF4$_0$	A	11.377	11.975	0.598	0.678	11.650	14.403	2.753	2.747	**0.802**			
	B	11.570	12.328	0.758		11.364	14.105	2.741					
FF4$_{30}$	A	11.450	12.136	0.686	0.808	11.431	14.357	2.926	2.830	**0.778**			
	B	11.366	12.296	0.930		11.378	14.112	2.734					
FF5$_0$	A	11.327	12.257	0.930	1.113	10.434	13.392	2.958	2.780	**0.714**			
	B	11.333	12.628	1.295		10.570	13.171	2.601					
FF5$_{30}$	A	10.546	13.232	2.686	1.809	11.270	13.348	2.078	2.164	**0.545**			
	B	11.385	12.317	0.932		11.301	13.550	2.249					
AF6$_0$	A	11.370	13.059	1.689	1.713	11.340	13.398	2.058	2.012	**0.540**			
	B	11.355	13.092	1.737		11.357	13.323	1.966					
AF6$_{30}$	A	11.326	12.874	1.548	7.045	11.360	13.442	2.082	2.330	**0.249**			
	B		12.541	12.541		11.349	13.926	2.577					

Sample code	Duplicate A/B	Weight of empty cup (g.)	Weight of dried unstable aggregates in cup (g.)	Wdu - Weight of unstable aggregates minus cup (g.)	Wdu Average	Weight of empty cup (g.)2	Weight of dried stable aggregates in cup (g.)	Wds - Weight of stable aggregates minus cup (g.)	Wds Average	**ASI - Aggregate Stability Index (Wds/Wdu+Wds)**	Average ASI (0-35cm)	Average ASI top-layer (0-5cm)	Average ASI sub-layer (30-35 cm)
DB1$_{0}$	A1	11.447	11.890	0.443	0.827	10.600	11.415	0.615	2.297	**0.735**	0.601	0.675	0.526
	A2			0.000		11.513	12.048	0.335					
	B1	11.302	12.512	1.210		11.636	13.023	1.187					
	B2			0.000		10.451	13.108	2.457					
DB1$_{30}$	A	11.305	14.805	3.500	3.237	11.290	11.805	0.315	0.502	**0.134**			
	B	11.363	14.336	2.973		11.292	12.181	0.689					
DB2$_{0}$	A	10.542	12.341	1.799	1.530	11.277	13.829	2.352	2.521	**0.622**			
	B	10.427	11.687	1.260		11.299	14.189	2.690					
DB2$_{30}$	A	11.286	13.029	1.743	1.245	11.317	13.359	1.842	2.263	**0.645**			
	B	11.286	12.033	0.747		11.335	14.218	2.683					
DB3$_{0}$	A	11.294	12.323	1.029	0.816	11.297	14.355	2.858	2.743	**0.771**			
	B	11.317	11.920	0.603		11.321	14.148	2.627					
DB3$_{30}$	A	11.300	12.465	1.165	1.293	11.300	14.144	2.644	2.494	**0.659**			
	B	11.279	12.700	1.421		11.281	13.825	2.344					
DB4$_{0}$	A	11.280	13.126	1.846	1.450	11.277	13.253	1.776	2.034	**0.584**			
	B	11.264	12.318	1.054		11.281	13.773	2.292					
DB4$_{30}$	A	11.266	11.892	0.626	1.198	11.289	13.498	2.009	1.960	**0.621**			
	B	11.304	13.074	1.770		11.296	13.407	1.911					
DB5$_{0}$	A	11.260	12.698	1.438	1.477	10.438	13.500	2.862	2.909	**0.663**			
	B	11.275	12.790	1.515		10.571	13.726	2.955					
DB5$_{30}$	A	11.337	13.231	1.894	1.839	11.284	13.917	2.433	2.468	**0.573**			
	B	10.547	12.330	1.783		11.295	13.998	2.503					

Sample code	Duplicate A/B	Weight of empty cup (g.)	Weight of dried unstable aggregates in cup (g.)	Wdu - Weight of unstable aggregates minus cup (g.)	Wdu Average	Weight of empty cup (g.)2	Weight of dried stable aggregates in cup (g.)	Wds - Weight of stable aggregates minus cup (g.)	Wds Average	**ASI - Aggregate Stability Index (Wds/Wdu+Wds)**	Average ASI (0-35cm)	Average ASI top-layer (0-5cm)	Average ASI sub-layer (30-35 cm)
CF1$_{0}$	A	11.362	12.334	0.972	0.973	10.549	13.427	2.678	2.683	**0.734**	0.738	0.766	0.710
	B	11.352	12.326	0.974		10.590	13.477	2.687					
CF1$_{30}$	A	11.306	11.719	0.413	0.445	11.263	14.623	3.160	3.125	**0.875**			
	B	11.279	11.756	0.477		11.283	14.573	3.090					
CF2$_{0}$	A	10.606	11.517	0.911	0.839	8.064	11.050	2.786	2.859	**0.773**			
	B	11.417	12.183	0.766		10.544	13.676	2.932					
CF2$_{30}$	A	10.440	11.448	1.008	1.111	10.537	13.678	2.941	2.821	**0.718**			
	B	7.977	9.190	1.213		10.546	13.447	2.701					
CF3$_{0}$	A	10.558	11.657	1.099	1.090	11.465	14.237	2.572	2.649	**0.708**			
	B	10.514	11.595	1.081		8.004	10.929	2.725					
CF3$_{30}$	A	10.636	11.327	0.691	0.780	11.551	14.614	2.863	2.895	**0.788**			
	B	11.485	12.354	0.869		8.046	11.173	2.927					
CF4$_{0}$	A	10.530	11.223	0.693	0.591	11.335	14.095	2.560	2.897	**0.831**			
	B	10.545	11.033	0.488		11.339	14.773	3.234					
CF4$_{30}$	A	11.265	12.594	1.329	1.339	11.341	14.596	3.055	2.714	**0.670**			
	B	11.265	12.614	1.349		11.424	13.996	2.372					
CF5$_{0}$	A	10.542	11.472	0.930	0.850	10.516	13.671	2.955	3.070	**0.783**			
	B	10.427	11.196	0.769		11.289	14.674	3.185					
CF5$_{30}$	A	11.286	13.152	1.866	1.933	11.307	13.487	1.980	1.931	**0.500**			
	B	11.284	13.283	1.999		11.322	13.404	1.882					

11.6.3 Aggregate stability: ANOVA & Tukey's HSD test results

```
> ANOVA(soildepth=topsoil, SQI="Agregrate.Stability", ylab="Aggregate Stab
ility Index"
            Df  Sum Sq  Mean Sq F value Pr(>F)
studysite    2 0.02233 0.011167   2.817 0.0993 .
Residuals   12 0.04756 0.003963
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
  Tukey multiple comparisons of means
    95% family-wise confidence level

Fit: aov(formula = FMAOVBP, data = soildepth)

$studysite
       diff         lwr        upr     p adj
DB-CF -0.09 -0.19622431 0.01622431 0.1008680
FF-CF -0.02 -0.12622431 0.08622431 0.8715893
FF-DB  0.07 -0.03622431 0.17622431 0.2248421

Call:
   aov(formula = FMAOVBP, data = soildepth)

Terms:
                 studysite  Residuals
Sum of Squares  0.02233333 0.04756000
Deg. of Freedom          2         12

Residual standard error: 0.06295501
Estimated effects may be unbalanced


> ANOVA(soildepth=subsoil, SQI="Agregrate.Stability", ylab="Aggregate Stab
ility Index"
            Df Sum Sq Mean Sq F value Pr(>F)
studysite    2 0.0901 0.04506   1.684  0.227
Residuals   12 0.3211 0.02676
  Tukey multiple comparisons of means
    95% family-wise confidence level

Fit: aov(formula = FMAOVBP, data = soildepth)

$studysite
        diff        lwr        upr     p adj
DB-CF -0.186 -0.4620003 0.09000035 0.2117537
FF-CF -0.060 -0.3360003 0.21600035 0.8331884
FF-DB  0.126 -0.1500003 0.40200035 0.4656050

Call:
   aov(formula = FMAOVBP, data = soildepth)

Terms:
                studysite Residuals
Sum of Squares    0.09012   0.32108
Deg. of Freedom         2        12

Residual standard error: 0.1635747
Estimated effects may be unbalanced
```

11.6.4 Bulk density & soil moisture raw data

Sample Code	Ring #	Tray ID	Weight of tray (g.)	Weight of ring sample on tray (g.)	Weight of soil sample - tray - ring (g.)	Weight after drying (g.)	Weight of dry soil sample (g.)	Weight of tray (g.)	Weight of empty ring (g.)	Bulk Density (g/cm³)	Soil moisture content (%)
FF1$_{0}$	343	H39	8.20	267.65	162.62	218.97	113.93	8.21	96.83	1.14	29.94
FF1$_{30}$	344	195	8.08	272.90	167.96	235.13	130.19	8.08	96.86	1.30	22.49
FF2$_{0}$	345	234	7.47	264.11	159.90	217.79	113.58	7.47	96.74	1.14	28.97
FF2$_{30}$	346	248	8.13	276.22	171.03	238.90	133.71	8.13	97.06	1.34	21.82
FF3$_{0}$	347	249	8.14	243.35	138.52	205.39	100.56	8.14	96.69	1.01	27.40
FF3$_{30}$	348	281	8.01	279.96	175.13	246.25	141.41	8.02	96.82	1.41	19.25
FF4$_{0}$	337	H407	8.18	257.74	153.19	217.28	112.72	8.19	96.37	1.13	26.42
FF4$_{30}$	338	H412	8.03	245.60	140.54	214.69	109.63	8.03	97.03	1.10	21.99
FF5$_{0}$	339	H449	8.09	272.31	167.44	224.77	119.87	8.12	96.78	1.20	28.41
FF5$_{30}$	340	H480	8.17	280.71	175.21	241.62	136.12	8.17	97.33	1.36	22.31
AF6$_{0}$	341	H696	8.47	275.86	170.96	231.88	126.99	8.46	96.43	1.27	25.72
AF6$_{30}$	342	H855	7.87	284.27	179.52	249.88	145.13	7.87	96.88	1.45	19.16
DB1$_{0}$	325	H39	8.20	224.77	120.08	151.57	46.86	8.22	96.49	0.47	60.98
DB1$_{30}$	326	195	8.08	278.03	173.37	216.49	111.82	8.09	96.58	1.12	35.50
DB2$_{0}$	333	234	7.47	222.27	122.15	172.67	72.55	7.47	92.65	0.73	40.61
DB2$_{30}$	334	248	8.12	266.71	162.40	209.71	105.36	8.16	96.19	1.05	35.12
DB3$_{0}$	327	249	8.14	234.91	130.13	179.99	75.21	8.14	96.64	0.75	42.20
DB3$_{30}$	328	281	8.00	280.23	175.98	227.48	123.21	8.02	96.25	1.23	29.99
DB4$_{0}$	329	H449	8.08	217.69	113.22	158.79	54.30	8.10	96.39	0.54	52.04
DB4$_{30}$	336	H480	8.16	275.72	170.43	218.71	113.41	8.17	97.13	1.13	33.46
DB5$_{0}$	331	H696	8.45	248.86	144.23	191.43	86.78	8.47	96.18	0.87	39.83
DB5$_{30}$	332	H855	7.86	271.31	167.13	217.22	113.01	7.89	96.32	1.13	32.38
CF1$_{0}$	330	H39	8.19	253.75	148.72	224.43	119.40	8.19	96.84	1.19	19.71
CF1$_{30}$	331	195	8.07	273.50	169.25	240.17	135.92	8.07	96.18	1.36	19.69
CF2$_{0}$	332	234	7.46	258.29	154.51	225.60	121.81	7.47	96.32	1.22	21.16
CF2$_{30}$	333	248	8.12	292.05	191.28	257.47	156.69	8.13	92.65	1.57	18.08
CF3$_{0}$	334	249	8.14	241.54	137.21	213.09	108.76	8.14	96.19	1.09	20.73
CF3$_{30}$	335	H480	8.16	296.62	191.75	262.30	157.42	8.17	96.71	1.57	17.90
CF4$_{0}$	325	281	8.00	268.39	163.90	233.35	128.86	8.00	96.49	1.29	21.38
CF4$_{30}$	326	H449	8.08	293.40	188.74	260.82	156.16	8.08	96.58	1.56	17.26
CF5$_{0}$	328	H696	8.46	274.07	169.36	238.04	133.33	8.46	96.25	1.33	21.27
CF5$_{30}$	329	H855	7.87	304.86	200.59	273.12	168.85	7.87	96.40	1.69	15.82

Indicator	**Range**			**Source**
	Low	*Medium*	*High*	
Soil moisture (%)	< 20	20 - 30	> 30	(Sparks, 2003)
Bulk density (g/cm³)	>1.32	1.32 - 1.72	>1.72	(USDA, n.d.)

11.6.5 Bulk density: ANOVA & Tukey’s HSD test results

```
ANOVA(soildepth=topsoil,SQI="Bulk.Density...g.cm.3. "
            Df Sum Sq Mean Sq F value   Pr(>F)    
studysite    2 0.8650  0.4325   32.25 1.49e-05 ***
Residuals   12 0.1609  0.0134                     
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
  Tukey multiple comparisons of means
    95% family-wise confidence level

Fit: aov(formula = FMAOVBP, data = soildepth)

$studysite
        diff        lwr         upr     p adj
DB-CF -0.552 -0.7473926 -0.35660744 0.0000191
FF-CF -0.100 -0.2953926  0.09539256 0.3885408
FF-DB  0.452  0.2566074  0.64739256 0.0001312
```

```
ANOVA(soildepth=subsoil,SQI="Bulk.Density...g.cm.3. "
            Df Sum Sq Mean Sq F value  Pr(>F)    
studysite    2 0.4419 0.22094   20.34 0.00014 ***
Residuals   12 0.1304 0.01086                    
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
  Tukey multiple comparisons of means
    95% family-wise confidence level

Fit: aov(formula = FMAOVBP, data = soildepth)

$studysite
        diff          lwr         upr     p adj
DB-CF -0.418 -0.593863284 -0.24213672 0.0001019
FF-CF -0.248 -0.423863284 -0.07213672 0.0070672
FF-DB  0.170 -0.005863284  0.34586328 0.0584294
```

11.6.6 Soil moisture content: ANOVA & Tukey's HSD test results

```
ANOVA(soildepth=topsoil[-c(6,9),] , SQI="Soil.Moisture...."
            Df Sum Sq Mean Sq F value   Pr(>F)    
studysite    2   3470  1734.9   304.2 1.11e-09 ***
Residuals   10     57     5.7                     
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
  Tukey multiple comparisons of means
    95% family-wise confidence level

Fit: aov(formula = FMAOVBP, data = soildepth)

$studysite
           diff        lwr       upr    p adj
DB-CF  42.84067  38.059706  47.62163 0.00e+00
FF-CF  13.01400   8.873567  17.15443 1.66e-05
FF-DB -29.82667 -34.607627 -25.04571 0.00e+00
```

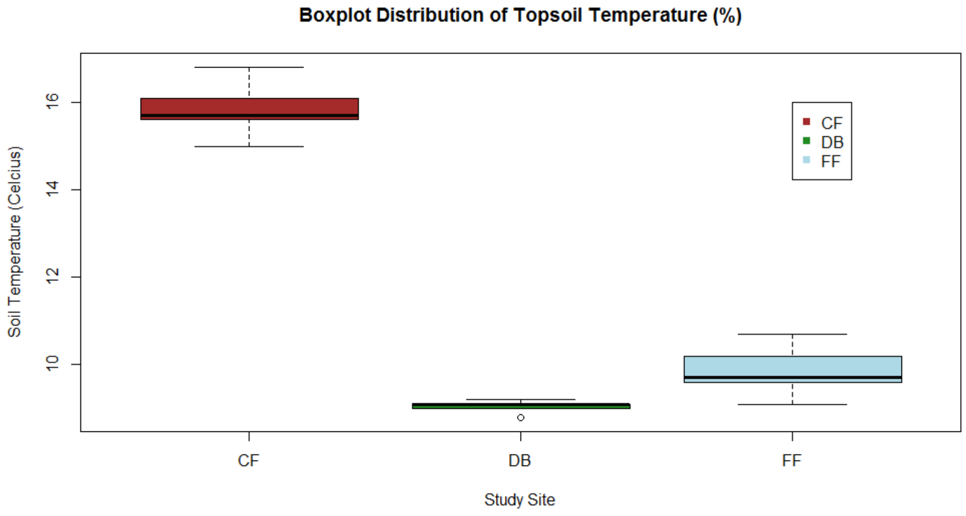
```
ANOVA(soildepth=subsoil, SQI="Soil.Moisture...."
            Df Sum Sq Mean Sq F value   Pr(>F)    
studysite    2 2248.6  1124.3   101.1 3.08e-08 ***
Residuals   12  133.4    11.1                     
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
  Tukey multiple comparisons of means
    95% family-wise confidence level

Fit: aov(formula = FMAOVBP, data = soildepth)

$studysite
         diff         lwr       upr     p adj
DB-CF  28.422  22.7964469  34.04755 0.0000000
FF-CF   5.922   0.2964469  11.54755 0.0390038
FF-DB -22.500 -28.1255531 -16.87445 0.0000005
```

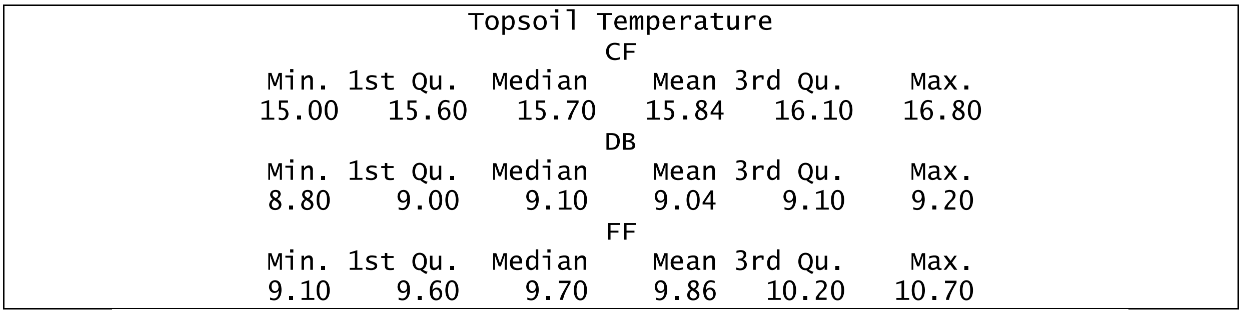
Data without omission of anomalous data:

```
ANOVA(soildepth=topsoil, SQI="Soil.Moisture...."
            Df Sum Sq Mean Sq F value  Pr(>F)    
studysite    2  13075    6537    13.1 0.00096 ***
Residuals   12   5987     499                    
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
  Tukey multiple comparisons of means
    95% family-wise confidence level

Fit: aov(formula = FMAOVBP, data = soildepth)

$studysite
         diff       lwr       upr     p adj
DB-CF  68.114  30.42515 105.80285 0.0011233
FF-CF  13.014 -24.67485  50.70285 0.6378188
FF-DB -55.100 -92.78885 -17.41115 0.0055279

Call:
   aov(formula = FMAOVBP, data = soildepth)
```

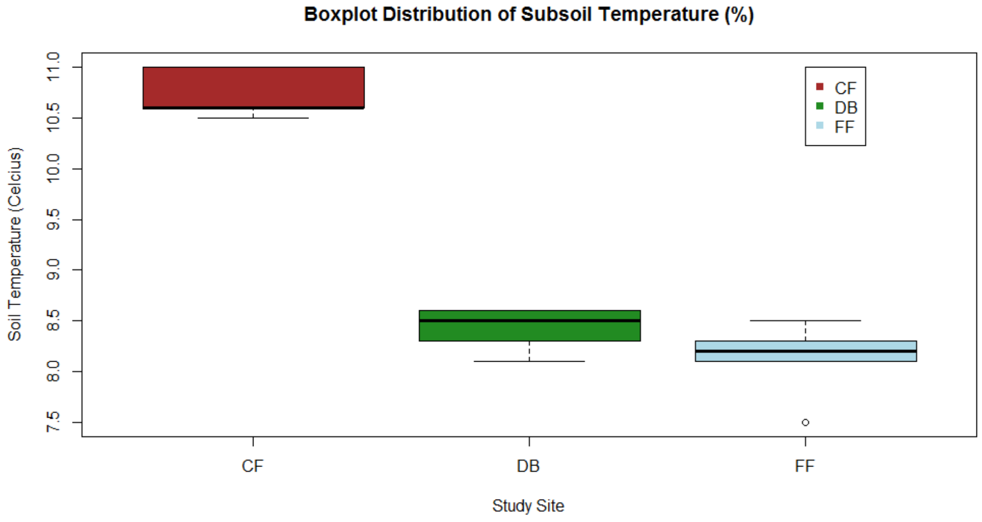
```
Terms:
                studysite Residuals
Sum of Squares  13074.819  5987.146
Deg. of Freedom         2        12

Residual standard error: 22.33672
Estimated effects may be unbalanced
```

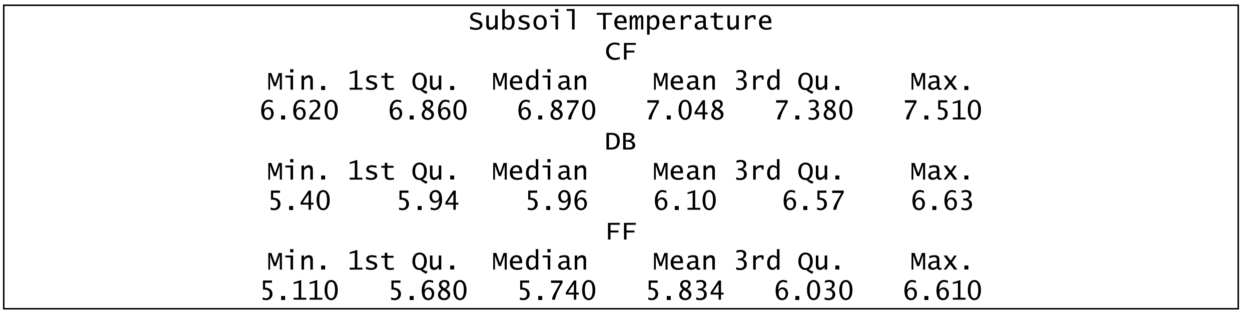
11.6.7 Soil temperatures: topsoil and subsoil boxplot results





```
                    Topsoil Temperature
                             CF
   Min. 1st Qu.  Median    Mean 3rd Qu.    Max.
  15.00   15.60   15.70   15.84   16.10   16.80
                             DB
   Min. 1st Qu.  Median    Mean 3rd Qu.    Max.
   8.80    9.00    9.10    9.04    9.10    9.20
                             FF
   Min. 1st Qu.  Median    Mean 3rd Qu.    Max.
   9.10    9.60    9.70    9.86   10.20   10.70
```





```
                    Subsoil Temperature
                             CF
   Min. 1st Qu.  Median    Mean 3rd Qu.    Max.
  6.620   6.860   6.870   7.048   7.380   7.510
                             DB
   Min. 1st Qu.  Median    Mean 3rd Qu.    Max.
   5.40    5.94    5.96    6.10    6.57    6.63
                             FF
   Min. 1st Qu.  Median    Mean 3rd Qu.    Max.
  5.110   5.680   5.740   5.834   6.030   6.610
```

11.6.8 Soil temperatures: ANOVA & Tukey's HSD test results

```
ANOVA(soildepth=topsoil, SQI="Soil.temp....C."
   Df Sum Sq Mean Sq F value   Pr(>F)
studysite    2 137.79   68.89   246.3 1.81e-10 ***
Residuals   12   3.36    0.28
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
  Tukey multiple comparisons of means
    95% family-wise confidence level

Fit: aov(formula = FMAOVBP, data = soildepth)

$studysite
       diff         lwr       upr     p adj
DB-CF -6.80 -7.69230634 -5.907694 0.0000000
FF-CF -5.98 -6.87230634 -5.087694 0.0000000
FF-DB  0.82 -0.07230634  1.712306 0.0728517


ANOVA(soildepth=subsoil, SQI="Soil.temp....C."
            Df Sum Sq Mean Sq F value   Pr(>F)
studysite    2 20.561  10.281   124.9 9.29e-09 ***
Residuals   12  0.988   0.082
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
  Tukey multiple comparisons of means
    95% family-wise confidence level

Fit: aov(formula = FMAOVBP, data = soildepth)

$studysite
       diff        lwr        upr     p adj
DB-CF -2.32 -2.8041517 -1.8358483 0.0000001
FF-CF -2.62 -3.1041517 -2.1358483 0.0000000
FF-DB -0.30 -0.7841517  0.1841517 0.2623872
```

11.6.9 Soil resistance data (summarised)

All soil resistance measurements per trial per cm have been omitted due to the large size of data. Below is a summary of the data showing the maximum, averages per trial and averages per site in the topsoil (0-30cm) and subsoil (30-80cm). For access to the complete dataset, please contact the author.

Trial plot	**FF1a**	**FF1b**	**FF1c**	**FF2a**	**FF2b**	**FF2c**	**FF3a**	**FF3b**	**FF3c**	**FF4a**	**FF4b**	**FF4c**	**FF5a**	**FF5b**	**FF5c**	**AF6a**	**AF6b**
Maximum	564	520	468	275	252	596	729	590	667	499	540	624	657	378	678	**348**	**235**
Topsoil average per sample point (0-30cm)	109.73	131.03	99.63	77.13	83.87	39.90	117.77	131.67	142.47	136.53	126.27	148.93	60.17	101.33	41.60	248.77	116.80
Subsoil average per sample point (30-80cm)	83.25	107.98	126.73	125.61	121.96	182.41	216.76	267.18	223.88	257.71	169.94	262.86	419.78	83.18	317.63	240.82	166.98

Trial plot	**DB1a**	**DB1b**	**DB1c**	**DB2a**	**DB2b**	**DB2c**	**DB3a**	**DB3b**	**DB3c**	**DB4a**	**DB4b**	**DB4c**	**DB5a**	**DB5b**	**DB5c**
Maximum	199	270	130	243	410	375	267	191	262	284	361	277	155	223	423
Topsoil average per sample point (0-30cm)	39.43	66.90	33.53	76.20	70.97	23.23	31.47	33.43	42.70	50.83	49.40	59.40	34.17	42.77	26.07
Subsoil average per sample point (30-80cm)	88.78	108.20	87.47	139.04	185.98	188.29	102.37	117.94	143.31	85.18	163.00	140.98	77.65	120.43	187.53

Trial plot	**CF1a**	**CF1b**	**CF1c**	**CF2a**	**CF2b**	**CF2c**	**CF3a**	**CF3b**	**CF3c**	**CF4a**	**CF4b**	**CF4c**	**CF5a**	**CF5b**	**CF5c**
Maximum	802	730	507	710	671	598	570	602	732	687	553	448	733	689	593
Topsoil average per sample point (0-30cm)	129.53	119.73	102.37	201.00	145.43	168.67	91.10	122.80	132.43	80.17	96.03	99.33	146.90	86.20	174.83
Subsoil average per sample point (30-80cm)	230.53	357.92	321.14	236.29	325.12	392.59	389.02	200.16	307.76	189.51	419.39	294.90	318.06	280.90	83.53

11.6.10 Soil resistance: ANOVA & Tukey’s HSD test results

```
AOVC=aov(Compaction2018$`Measured resistance (MPa)`~Compaction2018$Study_S
ite)
> summary(Compaction ANOVA)
                            Df   Sum Sq Mean Sq F value Pr(>F)    
Compaction2018$Study_Site    2 17115055 8557527   453.5 <2e-16 ***
Residuals                 3248 61295324   18872                   
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
394 observations deleted due to missingness

> TukeyHSD(Compaction)
  Tukey multiple comparisons of means
    95% family-wise confidence level

Fit: aov(formula = Compaction2018$`Measured resistance (MPa)` ~ Compaction
2018$Study_Site)

$`Compaction2018$Study_Site`
            diff        lwr        upr p adj
DB-CF -174.43506 -188.10326 -160.76686     0
FF-CF  -77.09567  -91.37322  -62.81812     0
FF-DB   97.33938   83.63460  111.04416     0


> Boxplot summary (0-80cm)
Compaction2018$Study_Site: CF
   Min. 1st Qu.  Median    Mean 3rd Qu.    Max.    NA's 
    4.0   108.5   251.0   272.5   401.0   802.0     192 
------------------------------------------------------------
Compaction2018$Study_Site: DB
   Min. 1st Qu.  Median    Mean 3rd Qu.    Max. 
   1.00   49.00   79.00   98.07  124.00  423.00 
------------------------------------------------------------
Compaction2018$Study_Site: FF
   Min. 1st Qu.  Median    Mean 3rd Qu.    Max.    NA's 
    1.0    96.0   164.0   195.4   247.0   729.0     202 
```

Topsoil resistance statistics (0-30cm)

```
> by(CompactionTop$`Measured resistance (kPa)`, CompactionTop$Study_Site,s
ummary)
CompactionTop$Study_Site: CF
   Min. 1st Qu.  Median    Mean 3rd Qu.    Max. 
    4.0    80.0   107.0   131.2   157.0   537.0 
--------------------------------------------------------------------------
-------
CompactionTop$Study_Site: DB
   Min. 1st Qu.  Median    Mean 3rd Qu.    Max. 
   1.00   23.00   41.00   46.23   66.00  149.00 
--------------------------------------------------------------------------
-------
CompactionTop$Study_Site: FF
   Min. 1st Qu.  Median    Mean 3rd Qu.    Max. 
    1.0    56.0    96.0   105.9   150.0   350.0 
```

Subsoil resistance statistics (30-80cm)

```
> by(CompactionSub$`Measured resistance (kPa)`, CompactionSub$Study_Site,s
ummary)
CompactionSub$Study_Site: CF
```

```
   Min. 1st Qu.  Median    Mean 3rd Qu.    Max.    NA's 
   38.0   289.2   378.0   390.2   490.5   802.0     192 
---------------------------------------------------------------------------
-------
CompactionSub$Study_Site: DB
   Min. 1st Qu.  Median    Mean 3rd Qu.    Max. 
   30.0    76.0   104.0   130.2   158.8   423.0 
---------------------------------------------------------------------------
-------
CompactionSub$Study_Site: FF
   Min. 1st Qu.  Median    Mean 3rd Qu.    Max.    NA's 
   60.0   166.0   223.0   271.4   341.0   729.0     202 
```

11.6.11 pH- H_2O raw data

Sample Code	A	B	Average
FF1$_{0}$	5.16	4.91	5.04
FF1$_{30}$	5.31	4.90	5.11
FF2$_{0}$	6.62	7.33	6.98
FF2$_{30}$	6.70	6.52	6.61
FF3$_{0}$	5.67	4.31	4.99
FF3$_{30}$	5.70	5.65	5.68
FF4$_{0}$	6.45	6.40	6.43
FF4$_{30}$	5.76	5.71	5.74
FF5$_{0}$	6.68	6.63	6.66
FF5$_{30}$	6.10	5.95	6.03
AF6$_{0}$	6.68	6.87	6.78
AF6$_{30}$	6.21	6.03	6.12
DB1$_{0}$	4.11	4.19	4.15
DB1$_{30}$	6.50	6.64	6.57
DB2$_{0}$	3.73	3.64	3.69
DB2$_{30}$	5.76	6.16	5.96
DB3$_{0}$	4.11	4.10	4.11
DB3$_{30}$	5.25	5.54	5.40
DB4$_{0}$	4.08	4.01	4.05
DB4$_{30}$	6.61	6.65	6.63
DB5$_{0}$	4.15	4.19	4.17
DB5$_{30}$	5.93	5.95	5.94
CF1$_{0}$	7.03	7.17	7.10
CF1$_{30}$	6.92	6.81	6.87
CF2$_{0}$	7.40	7.36	7.38
CF2$_{30}$	6.84	6.87	6.86
CF3$_{0}$	7.64	7.57	7.61
CF3$_{30}$	7.38	7.38	7.38
CF4$_{0}$	7.35	7.39	7.37
CF4$_{30}$	6.64	6.59	6.62
CF5$_{0}$	7.00	6.98	6.99
CF5$_{30}$	7.55	7.46	7.51

```
                  Topsoil pH
                      CF
        Min. 1st Qu.  Median    Mean 3rd Qu.    Max.
          6.99    7.10    7.37    7.29    7.38    7.61
                      DB
        Min. 1st Qu.  Median    Mean 3rd Qu.    Max.
  3.69    4.05    4.11    4.03    4.15    4.17
                      FF
        Min. 1st Qu.  Median    Mean 3rd Qu.    Max.
          4.99    5.04    6.43    6.02    6.66    6.98
```

Table 11.3: Boxplot summary details for topsoil pH at food forest Ketelbroek (FF), “De Bruuk” (DB) and conventional farm (CF)

```
                              Subsoil pH
                                  CF
   Min. 1st Qu.  Median    Mean 3rd Qu.    Max.
   6.62    6.86    6.87    7.05    7.38    7.51
                                  DB
   Min. 1st Qu.  Median    Mean 3rd Qu.    Max.
   5.40    5.94    5.96    6.10    6.57    6.63
                                  FF
   Min. 1st Qu.  Median    Mean 3rd Qu.    Max.
   5.11    5.68    5.74    5.83    6.03    6.61
```

Table 11.4: Distributional characteristics of subsoil pH for food forest Ketelbroek (FF), “De Bruuk” (DB) and conventional farm (CF)

11.6.12 pH : ANOVA & Tukey’s HSD test results

```
ANOVA(soildepth=topsoil, SQI="pH")

            Df Sum Sq Mean Sq F value   Pr(>F)    
studysite    2  26.93  13.466   41.22 4.21e-06 ***
Residuals   12   3.92   0.327                     
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
  Tukey multiple comparisons of means
    95% family-wise confidence level

Fit: aov(formula = FMAOVBP, data = soildepth)

$studysite
        diff       lwr        upr     p adj
DB-CF -3.256 -4.220365 -2.2916346 0.0000030
FF-CF -1.270 -2.234365 -0.3056346 0.0110292
FF-DB  1.986  1.021635  2.9503654 0.0003739
```

```
ANOVA(soildepth=subsoil, SQI="pH")
            Df Sum Sq Mean Sq F value  Pr(>F)   
studysite    2  4.072   2.036     8.7 0.00462 **
Residuals   12  2.808   0.234                   
---
Signif. codes:  
0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
  Tukey multiple comparisons of means
    95% family-wise confidence level

Fit: aov(formula = FMAOVBP, data = soildepth)

$studysite
        diff       lwr        upr     p adj
DB-CF -0.948 -1.764238 -0.1317616 0.0232360
FF-CF -1.214 -2.030238 -0.3977616 0.0049042
FF-DB -0.266 -1.082238  0.5502384 0.6688236
```

11.6.13 SOM & SOC Raw data

Sample Code	Crucible #	Weight of crucible (g.)	Weight of sample in crucible (g.)	Weight after drying (g.)	Weight after drying minus crucible (g.)	Weight after burning (g.)	Weight after burning minus crucible (g.)	Dry matter content (%)	Soil moisture content (%)	Organic Matter content (%)	Soil Organic Carbon (SOC) %
FF1$_{0}$	2	24.834	30.136	28.380	3.546	28.110	3.276	11.77	59.92	7.6	3.8
FF1$_{30}$	3	22.724	28.158	26.982	4.258	26.808	4.084	15.12	56.07	4.1	2.0
FF2$_{0}$	4	22.654	27.663	26.262	3.608	26.020	3.366	13.04	58.13	6.7	3.4
FF2$_{30}$	5	22.969	28.935	27.589	4.620	27.360	4.391	15.97	56.36	5.0	2.5
FF3$_{0}$	14	23.914	28.920	27.570	3.656	27.343	3.429	12.64	57.79	6.2	3.1
FF3$_{30}$	152	19.768	25.799	24.836	5.068	24.727	4.959	19.64	54.34	2.2	1.1
FF4$_{0}$	21	22.098	27.275	25.793	3.695	25.511	3.413	13.55	58.35	7.6	3.8
FF4$_{30}$	25	22.654	28.797	27.418	4.764	27.181	4.527	16.54	56.32	5.0	2.5
FF5$_{0}$	28	20.898	25.953	24.536	3.638	24.340	3.442	14.02	58.15	5.4	2.7
FF5$_{30}$	30	23.683	29.096	27.850	4.167	27.671	3.988	14.32	56.50	4.3	2.1
AF6$_{0}$	35	23.716	31.023	28.902	5.186	28.575	4.859	16.72	58.49	6.3	3.2
AF6$_{30}$	39	23.008	28.241	27.166	4.158	26.996	3.988	14.72	55.72	4.1	2.0
DB1$_{0}$	2	24.846	29.509	26.979	2.133	26.483	1.637	7.23	68.61	23.3	11.6
DB1$_{30}$	3	22.721	27.049	26.043	3.322	25.944	3.223	12.28	56.58	3.0	1.5
DB2$_{0}$	4	25.878	31.9	29.085	3.207	28.344	2.466	10.05	65.25	23.1	11.6
DB2$_{30}$	5	22.653	29.1	26.554	3.901	26.133	3.480	13.41	62.30	10.8	5.4
DB3$_{0}$	7	22.963	28.641	25.789	2.826	25.292	2.329	9.87	66.77	17.6	8.8
DB3$_{30}$	14	23.912	27.942	26.355	2.443	26.193	2.281	8.74	62.26	6.6	3.3
DB4$_{0}$	17	26.426	32.785	28.171	1.745	27.184	0.758	5.32	78.47	56.6*	28.3*
DB4$_{30}$	21	22.098	27.351	26.755	4.657	26.406	4.308	17.03	53.01	7.5	3.7
DB5$_{0}$	25	22.658	27.928	25.425	2.767	25.011	2.353	9.91	65.57	15.0	7.5
DB5$_{30}$	28	20.895	26.139	24.406	3.511	24.198	3.303	13.43	59.90	5.9	3.0
CF1$_{0}$	30	23.685	32.025	30.157	6.472	29.872	6.187	20.21	56.31	4.4	2.2
CF1$_{30}$	35	23.714	32.565	29.93	6.216	29.44	5.726	19.09	58.74	7.9	3.9
CF2$_{0}$	39	23.009	29.454	28.204	5.195	28.034	5.025	17.64	55.37	3.3	1.6
CF2$_{30}$	2	24.835	30.110	29.074	4.239	28.892	4.057	14.08	55.44	4.3	2.1
CF3$_{0}$	7	22.965	29.204	28.005	5.040	27.804	4.839	17.26	55.32	4.0	2.0
CF3$_{30}$	14	23.907	30.195	28.872	4.965	28.649	4.742	16.44	55.88	4.5	2.2
CF4$_{0}$	20	26.351	33.641	32.306	5.955	32.112	5.761	17.70	55.04	3.3	1.6
CF4$_{30}$	28	20.896	26.903	25.638	4.742	25.431	4.535	17.63	55.88	4.4	2.2
CF5$_{0}$	30	23.685	29.185	28.173	4.488	28.041	4.356	15.38	55.07	2.9	1.5
CF5$_{30}$	31	24.1	29.226	28.122	4.022	27.935	3.835	13.76	56.03	4.6	2.3

*data point omitted during data analysis

11.6.14 SOM & SOC : ANOVA & Tukey's HSD test results

Statistical analysis for topsoil SOM with omitted outlier

```
ANOVA(soildepth=topsoil[-9,], SQI="Organic.Matter.content....",
            Df Sum Sq Mean Sq F value Pr(>F)
studysite    2  634.2   317.1   62.24  1e-06 ***
Residuals   11   56.0     5.1
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
  Tukey multiple comparisons of means
    95% family-wise confidence level

Fit: aov(formula = FMAOVBP, data = soildepth)

$`studysite`
        diff         lwr       upr     p adj
DB-CF  16.17  12.0806641 20.259336 0.0000011
FF-CF   3.12  -0.7354628  6.975463 0.1178478
FF-DB -13.05 -17.1393359 -8.960664 0.0000088
```

Statistical analysis for subsoil SOM

```
ANOVA(soildepth=subsoil, SQI="Organic.Matter.content...."
      Df Sum Sq Mean Sq F value Pr(>F)
studysite    2  17.72   8.862   2.281  0.145
Residuals   12  46.61   3.884

---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
  Tukey multiple comparisons of means
    95% family-wise confidence level

Fit: aov(formula = FMAOVBP, data = soildepth)

$`studysite`
       diff       lwr       upr     p adj
DB-CF  1.62 -1.705461 4.9454611 0.4219608
FF-CF -1.02 -4.345461 2.3054611 0.6992623
FF-DB -2.64 -5.965461 0.6854611 0.1277355
```

Statistical analysis for topsoil SOC

```
ANOVA(soildepth=topsoil, SQI="Soil.Organic.Carbon..SOC
            Df Sum Sq Mean Sq F value   Pr(>F)
studysite    2 158.71   79.35   62.32 9.99e-07 ***
Residuals   11  14.01    1.27
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
  Tukey multiple comparisons of means
    95% family-wise confidence level

Fit: aov(formula = FMAOVBP, data = soildepth)

$studysite
        diff        lwr       upr     p adj
DB-CF  8.095  6.0504780 10.139522 0.0000010
FF-CF  1.580 -0.3475938  3.507594 0.1125992
FF-DB -6.515 -8.5595220 -4.470478 0.0000089
```

Statistical analysis for subsoil SOC

```
ANOVA(soildepth=subsoil, SQI="Soil.Organic.Carbon..SOC..."
            Df Sum Sq Mean Sq F value Pr(>F)
studysite    2  4.585  2.2927    2.39  0.134
Residuals   12 11.512  0.9593
  Tukey multiple comparisons of means
    95% family-wise confidence level

Fit: aov(formula = FMAOVBP, data = soildepth)

$studysite
       diff        lwr       upr     p adj
DB-CF  0.84 -0.8126405 2.4926405 0.3932075
FF-CF -0.50 -2.1526405 1.1526405 0.7058599
FF-DB -1.34 -2.9926405 0.3126405 0.1185858
```

11.6.15 Earthworm raw data

```
TukeyHSD(TEW)
  Tukey multiple comparisons of means
    95% family-wise confidence level

Fit: aov(formula = EW$Total.Earthworms..per.m..2. ~ studysite)

$studysite
          diff         lwr      upr     p adj
DB-CF  24.8675 -320.594206 370.3292 0.9833669
FF-CF 348.1450    2.683294 693.6067 0.0478803
FF-DB 323.2775  -22.184206 668.7392 0.0708585


by(EW$Total.Earthworms..per.m..2.,studysite, summary)
studysite: CF
   Min. 1st Qu.  Median    Mean 3rd Qu.    Max. 
    0.0   149.2   198.9   236.2   397.9   596.8 
---------------------------------------------------------------------------
-----------------
studysite: DB
   Min. 1st Qu.  Median    Mean 3rd Qu.    Max. 
    0.0     0.0     0.0   261.1   248.7  2387.0 
---------------------------------------------------------------------------
-----------------
studysite: FF
   Min. 1st Qu.  Median    Mean 3rd Qu.    Max. 
    0.0   397.9   596.8   584.4   696.3  1194.0 


summary(TEW)

             Df  Sum Sq Mean Sq F value Pr(>F)  

studysite     2 1207102  603551   3.713 0.0322 *

Residuals    45 7314347  162541                 

---

Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

11.6.16 Temporal data

Table 11.5: Temporal dataset for food forest Ketelbroek (FF), forest nature reserve “De Bruuk” (DB) and the conventional arable farm (CF) from 2005 to 2019

Date	**FF**	**DB**	**CF**	**Source**
09/12/2005	3.8			BLGG, 2005
12/01/2007			3	BLGG, 2007
06/12/2011			3.2	BLGG, 2011
16/02/2016			3.8	Eurofins, 2016
18/06/2016	4.14 [A]	7.84 [A]		Bakker, 2016
09/04/2018	6.71			Rebisz, 2018
12/04/2018		27.09		Rebisz, 2018
21/04/2018			3.57	Rebisz, 2018
06/12/2018			3.3	Eurofins, 2019
06/02/2019	7.66	28.44	4.67	Westhoff, 2019a
22/04/2019	6.92	22.27 [B]	4.18	Westhoff, 2019b
06/07/2019	8.82	36.01	4.13	Westhoff, 2019c

[A] SOM values were adapted from Bakker’s (2016) dataset. This SOM average was calculated using only corresponding sampling locations from his study.

[B] Average taken from DB1, 3 and 5 from Westhoff (2019b) dataset

Table 11.6: Extracted dataset used for temporal SOM study from Bakker (2016)

Site	SOM (%)
FF	4.25
FF	4.92
FF	3.26
DB	11.28
DB	5.29
DB	7.95
DB	9.9
DB	6.45

Statistical analysis for Bakker (2016) SOM data

```
SOMA=aov(SOM_B16$SOM~SOM_B16$Site)
summary(Bakker SOM Data 2016)
             Df Sum Sq Mean Sq F value Pr(>F)
SOM_B16$Site  1  30.46  30.462   7.207 0.0363 *
Residuals     6  25.36   4.227
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Table 11.7: Extracted dataset used for temporal SOM study from Westhoff (2019-unpublished)

Sample Code	**SOM_W**	**SOC_W**	**SOM_Sp**	**SOC_Sp**	**SOM_Su**	**SOC_Su**
FF1	5.541491	2.770745	8.108844	4.054422	7.125307	3.562654
FF2	8.221626	4.110813	5.69125	2.845625	9.819121	4.909561
FF3	8.330809	4.165404	7.396302	3.698151	8.510638	4.255319
FF4	10.40843	5.204216	7.201835	3.600917	7.013575	3.506787
FF5	5.803698	2.901849	6.221776	3.110888	7.407407	3.703704
DB1	27.26337	13.63169	30.45093	15.22546	22.07207	11.03604
DB2					23.72881	11.86441
DB3	9.777951	4.888975	26.18409	13.09205		
DB4		16.03484				
DB5	8.070618	4.035309	10.17886	5.089431	17.86834	8.934169
CF1	4.189803	2.094902	4.307251	2.153625	4.666667	2.333333
CF2	5.040605	2.520302	4.347826	2.173913	3.740648	1.870324
CF3	3.642937	1.821468	4.043253	2.021627	4.156479	2.07824
CF4	6.00408	3.00204	4.162656	2.081328	4.096386	2.048193
CF5	4.462086	2.231043	4.052443	2.026222	3.971963	1.985981

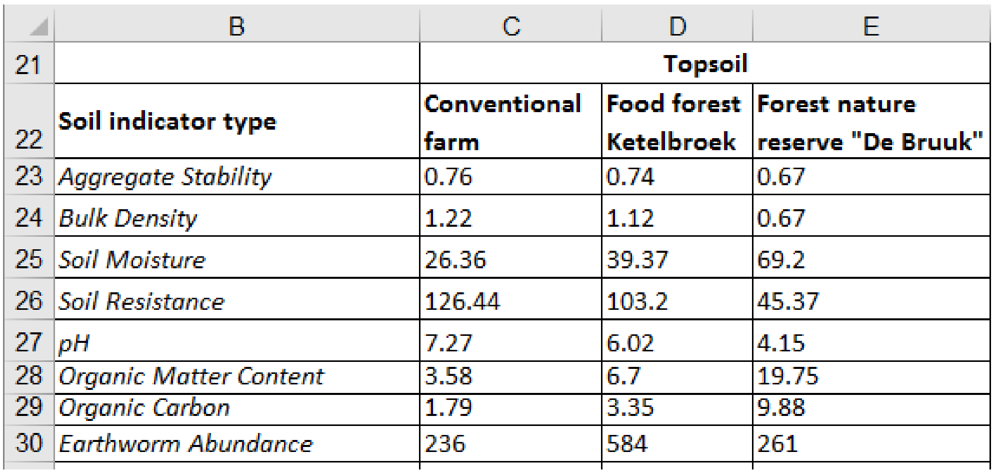
Statistical analysis for Westhoff (2019) SOM data

```
> Waov_W=aov(West$SOM_W~studysite)
> summary(Waov_W)
            Df Sum Sq Mean Sq F value Pr(>F)  
studysite    2  204.1  102.04   4.162 0.0484 *
Residuals   10  245.2   24.52                 
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
2 observations deleted due to missingness
> TukeyHSD(Waov_W)
  Tukey multiple comparisons of means
    95% family-wise confidence level

Fit: aov(formula = West$SOM_W ~ studysite)

$studysite
           diff         lwr       upr     p adj
DB-CF 10.369412   0.4567577 20.282067 0.0406504
FF-CF  2.993309  -5.5913015 11.577920 0.6194169
FF-DB -7.376103 -17.2887577  2.536551 0.1530121


> Waov_Sp=aov(West$SOM_Sp~studysite)

> summary(Waov_Sp)
            Df Sum Sq Mean Sq F value  Pr(>F)   
studysite    2  663.8   331.9   14.29 0.00117 **
Residuals   10  232.2    23.2                   
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
2 observations deleted due to missingness
> TukeyHSD(Waov_Sp)
  Tukey multiple comparisons of means
    95% family-wise confidence level

Fit: aov(formula = West$SOM_Sp ~ studysite)
```

```
$studysite
             diff        lwr       upr     p adj
DB-CF  18.088608   8.440915 27.736302 0.0011544
FF-CF   2.741315  -5.613833 11.096463 0.6528204
FF-DB -15.347293 -24.994987 -5.699599 0.0036823


Waov=aov(West$SOM_Su~studysite)
> summary(Waov)
            Df Sum Sq Mean Sq F value   Pr(>F)    
studysite    2  568.3  284.13   116.6 1.18e-07 ***
Residuals   10   24.4    2.44                     
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
2 observations deleted due to missingness
> TukeyHSD(Waov)
  Tukey multiple comparisons of means
    95% family-wise confidence level

Fit: aov(formula = West$SOM_Su ~ studysite)

$studysite
             diff        lwr        upr     p adj
DB-CF  17.096646  13.971006  20.222287 0.0000001
FF-CF   3.848781   1.141897   6.555665 0.0076049
FF-DB -13.247865 -16.373505 -10.122224 0.0000011
```

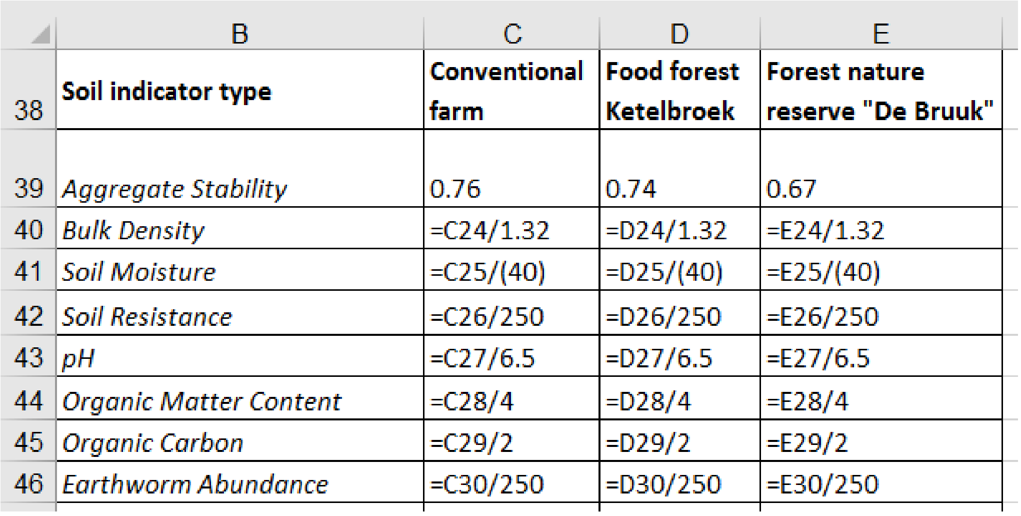
11.6.17 Soil health radar graphs: dataset and formulae

Topsoil results table



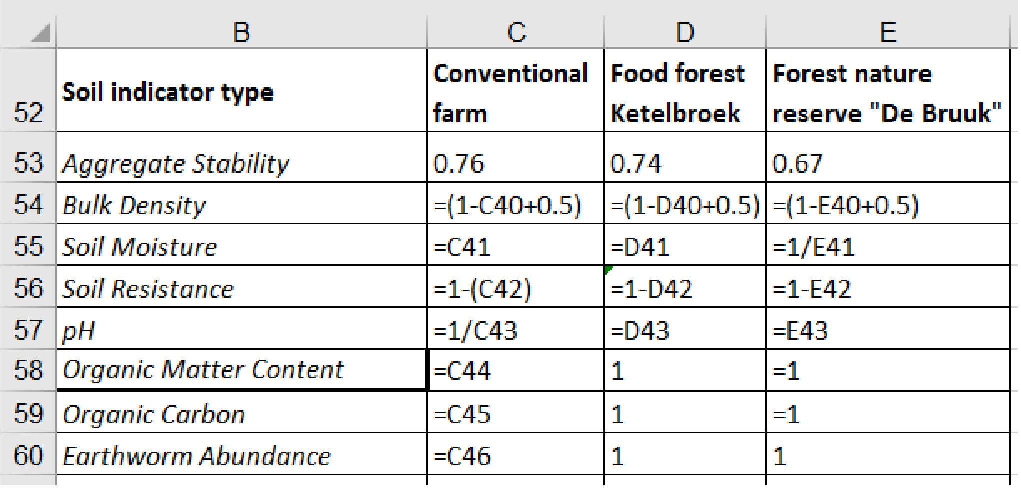
	B	C	D	E
21		**Topsoil**		
22	**Soil indicator type**	**Conventional farm**	**Food forest Ketelbroek**	**Forest nature reserve "De Bruuk"**
23	*Aggregate Stability*	0.76	0.74	0.67
24	*Bulk Density*	1.22	1.12	0.67
25	*Soil Moisture*	26.36	39.37	69.2
26	*Soil Resistance*	126.44	103.2	45.37
27	*pH*	7.27	6.02	4.15
28	*Organic Matter Content*	3.58	6.7	19.75
29	*Organic Carbon*	1.79	3.35	9.88
30	*Earthworm Abundance*	236	584	261

Results converted to ratio according to benchmark reference points



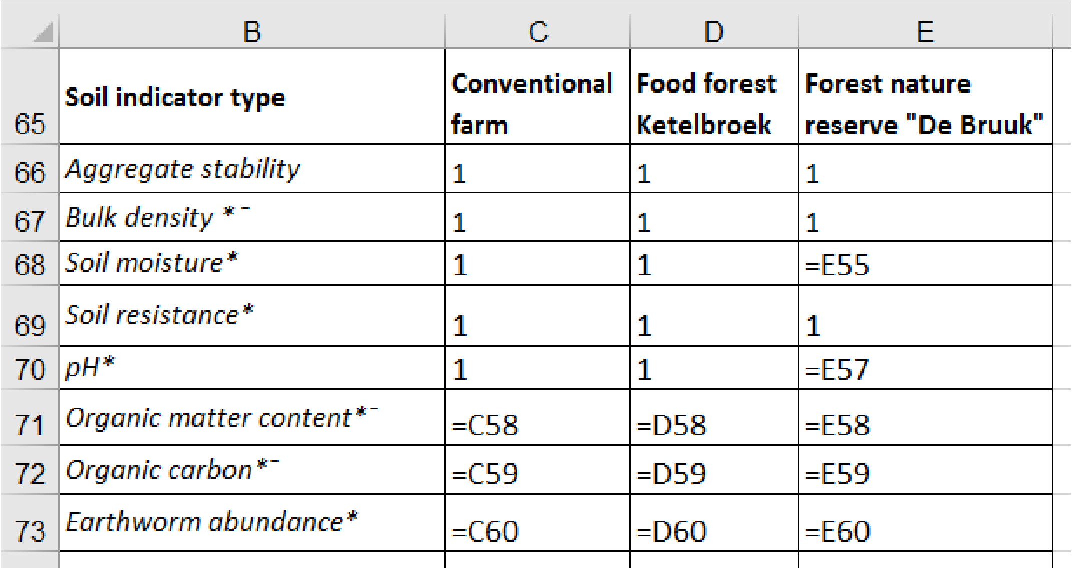
	B	C	D	E
38	**Soil indicator type**	**Conventional farm**	**Food forest Ketelbroek**	**Forest nature reserve "De Bruuk"**
39	*Aggregate Stability*	0.76	0.74	0.67
40	*Bulk Density*	=C24/1.32	=D24/1.32	=E24/1.32
41	*Soil Moisture*	=C25/(40)	=D25/(40)	=E25/(40)
42	*Soil Resistance*	=C26/250	=D26/250	=E26/250
43	*pH*	=C27/6.5	=D27/6.5	=E27/6.5
44	*Organic Matter Content*	=C28/4	=D28/4	=E28/4
45	*Organic Carbon*	=C29/2	=D29/2	=E29/2
46	*Earthworm Abundance*	=C30/250	=D30/250	=E30/250

Ratios adjusted to 1 being positive and max value



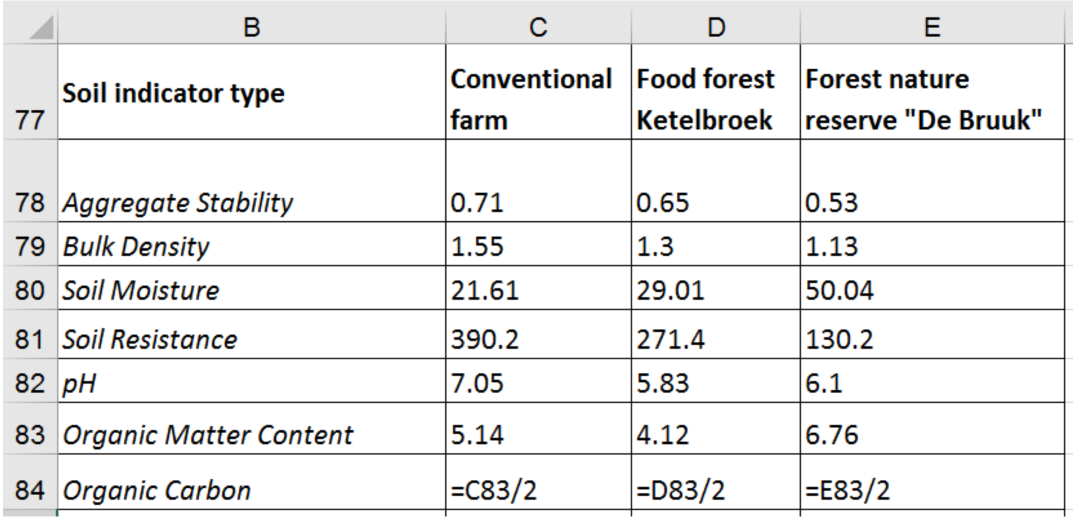
	B	C	D	E
52	**Soil indicator type**	**Conventional farm**	**Food forest Ketelbroek**	**Forest nature reserve "De Bruuk"**
53	*Aggregate Stability*	0.76	0.74	0.67
54	*Bulk Density*	=(1-C40+0.5)	=(1-D40+0.5)	=(1-E40+0.5)
55	*Soil Moisture*	=C41	=D41	=1/E41
56	*Soil Resistance*	=1-(C42)	=1-D42	=1-E42
57	*pH*	=1/C43	=D43	=E43
58	*Organic Matter Content*	=C44	1	=1
59	*Organic Carbon*	=C45	1	=1
60	*Earthworm Abundance*	=C46	1	1

Value of 1 assigned when result is in optimum range



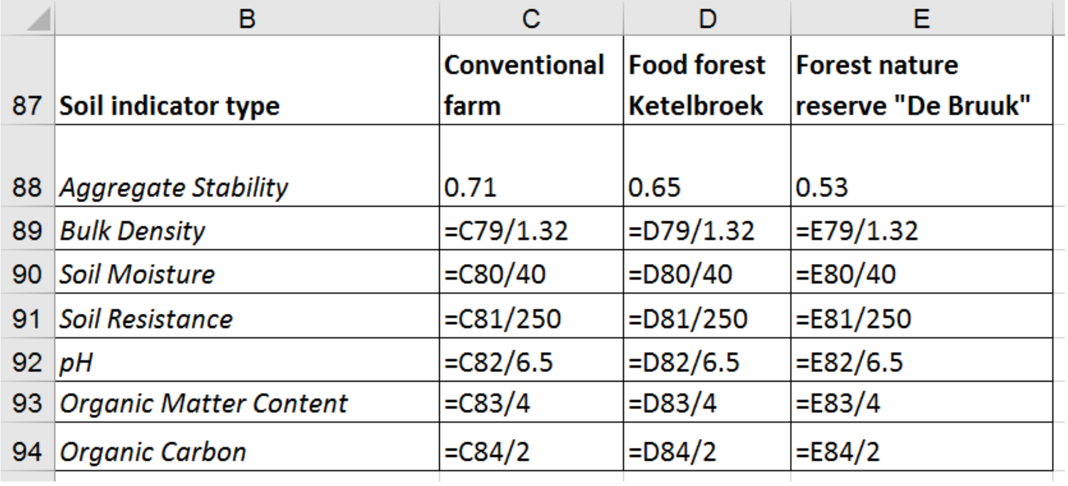
	B	C	D	E
65	**Soil indicator type**	**Conventional farm**	**Food forest Ketelbroek**	**Forest nature reserve "De Bruuk"**
66	*Aggregate stability*	1	1	1
67	*Bulk density *-*	1	1	1
68	*Soil moisture**	1	1	=E55
69	*Soil resistance**	1	1	1
70	*pH**	1	1	=E57
71	*Organic matter content*-*	=C58	=D58	=E58
72	*Organic carbon*-*	=C59	=D59	=E59
73	*Earthworm abundance**	=C60	=D60	=E60

Subsoil results table



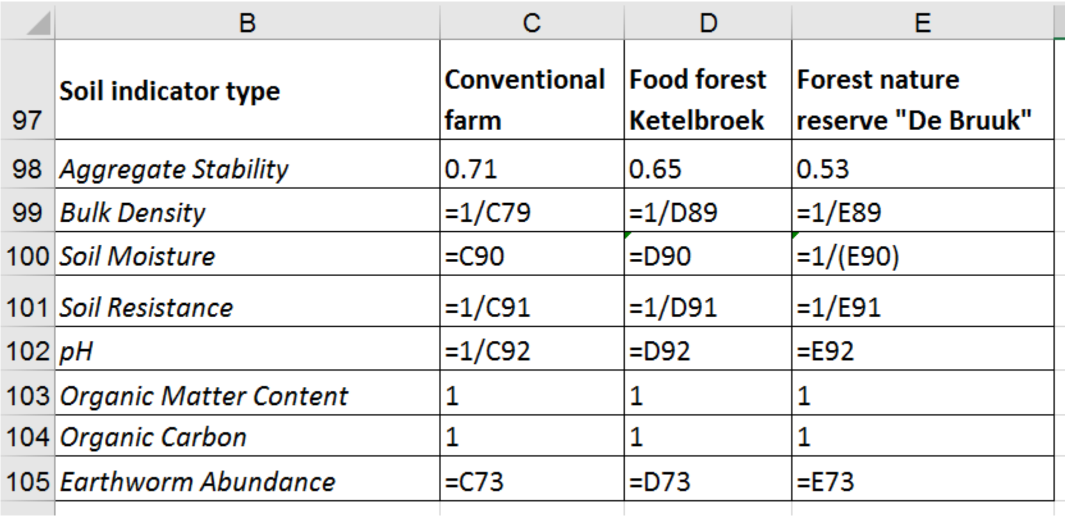
	B	C	D	E
77	**Soil indicator type**	**Conventional farm**	**Food forest Ketelbroek**	**Forest nature reserve "De Bruuk"**
78	*Aggregate Stability*	0.71	0.65	0.53
79	*Bulk Density*	1.55	1.3	1.13
80	*Soil Moisture*	21.61	29.01	50.04
81	*Soil Resistance*	390.2	271.4	130.2
82	*pH*	7.05	5.83	6.1
83	*Organic Matter Content*	5.14	4.12	6.76
84	*Organic Carbon*	=C83/2	=D83/2	=E83/2

Results converted to ratios (0-1)



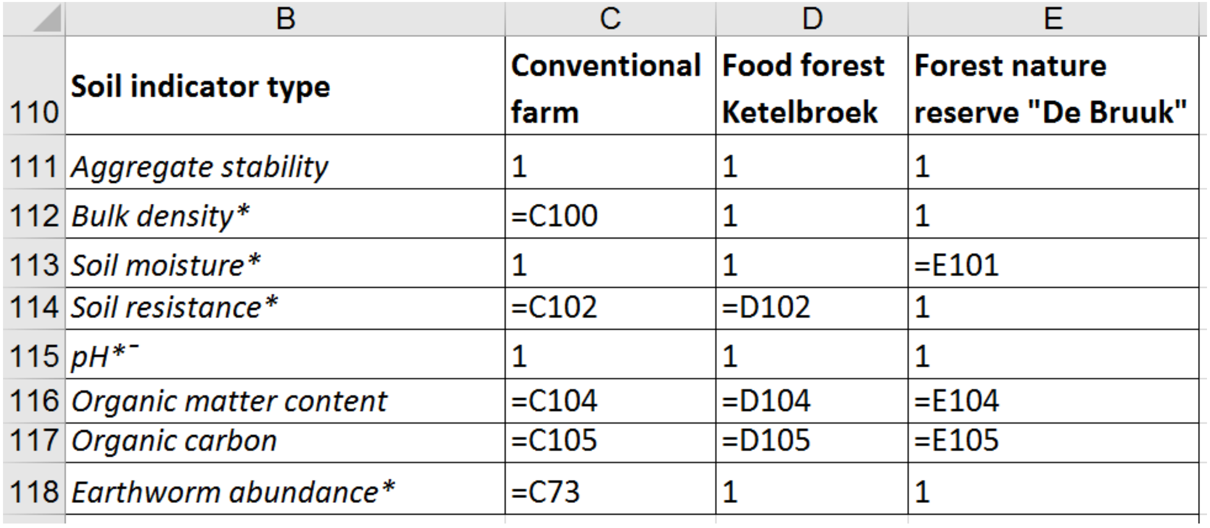
	B	C	D	E
87	**Soil indicator type**	**Conventional farm**	**Food forest Ketelbroek**	**Forest nature reserve "De Bruuk"**
88	*Aggregate Stability*	0.71	0.65	0.53
89	*Bulk Density*	=C79/1.32	=D79/1.32	=E79/1.32
90	*Soil Moisture*	=C80/40	=D80/40	=E80/40
91	*Soil Resistance*	=C81/250	=D81/250	=E81/250
92	*pH*	=C82/6.5	=D82/6.5	=E82/6.5
93	*Organic Matter Content*	=C83/4	=D83/4	=E83/4
94	*Organic Carbon*	=C84/2	=D84/2	=E84/2

Ratios adjusted to 1 being positive and max value



	B	C	D	E
97	**Soil indicator type**	**Conventional farm**	**Food forest Ketelbroek**	**Forest nature reserve "De Bruuk"**
98	*Aggregate Stability*	0.71	0.65	0.53
99	*Bulk Density*	=1/C79	=1/D89	=1/E89
100	*Soil Moisture*	=C90	=D90	=1/(E90)
101	*Soil Resistance*	=1/C91	=1/D91	=1/E91
102	*pH*	=1/C92	=D92	=E92
103	*Organic Matter Content*	1	1	1
104	*Organic Carbon*	1	1	1
105	*Earthworm Abundance*	=C73	=D73	=E73

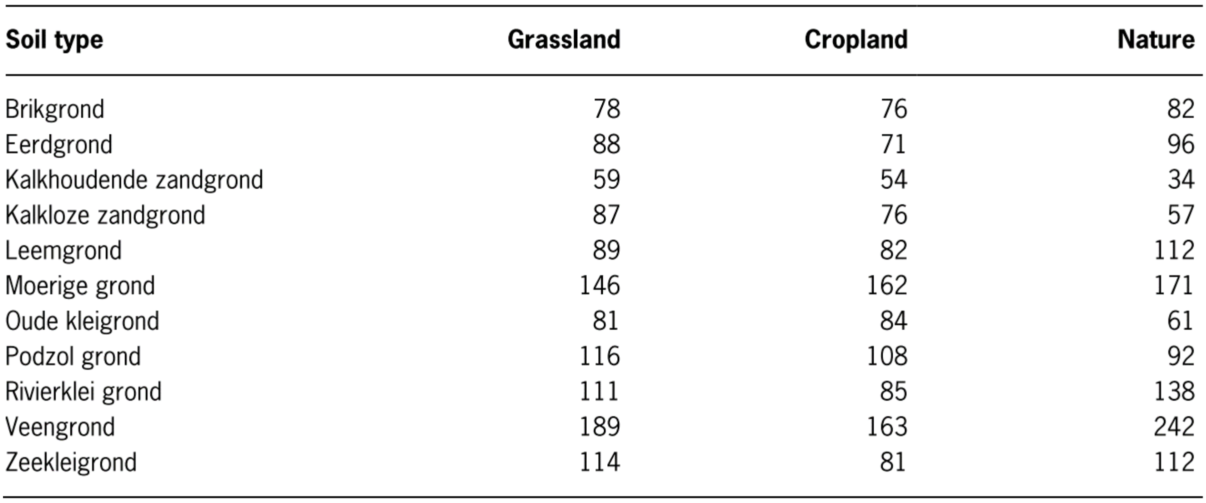
Value of 1 assigned when result is in optimum range



	B	C	D	E
110	**Soil indicator type**	**Conventional farm**	**Food forest Ketelbroek**	**Forest nature reserve "De Bruuk"**
111	*Aggregate stability*	1	1	1
112	*Bulk density**	=C100	1	1
113	*Soil moisture**	1	1	=E101
114	*Soil resistance**	=C102	=D102	1
115	*pH*-*	1	1	1
116	*Organic matter content*	=C104	=D104	=E104
117	*Organic carbon*	=C105	=D105	=E105
118	*Earthworm abundance**	=C73	1	1

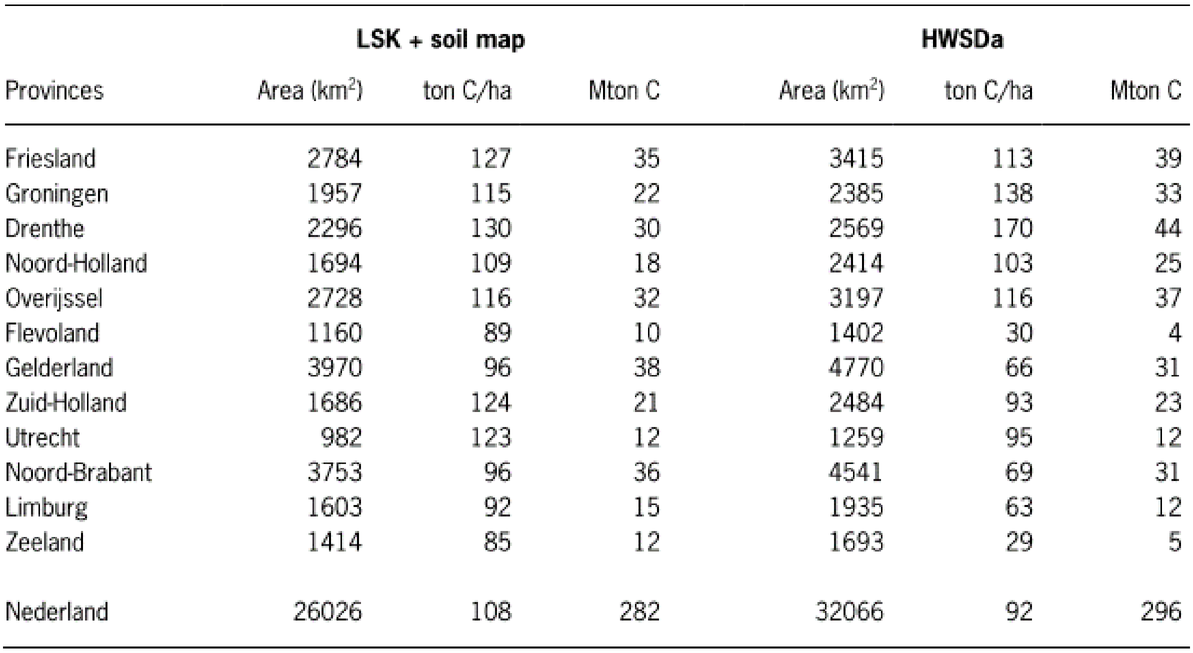
11.6.18 Soil organic carbon stocks in the Netherlands

Table 11.8: Average soil organic carbon stock (t/ha) per soil type and land use (Conijn & Lesschen, 2015; Appendix III).



Soil type	**Grassland**	**Cropland**	**Nature**
Brikgrond	78	76	82
Eerdgrond	88	71	96
Kalkhoudende zandgrond	59	54	34
Kalkloze zandgrond	87	76	57
Leemgrond	89	82	112
Moerige grond	146	162	171
Oude kleigrond	81	84	61
Podzol grond	116	108	92
Rivierklei grond	111	85	138
Veengrond	189	163	242
Zeekleigrond	114	81	112

Table 11.9: Soil organic carbon content (ton C/ha) and total amount (Mton C) in the top 30cm per province and for the Netherlands (area (km^2) refers to the part of each province including grasslands, arable land and nature) (Conijn & Lesschen, 2015; Appendix III).

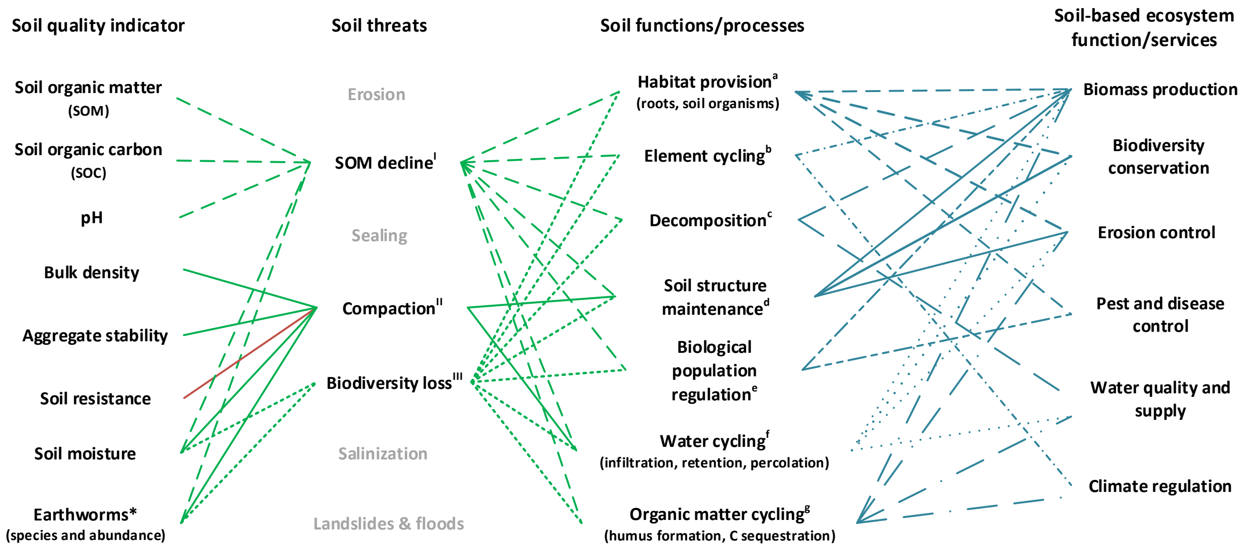


	LSK + soil map			**HWSDa**		
Provinces	Area (km^2)	ton C/ha	Mton C	Area (km^2)	ton C/ha	Mton C
Friesland	2784	127	35	3415	113	39
Groningen	1957	115	22	2385	138	33
Drenthe	2296	130	30	2569	170	44
Noord-Holland	1694	109	18	2414	103	25
Overijssel	2728	116	32	3197	116	37
Flevoland	1160	89	10	1402	30	4
Gelderland	3970	96	38	4770	66	31
Zuid-Holland	1686	124	21	2484	93	23
Utrecht	982	123	12	1259	95	12
Noord-Brabant	3753	96	36	4541	69	31
Limburg	1603	92	15	1935	63	12
Zeeland	1414	85	12	1693	29	5
Nederland	26026	108	282	32066	92	296

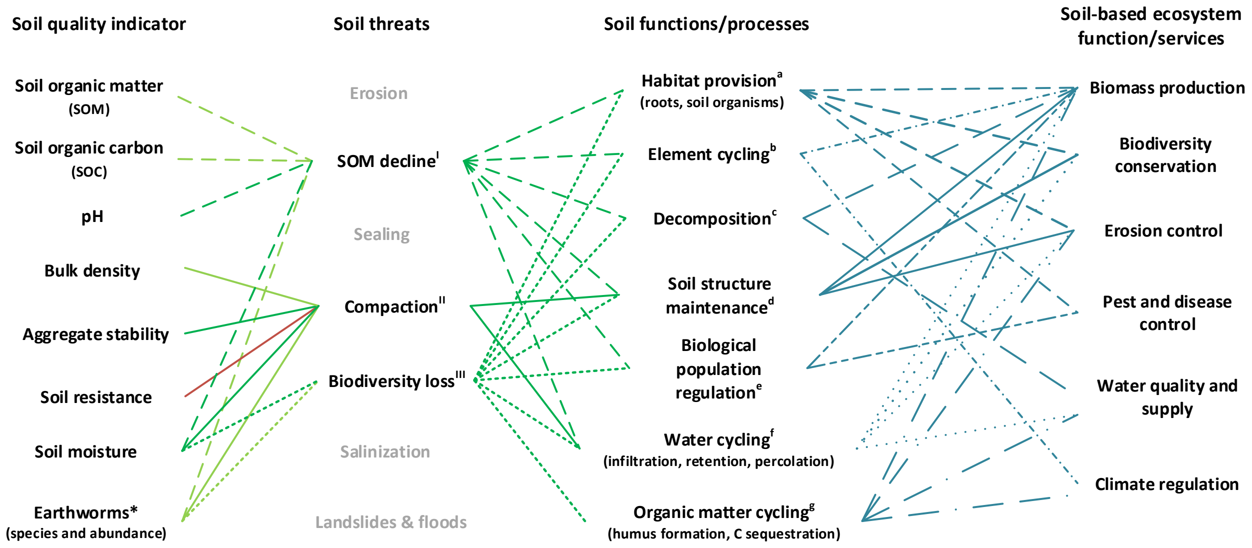
11.7 Linking soil quality results to soil compass

Soil compasses were created based on linking the results from this study to soil threats in a colour-coded approach. Results within the optimal range were coloured green. Results in the average range were coloured light green. Results that were sub-optimal were coloured orange and results that were crossed a certain threshold were coloured red.

Food forest



Conventional farm



Forest “De Bruuk”