Integrating Food Production and Biodiversity

Energy and Scale Issues in Implementation

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Integrating food production and biodiversity – energy and scale issues in implementation

Abstract

The aim of this thesis was to test the hypotheses that (1) biodiversity at a farm level differs between small and large farms, and (2) it is possible to combine high biodiversity at farm level with high food production, sustainable nutrient circulation, and self-sufficiency in fuels. In the research area in SE Sweden, six small farms (<52 ha) and six large farms (>135 ha) were selected for the studies. The farm with the highest biodiversity was selected as a case study farm for the productivity and biofuel studies. Differences in biodiversity between small and large farms were assessed by comparing number of birds and herbaceous plant species plus the number of bird territories, bumblebees, and butterflies. Both on-farm heterogeneity and surrounding landscape heterogeneity were measured by calculating the Shannon-Wiener Diversity Index. Productivity was measured as the number of people supplied with food with different livestock combinations and types of biofuels. The biofuel scenarios were evaluated regarding their impact on the number of people supplied with food, and NPK fluxes at farm level. The biofuels were crude rapeseed oil, horse draft, ethanol from wheat, and ethanol from potatoes. The results showed that twice as many butterflies, breeding bird species and bird territories, five times as many bumblebees, and almost twice as many herbaceous non-crop plant species were found on the small farms compared to the large farms. The small farms also had significantly higher on-farm landscape heterogeneity. Globally, on average, 0.2 ha of farmland is available per capita, i.e. every ha supports 5 persons. This production, and even slightly more was achieved when using a combination of a workhorse and a crude rapeseed oil-fuelled tractor. Ethanol from wheat had the largest impact on food production. All biofuels tested resulted in a positive balance for N, but in deficits for P and K. The results show that high biodiversity and high production of food and biofuels can be combined on the same farm. The results also suggest that this combination of high biodiversity and high production is enhanced by small-scale farming.

Keywords: small-scale farming, agriculture, biodiversity, landscape heterogeneity, biofuels, food production, self-sufficiency, horse draft.

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Till

Kerstin

Du har varit med från allra första början. Nu kommer de tillbaka, 85 år efter du såg dem!

Contents

List of Publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I Belfrage, K., Björklund J., and Salomonsson L. (2005). *The effects of farm size and organic farming on diversity of birds, pollinators, and plants in a Swedish landscape*. Ambio 34, 8: 582–588

II Belfrage, K., Salomonsson L., and Björklund J. (2014). *The effects of farm size and on-farm landscape heterogeneity on biodiversity; case-study of twelve farms in a Swedish landscape*. Submitted to Agroecology and Sustainable Food Systems

III Johansson, S., Belfrage K., and Olsson M. (2013). *Impact on food productivity by fossil fuel independence – A case study of a Swedish small-scale integrated organic farm.* Acta Agriculturae Scandinavica. Section B – Soil & Plant Science. DOI: 10.1080/09064710.2012.733020

IV Johansson, S., Ohlander L., Belfrage K., Sundberg C., and Hansson P.-A. (2013). *How the choice of biofuel system in a small-scale Swedish organic farm affects food production and NPK balance.* Acta Agriculturae Scandinavica. Section B – Soil & Plant Science. DOI: 10.1080/09064710.2013.867071

The contribution of Kristina Belfrage to the papers included in this thesis was as follows:

I Kristina Belfrage decided the hypothesis, designed the research, performed all the censuses, and compiled the input data for the statistical calculations. Lennart Salomonsson performed most of the statistical analyses. The outcome of the computer calculations was discussed together in the author group. Kristina did the writing and layout of the paper; however, with valuable comments from Lennart Salomonsson and Johanna Björklund.

II Kristina formulated the hypothesis. The design of the research was decided in cooperation with Lennart Salomonsson. Kristina performed all assessments and compiled the input data for the statistical analyses. Lennart Salomonsson carried out most of the statistical calculations and the outcome of the computer calculations was discussed together. Kristina wrote and did the layout of the paper; however, incorporating valuable comments from Lennart Salomonsson and Johanna Björklund.

III Kristina performed all the field trials and measurements and quantifications of e.g., harvest levels, animal productivity, crop rotations, and resource usage and compiled the input data for the computer calculations. Sheshti Johansson carried out the computer calculations. The paper was written in collaboration between the authors with Sheshti being the main responsible author. Mats Olsson contributed to the structure and layout of the paper.

IV Kristina performed all field trials and all assessments of, e.g., diesel consumption, labor demand, feed requirements, and yields. Sheshti carried out the computer calculations and was responsible for the main part of the writing of the paper with contributions from Lars Ohlander and Kristina Belfrage. Cecilia Sundberg and Per-Anders Hansson contributed to the structure of the paper.

1 Introduction

1.1 Setting the scene

Humanity has become a major force in the functioning of all ecosystems on Earth (Goldewijk et al., 2011; FAO, 2011; Bai et al., 2008). So far, we have transformed two-thirds of the Earth's land area, and the speed of this ongoing transformation escalates in pace with the growth of the world population. Some researchers have even termed the current era "Anthropocene" with reference to the strong human influence on the planet (Crutzen and Stoermer, 2000).

Associated with the transformation of Earth are large losses of ecosystem services, manifesting as e.g., topsoil degradation, freshwater shortage, loss of biodiversity, and accumulation of toxic agents (Carpenter et al., 2009; Steffen et al., 2004; MA, 2003; Tyson et al., 2001; Turner et al., 1990). Ecosystem services support agricultural productivity and are therefore crucial for the development of a more sustainable agriculture (Bommarco et al., 2013; Altieri, 1999; Baskin, 1997). They are decisive for the adaptability of agriculture to the demands for food and raw materials under changing environmental and climatic conditions, as well as for the ability to reduce the use of non-renewable resources (Tscharntke et al., 2012; Wall and Smith, 2005; Tilman et al., 2002). One of the greatest challenges for humanity today is to sustain the generation of ecosystem services while staying on sustainable pathways of societal development (Elmqvist et al., 2013; Odum and Odum 2008; Tengö, 2004; Folke et al., 2004; Gunderson and Holling, 2003; De Groot et al., 2001). This challenge is enormous, especially considering the need for increased food production for a growing world population and millions of environmental refugees (IPCC, 2013; Godfray et al., 2010; FAO, 2009).

1.2 Climate change and biofuels

The reports from the Intergovernmental Panel on Climate Change (IPCC) (2013; 2007) predict a continued rise in global mean temperature, due to emissions of greenhouse gases as a result of human activities. Since 1880, the global mean temperature has risen by +0.8°C (NASA GISS, 2012). This increase in temperature has resulted in more turbulent weather globally, with more severe periods of drought, as well as flooding and storms (IPCC, 2013; 2007). The mean sea level is rising by 4 mm every year, which together with an increase in the magnitude and number of storms has caused several severe natural catastrophes in lowland areas and coastal settlements (IPCC, 2013). If the temperature increases too fast, the complex structures that build up the ecosystem may not be able to adapt and the whole ecosystem would collapse, resulting in a massive loss of species (Walther et al., 2002). Hence, a rapid and strong reduction in the emissions of greenhouse gases is needed.

Moreover, there is a growing awareness that finite resources like raw phosphate and fossil fuels will become scarce in the future (UN, 2014; Cordell, 2010; Höök and Aleklett, 2010; Aleklett et al., 2010). Not surprisingly, there is a large interest in biofuels, both to replace fossil fuels and to mitigate climate change by reducing emission of carbon dioxide to the atmosphere (IEA, 2007). To substitute diesel in agriculture to keep the fuel costs down, wheat and other food sources have been suggested as feedstock for fuel production. However, since modern agriculture is highly dependent on fossil fuels for irrigation and tractive power, and for producing chemicals and fertilizers, higher oil prices will also lead to higher food prices (Johansson, 2013). Additionally, the interest in using food as fuel emanates from a conception that there is global overproduction of crops. However, from a global perspective, it has been shown that there is no surplus (Misselhorn et al., 2012; Johansson et al., 2010). Furthermore, the goal to eliminate famine globally suggests that a redistribution of resources is needed (UN Millenium Project, 2005).

Several studies dealing with the transformation from a fossil fuel-dependent agriculture to an agriculture based on biofuels from energy crops have been conducted over the last years. The approaches used in these studies concern mainly (1) lifecycle assessment (LCA) (see, e.g., Rehl et al., 2012; Kimming et al., 2011), (2) the net energy balance (e.g., Prade et al., 2012; Silva Lora et al., 2011), and (3) emergy analysis (e.g., Ciotola et al., 2011; Odum, 2007; Ulgiati, 2001). However, none of these approaches manage to capture the complex relations at farm level from a more practical viewpoint, e.g., illustrating how bioenergy production is linked to food production and nutrient flows, or showing interactions between bioenergy production and sustainable crop rotations, or the interaction between energy crops and animal production. None of the studies that deal with self-sufficiency in fuels in Swedish agriculture (e.g., Kimming et al., 2011; Ahlgren et al., 2010; Hansson et al., 2007; Fredriksson et al., 2006) have been tested under real conditions, i.e., on farms. Additionally, they do not include the impact the different biofuels might have on food production ability. There is a need for research that aims to capture the dynamics of the relations between biofuel production and food production and nutrient fluxes at a farm level, based on real data.

1.3 Exceeding the safe planetary boundaries

According to Rockström and coworkers (2009), at least three planetary boundaries are being exceeded; the nitrogen cycle, the climate change boundary, and the rate of biodiversity changes. Agriculture has been identified as one of the main causes of the excess artificial fixation of atmospheric nitrogen and the rapid loss of biodiversity. The production of nitrogen fertilizer has significantly altered the global nitrogen cycle, as the total fixation of atmospheric nitrogen has more than doubled over the last century (Sutton and Van Grinsven, 2011; Rockström et al., 2009). The resulting consequences include eutrophication and acidification of fresh waters, foliar damage, and increased susceptibility to pathogens in plants (Keating et al., 2010). The environmental costs in Europe have been estimated to be €70–320 billion per year, due to, e.g., losses in air quality, water quality, and human health. These costs outweigh the direct economic benefits of higher yields due to nitrogen fertilization in agriculture (Sutton and Van Grinsven, 2011).

Humanity is today causing a rate of species extinction unlike any that has occurred since the last global mass extinction events, 50 million years ago (Sahney and Benton, 2008). The rate of extinction is between 100 and 1000 times higher than could be considered natural, and is mainly caused by conversion of natural ecosystems into agricultural and urban areas, introduction of new species, and climate change (Murphy and Romanuk, 2014; Mace et al., 2005; Diaz et al., 2005). Recently performed studies of birds in the European agricultural landscape show that the populations of common farmland bird species have decreased by 52% since 1980, corresponding to a loss of more than 300 million birds (PECBMS, 2012; Eaton et al., 2010). This decline in birds is especially severe given that bird abundance is considered to reflect biodiversity also at lower trophic levels (Gregory et al., 2005; 2003). These species, which make up the diversity at different trophic levels, including their complex and still largely unknown interactions, are in turn crucial for the generation of ecosystem services necessary to support sustainable food and biofuel production (Tscharntke et al., 2012; Daily, 1997).

1.4 Structural rationalization

In Europe, the European Union (EU) subsidizes farmers to adopt practices that maintain biodiversity. Despite these subsidies, the biodiversity and heterogeneity of the agricultural landscape of Europe is still decreasing (Donald et al., 2006; Wretenberg, 2006; Firbank, 2005; Donald et al., 2001). The fact is that, according to some studies regarding birds by Donald and coworkers (2001 and 2002), the EU's Common Agricultural Policy (CAP) seems to have worsened the situation. In line with other studies (e.g. Chamberlain et al., 2000), the authors have shown a sharp division between countries participating in the CAP, on the one hand, and European countries outside the CAP, on the other, where this decline of farmland birds was less pronounced,. Focus on high yield that has led to increasing monocultures and specialization in production, were among the explanations suggested by the authors. This is in line with accumulated evidence that the combination of high agrochemical inputs and agricultural structural rationalization, resulting in losses and fragmentation of habitats and decreasing heterogeneity at different spatial and temporal scales, is among the primary causes for the widespread decrease in biodiversity in the agricultural landscape (Krauss et al., 2010; Geiger et al., 2010; Donald et al., 2006; Tscharntke et al., 2005; Firbank, 2005; Benton et al., 2003; Robinson and Sutherland, 2002; Forman, 1995). Another strong driver mentioned for the declining biodiversity, at least in the European agricultural landscape, is the decreasing number of farms with livestock held outdoors, especially cattle (Hiron et al., 2013; Wretenberg et al., 2007).

In Sweden, the intensification of agriculture has significantly altered the agricultural landscape. In 1920, there were almost 430 000 small farms in Sweden, creating a patchwork of fields, meadows, pastures, and grazed forests. The grazing animals shaped an environment rich in insects and birds. Since then, the number of small farms has decreased by almost 80% (Jordbruksverket, 2005) and the number of cow herds has decreased by over 90% (Svensk mjölk, 2013). The enlargements of fields, draining of wetlands, conversion of open ditches to subsoil drainage, and, last but not least, the decreasing numbers of animal herds have led to a more homogenous landscape characterized by large cereal fields and fewer non-cultivated habitats, such as ditches, within-field islands, hedgerows, and bushes (Wretenberg et al., 2007; Ihse, 1995). At the same time, large areas of previously cultivated or grazed land have been abandoned, also resulting in decreased biodiversity (Wretenberg et al., 2007; Wretenberg, 2006; EEA, 2004).

Despite the fact that numerous studies deal with the relation between small-scale landscape structure and biodiversity (Krauss et al., 2010; Wretenberg, 2006; Thiess et al., 2005; EEA, 2004; Weibull et al., 2003; Weibull and Östman, 2003; Tscharntke et al., 2002; Östman et al. 2001; Söderström and Pärt, 2000; Weibull et al., 2000; Tscharntke and Kreuss, 1999; Robertson et al., 1990), very few studies deal with the relation between farm size and biodiversity (Tscharntke et al., 2012; Ong'wen and Wright, 2007). However, with the same field area available, it could be expected that a larger number of small farms would create a more textured and patchy landscape compared to a smaller number of large farms. In line with the abovementioned research, such a patchy landscape created by large number of small farms could be expected to favor biodiversity, especially considering that the farmsteads themselves are shown to be biodiversity hotspots (Hiron et al., 2013).

1.5 The role of biodiversity

A large proportion of non-cultivated habitats at farm level are decisive for successful pest regulation and pollination since the pollinators, parasite predators, and parasitoids rely on non-cultivated habitats for hibernation, nesting, shelter, and alternative food sources (Garibaldi et al., 2011; Thies et al., 2005; Tscharntke et al., 2002; Östman et al., 2001; Tscharntke, 2000; Tscharntke and Kreuss, 1999; Thies and Tscharntke, 1999; Burel and Baudry 1995; Altieri, 1995; Powell, 1986). Additionally, the pest predators and parasitoids must be able to both move between non-crop habitats and fields at critical times and recolonize the annual crops at the start of the growing season since the timely arrival of pest predators is utterly important in decreasing pest populations (Ruberson, 1999; Landis and Van der Werf, 1997; Wissinger, 1997). Research has shown that there seems to be a threshold value of 20% of non-cultivated area, above which pest control could be observed throughout the fields (Tscharntke et al., 2002). However, many natural pest controllers, such as parasitoids, syrphids, and chrysophytes, are more abundant near field edges than in the fields (Tylianakis et al., 2004; Thies and Tscharntke, 1999). Hence, the smaller the distance from uncultivated habitats, the more efficient we can expect pest regulation of the crops to be.

However, not just non-cultivated habitats, but a variety of different non-cultivated habitats are needed to achieve efficient pest control and pollination, e.g., flowering plants attract pollinators and parasitoids and perennial grasses, bushes, hedgerows, beetle banks, wood lots, and water attract flying and ground-dwelling predators, toads, frogs, and birds (Lee et al., 2004; Tylianakis et al., 2004; Östman, 2004; Östman et al., 2003; Bianchi and Van der Werf, 2003; Collins et al., 2002; Wäckers, 2001; Landis et al., 2000; Tscharntke and Kreuss, 1999). Adjacent grazed areas have also been shown to be very important in increasing the number of pest regulating organisms (see, e.g., the review by Bianchi et al., 2006) and pollinators (Öckinger and Smith, 2007).

Furthermore, it should be emphasized that successful pest and disease control also requires locally adapted crop rotations that take advantage of mycorrhiza as well as the capability of different crops to deter weeds and sanitize the soil and control soil-borne diseases (Jonsson et al., 2014; Rusch et al., 2013; Bertholdsson, 2012; Zeng et al., 2008; Lampkin, 2002; Rydberg and Milberg, 2000; Kling and Jacobsen, 1998; Ohlander, 1990).

The current view of biodiversity, that regards biodiversity and production as a tradeoff situation, advocates segregation of land for conservation from land for production (Phalan et al., 2011a; 2011b). But what if this is based on misconception? What if combining biodiversity and food and biofuel production is a win–win solution? In a future with several ecological and societal stresses, e.g., climate change and declining access to cheap fossil fuels and artificial fertilizers, it is likely that agriculture will have to rely more, or perhaps exclusively, on local resources. Such a scenario will force us to develop an agriculture based on well-functioning agro-ecosystems with high diversity and number of ground-dwelling and above-ground fauna and flora, capable of delivering all the necessary ecosystem services, e.g., nutrient circulation and pest and disease control, necessary to substitute the external inputs used in agriculture today (Jonsson et al., 2014; Lundin et al., 2013; Rusch et al., 2013; Sigfridsson, 2013; Garibaldi et al., 2011; Tilman et al., 2002; Altieri, 1999; Daily, 1997).

2 Aim

The main hypotheses in this thesis were that biodiversity at farm level differs between small and large farms and that it is possible to combine high biodiversity at farm level with high food and biofuel production and sustainable nutrient circulation.

The aim of the thesis was to test these hypotheses from different perspectives. The objectives were:

(1) to investigate the connection between farm size and biodiversity, measured as the number of bird and herbaceous plant species, plus the number of bird territories, butterflies, and bumblebees, on small and large farms (Paper I).

(2) to investigate the connection between (a) farm size and on farm landscape heterogeneity, and (b) on farm landscape heterogeneity and biodiversity (Paper II).

(3) to evaluate the productivity, measured as the number of people supplied with food, of a high biodiversity case study farm that is independent on fossil fuels, artificial fertilizers, and agrochemicals (Paper III).

(4) working at a farm level, to compare different biofuel scenarios for self-sufficiency in fuels regarding the impact on (a) the number of people supplied with food, and (b) nitrogen, phosphorus, and potassium fluxes (Paper IV).

3 Research site and Methods

3.1 Research site

The research site was located in Roslagen (Fig. 1) in southeastern Sweden (ca 59°5′ N, 17°4′ E).

Figure 1. Map of Sweden with Roslagen highlighted.

The area is characterized by a fairly flat landscape with altitudes ranging from 0 m to 70 m above sea level. The landscape is patchy (Fig. 2), with small fields consisting of water-laid sediments and decomposing peat, intersected by hills of bedrock and glacial till. The sediments are commonly calcareous and show very different textural composition, from sandy to clayey. Some of the sediments are formed in shallow water and are rich in organic matter mixed with clay (gyttja) (SGU, 1998).

The climate is characterized by an average annual precipitation of 637 mm and an average annual temperature of 5.7°C, with daily temperatures ranging from -30°C to +30°C (SMHI, 2010). The climate is humid, with annual precipitation exceeding evapotranspiration. However, during the growing season, from May to September, there may be a water deficit, and droughts frequently occur in the early growing season. The variation between years is, however, large. The short cropping season, cold winters, and local dry spells in early spring affect crop production success.

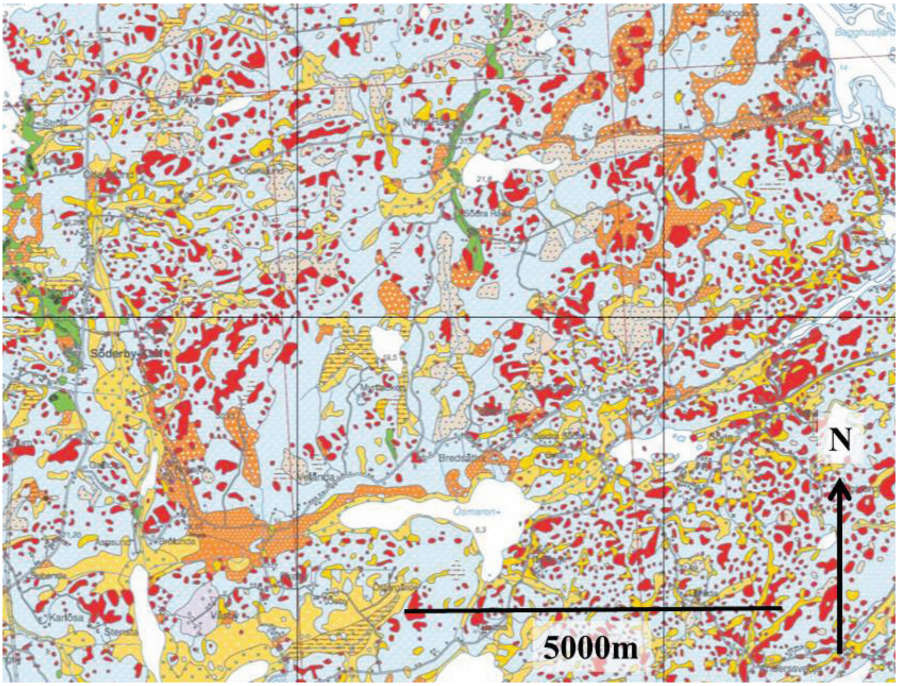

Figure 2. Figure 3. Quaternary deposit map showing a patchy landscape with various soil parent materials. From the Swedish Geological Survey (SGU). Reprinted with kind permission of SGU.

3.2 Farmer reference groups

Two reference groups have been linked to the studies in this thesis. Seven farmers were involved in the biodiversity and landscape heterogeneity studies, presented in Papers I and II. They were all part of an informal, collaborative network of smallholder farmers in the region, Roslagen, where the studies were performed. The network included a village senior who acted as a repository of local ecological knowledge. The group members helped in selecting the small and large farms included in the studies. Additionally, they participated in choosing methods and evaluating the results. Not least, they helped putting the compiled data into context. One of the members in this group continued participating in the reference group connected to the studies at the case study farm, presented in Papers III and IV.

Regarding the studies performed on the case study farm, a group of eight farmers were connected to the studies to contribute with their expertise. All eight farmers had long-term experience as organic smallholder farmers and the group members were also, in parallel with the studies in this thesis, involved in a participatory research project dealing with climate-smart agriculture (Björklund and Helmfrid, 2010). The group members were involved from the very beginning, from selecting the case study farm and designing the research and crop rotation field trials, to the evaluation of the results. When the final results from the studies were to be evaluated, the reference group was expanded by farmers from the Farmers' Union (*Lantbrukarnas Riksförbund*) local district group, managing mainly conventional, large-scale farms. The findings from the whole thesis were discussed with this expanded reference group and future research needs were identified.

3.3 Biodiversity assessments

For the biodiversity assessments (Papers I and II), twelve farms, six small farms (<52 ha) and six large farms (>135 ha), were selected with help from the reference group. The farms were selected as being representative of their size and of the main farming practices for this particular region. Four of the small farms and two of the large farms were certified organic.

To answer the question of how biodiversity differed between small and large farms, we performed assessments of the number of bird territories (i.e. number of breeding bird pairs), and number of breeding bird species and herbaceous non-crop plant species, plus number of bumblebee and butterfly individuals. To evaluate how many birds and bird species could find nesting opportunities per area, we compared a fixed sample area of 1200 m x 200 m on each farm. To make the sample areas as comparable as possible, all selected areas included the farmstead and its immediate surroundings. A transect was drawn in the middle of each sample area and divided into ten bird counting points, as described by Svensson (1975) and Bibby and coworkers (1992). The counting points used for the bird censuses were, with small modifications, also used for the pollinator censuses (Weibull et al., 2000) and for the plant censuses – however, combined with the species list method described by Johansson (2001).

3.4 Landscape heterogeneity assessments

On all twelve farms included in the biodiversity assessment study, landscape heterogeneity was measured at two different scales; at farm level and surrounding landscape level. This was to avoid any biases due to large differences in the surrounding landscape that could affect on farm landscape heterogeneity. Both on-farm and large-scale landscape heterogeneity were measured by using the Shannon-Wiener diversity index (Magurran 1998), as used in several Swedish studies dealing with the same types of landscape heterogeneity studies as those presented in this thesis (e.g., Östman et al., 2001; Weibull et al., 2000).

The surrounding landscape heterogeneity, embedding each farm, was measured by, on a map (1:10 000), placing a 5 x 5 km^2 square grid over each farm and calculating the Shannon-Wiener diversity index for four different land-types; forest, open land, wetland and built-up areas. As the farms were situated in a relatively small limited region, some of the large-scale grids overlapped. The on farm landscape heterogeneity measurements on each farm were performed by using the same sample areas as used for the bird, pollinator, and herbaceous plant censuses. The sample areas (one on each of the twelve farms) were divided into ten squares; i.e., every square corresponded to one bird sampling point with the sample point located in the middle of the square. In each square, two diagonals were drawn along which all different habitat types were measured; e.g., 10 m spring crop, 3 m ditch, 20 m pasture, etc. The different habitat types included in the survey were the following; grazed pastures, field margins, ruderal land (e.g., sand banks, rock-faces and soils damaged by trampling and driving), forests, forest margins, wet areas (e.g., swamps, dams and flooded meadows), ditches, roads and the different crops cultivated within the sample areas (spring crop, winter crops, ley, vegetables). In addition to the length and numbers of different habitats, spot structures situated within the squares were also counted and recorded; berry trees, buildings, tiled roofs, field islets, dung hills, cairns and stone walls.

3.5 Interviews

To be able to capture more of the management practices used on the twelve farms included in the biodiversity and landscape heterogeneity surveys, a qualitative research approach was used (Mikkelsen, 1995). At least one representative of the household on each farm was interviewed at least once. The interviews were structured using checklists of key aspects of farm management including farm size, number of fields, crops used in the rotations, number and species of livestock, and use of artificial fertilizers and agrochemicals (Kvale, 1996). Together with the farmers, a map of the farm was studied, on which we identified the transect and sample area, and calculated average field sizes and number of crops per ha.

3.6 Case study farm

For the food productivity and biofuel studies, we decided to use a slightly different approach than the ones commonly used. Instead of selecting a number of farms, assessing their demand for fossil fuels, and investigating how to replace these with renewable fuels, we decided to start at the other end of the procedure. We stated that the primary task for agriculture is to provide humanity with food and that this must be done in a way that is less dependent on a supply of fossil fuels. The management practices used should further be designed in such a way that they would not contribute to climate change and environmental degradation. For these reasons, we decided to do all calculations and field trials on one case study farm. We selected the small organic farm which showed the highest on farm biodiversity in the biodiversity assessment studies (presented in Paper I). The case study farm had managed several research projects, which means that it has been used for quantifying resource usage, both local and auxiliary, as well as measuring data such as harvest levels for several years. The land distribution at the farm followed the typical pattern for this region of Sweden, with the largest portion of land being forest, and the second largest being arable land (Fig. 3).

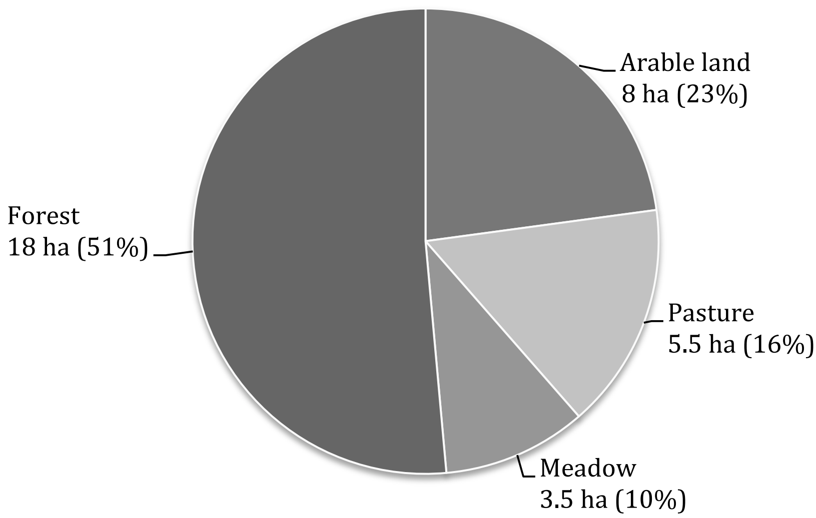

Figure 3. Land use distribution on the case study farm shows a typical pattern for this region, with mainly forest followed by arable land.

3.7 Field trials and pilot experiments

In collaboration with the farmer reference group, we performed several field trials on the case study farm. Our aim was to test different crop rotations and animal combinations with different species and breeds, regarding total food production output, yield, and fuel (diesel) consumption. We conducted pilot experiments on the study farm with large numbers of crops both domestic and exotic. Crops were cultivated in plots and evaluated regarding harvest levels, weed pressure, and nutrient, water, and labor demand. Also, we performed pilot experiments with different crop rotations on the farm and performed evaluations on these from a sustainability and practical perspective, where weed pressure, nutrient circulation, disease control, and labor and fuel demand, were among the most important parameters acknowledged. The crop rotation that was most resistant to weed and pests, had the highest yields, and required the least diesel (in this case, equivalent to least tillage) was selected for all biofuel scenarios in the following studies.

The selected crop rotation used intercropping with leguminous crops to reduce weed pressure and fixate nitrogen from the air. The intercropped nitrogen fixating crops also enriched the harvest residues that were used as feed. The crops included in the sequence were lucerne (*Medicago sativa* L.), winter rapeseed (*Brassica napus* L. ssp. *Oleifera*), winter wheat (*Triticum aestivum* L.) intercropped with blood clover (*Trifolium incarnatum* L.), potatoes (*Solanum tuberosum* L.) and vegetables, buckwheat (*Fagopyrum esculentum*), oat (*Avena sativa* L.), undersown with lucerne.

Regarding combination of different livestock on the farm, our basic prerequisite was that animals should not eat any foodstuffs, only the feed not edible for humans. The number of livestock was consequently decided by the amount of forage and pastures, including grazed forests, available. The amount of forage was fixed since we tested a fixed crop rotation in all scenarios. For further details see section 3.10.

3.8 Literature review

A literature review was performed to find out which biofuels could be tested on the farm, and also to find out their fuel efficiencies. The biofuels considered were: rapeseed oil, first and second generation ethanol, biogas, generator gas, and horse draft. The considerations regarding the choice of biofuels included in the computer modeling are further described below under "Methodological limitations and framing of the biofuel scenarios."

3.9 Statistical analyses

Methods suitable for unbalanced experimental designs were used to compare small and large farms regarding biodiversity. Analyses were performed for number of breeding bird species and herbaceous non-crop plant species, number of bird territories, and the average number of bumblebees and butterflies recorded. Box plots on medians (Velleman and Hoaglin, 1981) and two-way analysis of variance (ANOVA), including interactions calculated by using the General Linear Model (GLM) procedure and Type III sums of squares, were used to compare small and large farms. Both box plots and the GLM procedure enable analysis of unbalanced experimental designs.

Regression analyses of variables were done on relationships between the Shannon-Wiener diversity index of on farm landscape heterogeneity, and the biodiversity indicator groups. The Pearson product-moment method was used for these analyses, as we saw clear linear relationships between the Shannon-Wiener diversity index and the assessed biodiversity indicator data. The software Data Desk for Macintosh (Data Description, Inc., Ithaca, NY, USA) was used for all the statistical calculations.

Occurrence of habitats that could be considered especially important, or even decisive, for the presence of single bird species was tested on nine common bird species found on both the small and the large farms: skylark (*Alauda arvensis*), yellowhammer (*Emberiza citrinella*), lapwing (*Vanellus vanellus*), pied wagtail (*Motacilla alba*), northern wheatear (*Oenanthe oenanthe*), tree sparrow (*Passer montanus*), green finch (*Carduelis chlorus*), blue tit (*Parus caeruelis*), and great tit (*Parus major*). Multivariate regression, Partial Least Square (PLS) regression analysis, was used to identify relationships (as multivariate regression strength) between the measured habitat data (used as X-matrix) and the number of breeding pairs of the nine analyzed bird species (used as Y-matrix). The measurements were done at each census spot (ten per farm transect), but the multivariate calculation was done for the sum of these ten spots, i.e. adding up the length of a specific habitat type at each spot to a total length of that specific habitat type for all the ten spots. The same procedure was used to sum up the total number of bird territories data of each bird species for the ten spots. The statistical package Unscrambler, version 9.0 was used for these analyses.

3.10 Computer modeling

We could not find a suitable existing computer model for our food productivity and biofuel scenarios in Papers III and IV. Hence, we developed a model in Excel that could convert the amount of food produced at the case study farm into energy units and calculate how many people could be supplied with food from the farm in different scenarios of self-sufficiency in fuel.

Data needed to evaluate the amount of fodder produced was derived from Spörndly (1989). Based on this data, we calculated the number of animals the farm could keep. We based our calculations of amounts of meat, egg, and milk on number of livestock, and also calculated the energy content of these products. The energy content of livestock products and food crops was taken from the food database of the Swedish Food Administration (Livsmedelsverket, 2013) and from Johansson and Liljequist (2009). The average energy requirement for humans was estimated to be 2500 kcal/day/capita (Livsmedelsverket, 2013). The energy content of the farm production was divided by the average energy requirements of a human being to calculate the number of people the farm would be able to supply with food.

The input data to the model was the amount of forage available at the farm from harvest and grazing, as well as all food crops from the selected crop rotation at the farm. The calculations in the model included feed plans for cattle, horses, sheep, and poultry as well as food requirements for humans. We used energy units (MJ) to measure the amount of forage, crops, and food and feed requirements. For the feed plans, we considered the protein requirements, but because the protein demand turned out to be met when the energy requirement was fulfilled (due to the protein rich lucerne leys), we decided to leave it out of the model for reasons of simplicity. Hence, we only used the energy requirement as a mean for evaluating the number of animals the farm could keep, as well as the number of humans the farm could feed.

The estimated net edible production included deduction of seed for reproduction, discarded cereals (fed to poultry), 1% shrinkage, 20% postharvest losses (potatoes and vegetables), and milling percentage of 78% for wheat and 70% for oats, according to Johansson and Liljequist (2009). The chaff and bran from milling was fed to poultry.

The model was run both for different animal combinations and harvest and forage availability, in order to find out how many humans could be supplied with food in a given area (Paper III) and to test different scenarios where a part of the production was used for biofuel production (Paper IV).

Based on the forage available, for every scenario we first set the number of cows and horses. The number of sheep was decided as a function of what forage was left. The number of poultry depended on the variable amount of slaughter waste produced by different numbers of cows and sheep, plus the available amounts of screenings and discarded cereals.

Dividing the world population of roughly 7 billion (US Census Bureau, 2012) by the global arable land area of 1.4 billion ha (FAOSTAT, 2012) gives that, under present conditions, every ha on the case study farm has to feed at least five people, i.e. the 11.5 ha of arable land and meadows had to provide at least 58 persons with food. Where this goal is fulfilled the surplus can be considered available as feedstock for biofuel production. The diesel requirement for the year 2010 was measured and used as a reference for how much energy the farm must produce in order to eliminate its fossil fuel dependency. The energy content per ha of the different energy crops included was calculated to estimate the arable land needed to meet the farm’s needs for energy.

Four scenarios of fuel for tractive power were studied:

1. Diesel as tractor fuel (reference scenario)
2. Rapeseed oil as tractor fuel, combined with one workhorse
3. Ethanol from wheat, produced off-farm, as tractor fuel
4. Ethanol from potatoes, produced on the farm, as tractor fuel

In Paper IV, we combined the model with the Focus on Nutrients (*Greppa Näringen*) program (Jordbruksverket, 2013), in which changes in nitrogen, phosphorus and potassium (NPK) balances can be calculated. The calculator of this program includes a database on the content of NPK for most crops, livestock products, feed, and fertilizers available in Sweden. It also includes functions for nitrogen fixation from different types of ley and annual atmospheric deposition; however, the model does not include nutrient leakage. Nitrogen and phosphorus leakage from arable land has been modeled by Johansson and coworkers (2008). We used their average values for 2005 for the crops included in our crop rotation. Because potassium has very little impact on eutrophication there is little or no data available on leakage of potassium. Consequently, leakage of potassium was not included in this study.

The amount of recirculated human feces and urine was based on the number of people the different biofuel scenarios could supply. We estimated that it would be possible to recirculate 80% of the available amount. The nutrient values and daily per capita production of excreta were taken from Björklund (2002), Hellström and Kärrman (1997), and Feachem and coworkers (1983).

The amount of recirculated slaughter waste and bones depended on the number and mixture of livestock that could be kept at the farm in the different biofuel scenarios.

4 Methodological limitations and framing of the biofuel scenarios

4.1 Methodological uncertainties

There are several uncertainties and drawbacks in this thesis that ought to be addressed. Perhaps the largest drawback is the small number of farms included. For the results from the biodiversity comparisons to be generalizable, more than hundreds of randomized samples of farms across many regions would have been a more appropriate number than just twelve farms in one region. Also, the fact that all censuses were performed in one restricted area in Sweden suggests that the results cannot easily be generalized. For the studies presented in Papers III and IV, this limitation is even more obvious since the studies concern only one farm. Additionally, the time span of the studies in Papers III and IV is very short. Some of the crops included in the crop rotation were biennials, e.g., winter wheat and winter rape, hence only one harvest could be measured. Another possible source of error is the field trials, performed to test different crop rotations. Since the sequences were only cultivated on a small area (every crop in the sequence was cultivated on 0.1 ha), yields and yield losses due to weed and pest pressure had to be multiplied by 10 to calculate yields for the whole farm (8 ha of arable land and an 8 year crop rotation). This means that every error in the initial data collection was amplified by 10. To minimize such accumulations of errors we in Paper III adjusted the measured yields to those of neighboring organic farms and data found in literature.

Because the yields of the farm's crop production in Paper III and IV were based on a "normal" year level, not taking into consideration that losses due to drought, pests, and diseases may vary greatly from year to year, the number of people that every scenario can supply with food should only be seen as the ideal situation, i.e., the theoretical capacity of the system. One further uncertainty is the yields of the leys, which is the basis for meat and milk production. Lucerne dominated leys were used, which means that the measured yields are relatively large compared to average yields in Sweden (Frankow-Lindberg, 2003). Lucerne is an extremely high yielding but tricky crop that needs special conditions to thrive. Years with more unfavorable weather would have given lower yields. Another source of error may be the milk production that varies greatly between individual cows.

A serious uncertainty in the biofuel scenarios is that the calculations are not purely reality based. The case study farm already had a skilled workhorse, so half of the horse draft/rapeseed oil scenario could be tested in reality. However, the tractor used should in that scenario have been fuelled with crude rapeseed oil. However, there were concerns about coke formation in the tractor that could not be ignored, so we decided to drive the tractor on diesel. Any adjustments of the tractor would have been too costly for the project to carry, and using crude rapeseed oil and causing engine breakdown would have meant jeopardizing the whole economy of the farm. Instead, we theoretically converted the diesel requirement into rapeseed oil requirement and calculated the area needed to fulfill this requirement. The wheat and potato ethanol scenarios are even more theoretical because on farm distillation of potato to ethanol is prohibited and the other scenario, to send the wheat back and forth to the nearest distillation plant 250 km away, did not seem practically possible. Hence, both ethanol scenarios were purely theoretical. As previously, we converted the diesel requirement into the area of arable land needed for producing the ethanol required.

4.2 Framing of the biofuel scenarios

As previously mentioned, we performed a literature study to find out which biofuels could be tested on the farm. The biofuels considered were: rapeseed oil, first and second generation ethanol, biogas, generator gas, and horse draft, as discussed below.

The efficiency of a diesel-fuelled tractor engine is approximately 35%. However, when calculating the fuel efficiency of biofuels (i.e., the conversion of chemical energy in biomass to mechanical energy), several losses have to be taken into consideration. For crude rapeseed oil, the oil content of rapeseed, extractable for fuel use, is 50%, hence, 50% of the mass is lost. Oil contains more energy compared to carbohydrates and proteins, almost double the amount. Hence, approximately one-third of the energy content is “lost.” If the engine operates on rapeseed oil with the same efficiency as with conventional diesel (35%), and differences in energy content are not taken into account, the efficiency of the chemical energy of the biomass into work is reduced to 23% (Bernesson, 2004).

To use pure rapeseed oil seemed to be a fairly attractive option since no large investments had to be made to upgrade the fuel, and the oil could be used on the farm without any fuel transport needed. The conversion of the tractor also seemed relatively easy compared to using, e.g., electricity or biogas, which most probably would have required investment in a new tractor. An indirect effect of using rapeseed oil is that a high nutritional value of food production is lost. From an economic point of view, rapeseed oil is worth much more as a food commodity, than it is for replacing diesel.

The fuel efficiency of biogas in an engine that converts methane into work with the same efficiency as a conventional diesel engine (35%) varies between 9% and 21% because the energy in the biomass converted into methane ranges from 25% to 60% (Alvarez, 2006). Since the fermentation process itself produces very little heat, the digestion chamber has to be insulated and heated to keep the temperature at +37 C°, which is an optimal temperature for the fermentation process. Biogas that is to be used in a vehicle needs to be cleaned. Typically, it consists of 65% methane and 30% carbon dioxide, and the rest is approximately 3% ammonia and 2% hydrogen sulfides (Alvarez, 2006). The sulfides are very corrosive and it is crucial to eliminate them if the gas is to be used in an engine. To avoid a too low efficiency and weak capacity, it is preferable to get rid of most of the carbon dioxide as well (Bernesson, 2004). All options for biogas production on this small scale are likely to become very costly, especially per unit of biogas produced (Tersbol and Jorgensen, 2009). Not only are investments needed for the biogas plant, but some kind of upgrading is needed for the biogas to be usable. On top of this, the farm would need storage for the fermented slurry, which serves as a fertilizer, as well as needing systems for fertilizer spreading. Another problem is the water availability, which might prevent the system from working at all. A possible solution to the water scarcity might be to use liquid manure; however, for the case study farm, which used deep litter beds in all stables, such a transition would have been a very large investment. As a conclusion, biogas as fuel seemed less attractive than rapeseed oil. For this reason, the biogas option was excluded from the study.

Regarding ethanol, there is first and second generation ethanol conversion. First generation conversion is a commercially available technology, and uses products rich in starch, such as wheat and potato. Second generation conversion technology is still under development, but will be able to convert materials rich in cellulose into ethanol (Thomsen et al., 2003). Because the second generation biofuel technologies (producing ethanol from cellulose) are not fully developed and are likely to be expensive to implement on a small farm, they were not considered in this study.

The fuel efficiency of first generation ethanol differs between 17% and 20%, depending on the engine and feedstock used (Johansson and Liljequist, 2009; Lowisin, 2007). However, since there is only one producer of fuel ethanol in Sweden, namely in Norrköping, the case study farm would have to transport all wheat about 250 km, back and forth. Besides this additional energy and cost, several more or less energy-consuming products have to be added at the Norrköping ethanol plant, e.g., phosphoric acid, sodium hydroxide, sulfuric acid, enzymes, yeast, urea, ammonia, calcium carbonate, and large quantities of both fresh water and sewage water (Paulsson, 2007). Hence, to regard ethanol as renewable is questionable. However, the method was possible to use from a crop rotation and economic perspective, so we decided to include it in our calculations. As an alternative, we also included a more "traditional" ethanol producing method with malt (from own produced oat) and distillation of potatoes, as theoretically calculated for the farm. The method has been used for long time; however, not for fuel purposes. All residual products can be recycled on the farm and no chemicals are demanded, meaning that this system could be regarded as more renewable, compared to the industrial version. However, it is prohibited to distill your own ethanol and consequently, the scenario is somewhat hypothetical.

An older method, generator gas derived from wood, was also taken into consideration. It has a lower energy density, resulting in a slower combustion compared to petroleum or diesel. In an Otto engine, there will be a decrease in power output of up to 40–50%, and for a diesel engine, the fuel efficiency will be around 17% (Bernesson, 1993). Since the engine needs diesel for ignition, the system will not be totally renewable, unless e.g. rape methyl ester (RME) or ethanol is used as ignition aid. Generator gas is also associated with severe health hazards, due to carbon monoxide poisoning. These considerations made us rule out generator gas as well in this project.

When we calculated the energy efficiency of horse draft, approximately one-third of the gross energy intake in forage was estimated as being lost in manure (Pinney, 2003; Rydberg and Jansen, 2002). The energy requirement for maintenance is 73% of the metabolizable energy (Björnhag et al., 1989). The metabolizable energy is approximately 95% of the digestible energy, i.e., 5% is lost in urine and methane (Björnhag et al., 1989). Hence, approximately 17% of the energy in the fodder intake is convertible into tractive power (see Paper III for detailed calculations).

Our conclusion was that on this small farm, horses definitely could be a realistic biofuel alternative, especially when we could take advantage of the higher plant density in several crops due to narrower rows and smaller turning areas.

Figure 4. Horse draft may sound like an old-fashioned biofuel, but the development of modern horse-drawn equipment is fast, including, e.g., ground-driven transmission and hydraulic two-way lifts (photo: M. Olsson).

This practical-theoretical reasoning led to the conclusion that the biofuels possible in the studied context were restricted to pure rapeseed oil, cold pressed at the farm, horse draft, ethanol from wheat, processed at a commercial plant, and ethanol from potatoes, processed at the farm. The fuel efficiencies of the different biofuels included in the literature review are summarized below (Fig. 5).

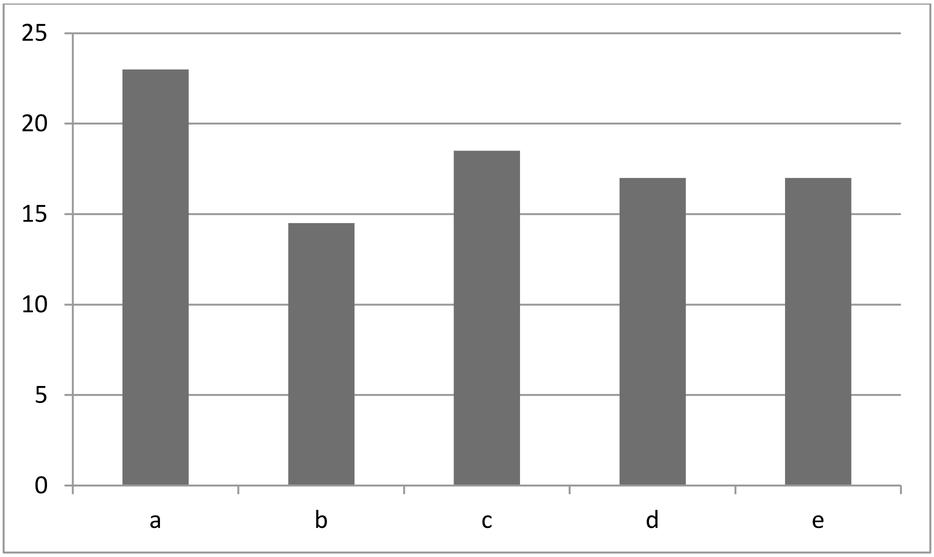

Figure 5. Fuel efficiencies (%), i.e., the conversion of chemical energy in biomass into mechanical energy, of the different biofuels included in the literature review: (a) crude rapeseed oil, (b) biogas (mean number; fuel efficiency range of 9–21%), (c) ethanol from wheat and potatoes (mean number; ranges of 17–20%), (d) generator gas, and (e) horse draft.

5 Results

5.1 Interviews

The results of the interviews with the farmers managing the twelve farms in the biodiversity and landscape heterogeneity assessment studies showed that the small and large farms differed in several farm characteristics e.g., livestock composition, crop rotation, and use of agrochemicals (Table 1).

Table 1. Main characteristics of the twelve farms (coded 1–12) included in the survey. S=small, L=large, O=organic, C=conventional. (The case study farm in Papers III and IV is coded SO2). Livestock density is expressed as animal units per ha (au/ha). Art. fert.= use of artificial fertilizer.

Farm	Arable land (ha)	Ley in crop rot.	Staple crops	Livestock	au/ha	Art. fert.	Herbi-cides	Insecti-cides
SO1	25	Yes	Cereals, ley, berries, vegetables	Sheep, geese, hens	0.34	No	No	No
SO2	12	Yes	Cereals, ley, vegetables	Cattle, sheep, horses	0.52	No	No	No
SO3	52	Yes	Cereals, ley	Cattle, sheep	0.53	No	No	No
SO4	52	Yes	Cereals, ley	Cattle, sheep	0.48	No	No	No
SC5	14	Yes	Cereals, ley	Cattle, horses	0.85	Yes	Yes	No
SC6	32	Yes	Cereals, ley	Cattle, hens	1.00	Yes	No	No
LO7	230	Yes	Cereals, ley	Pigs	0.52	No	No	No
LO8	135	Yes	Cereals, ley	Cattle, pigs, sheep	0.34	No	No	No
LC9	135	No	Cereals	Pigs	2.20	Yes	Yes	Yes
LC10	280	No	Cereals	Hens	0.13	Yes	Yes	Yes
LC11	300	Yes	Cereals	Horses	0.03	Yes	Yes	Yes
LC12	200	No	Cereals	Horses	0.10	Yes	Yes	Yes

5.2 Correlation between farm size and biodiversity

The results from the biodiversity comparison between small and large farms (Paper I) showed that all assessed biodiversity parameters were significantly higher on the small farms compared to the large ones. For example, more than twice as many butterflies, breeding bird species and bird territories, five times as many bumblebees, and almost twice as many herbaceous non-crop plant species were found on the small farms compared to the large farms (Fig. 6). All differences, except for bumblebees, were statistically significant. The non-significant difference in number of bumblebees is due to large variations within the two groups, small and large farms.

Sizes of fields differed significantly between small and large farms, with the smallest field sizes found on the small farms. The diversity of cultivated crops was significantly higher on the small farms (Fig. 6). There was a strong relationship between field size and number of breeding bird species (Spearman rho = -0.88), number of bird territories (Spearman rho= -0,81) number of bumblebees (Spearman rho = -0.86) and number of butterflies (Spearman rho = -0.64). There was also a relationship between crop diversity, and number of breeding bird species (Spearman rho = 0.51), bird territories (Spearman rho= 0.75), number of bumblebees (Spearman rho = 0.78), and number of butterflies (Spearman rho = 0.64). The correlation coefficients (r^2) for linear regression between field size and the biodiversity indicator groups were; 0.76 (***) for number of bird territories, 0.87 (***) for number of breeding bird species, 0.43 (*) for number of bumblebees and 0.65 (**) for number of butterflies. Corresponding correlation coefficients between crop diversity and the biodiversity indicator groups were; 0.61 (**) for number of bird territories, 0.43 (*) for number of breeding bird species, 0.28 (n.s.) for number of bumblebees and 0.50 (**) for number of butterflies.

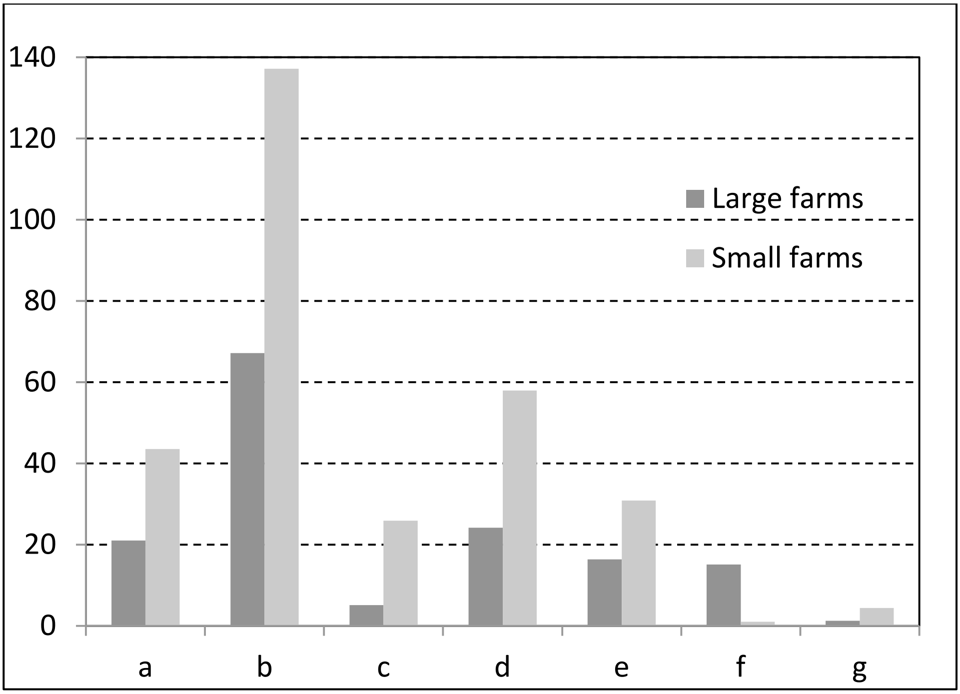

Figure 6. Differences between six small and six large farms regarding mean value per sample area of (a) number of breeding bird species, (b) number of bird territories, (c) number of bumblebees, (d) number of butterflies, (e) number of herbaceous non-crop plant species, and (f) average field size on the small and large farms (measured in ha), and (g) average number of crops cultivated per ha on the small and large farms.

When investigating differences between organic and conventional farms, we found that all parameters, except for bumblebees, were significantly higher on the organic farms than on the conventional farms. The largest differences were found when small organic farms were compared with large conventional farms. When comparing small and large organic farms, one and a half times more breeding bird species were found on the small organic farms than on the large organic farms although neither of them used any pesticides.

5.3 Correlations between on farm landscape heterogeneity, farm size, and biodiversity

When measuring surrounding landscape heterogeneity, the Shannon-Wiener diversity index for farm 1 to 6 (small farms) and 7 to 12 (large farms) were respectively: 1.078, 0.992, 0.992, 0.870, 0.992, 0.843, 0.953, 0.856, 0.753, 0.919, 0.929, 1.000, i.e. no statistically significant difference in the surrounding landscape heterogeneity could be detected. Despite no significant difference in surrounding landscape heterogeneity, the landscape heterogeneity on farm level was significantly higher on the small farms compared to the large farms. The small farms had on average 56% higher Shannon-Wiener diversity index regarding on farm landscape heterogeneity than the large farms.

We found a very strong positive correlation between on farm landscape heterogeneity and the abundance and diversity of breeding birds. A strong positive correlation was found between on farm landscape heterogeneity and number of butterflies and herbaceous non-crop plant species (Fig. 7). This is in line with other research dealing with the connection between landscape heterogeneity and biodiversity (Weibull and Östman, 2003; Weibull et al., 2003; Atauri and De Lucio, 2001; Banazak, 1992; Robertson et al., 1990).

All the bird species included in the single species analyses, except for skylark, i.e. eight of nine species, showed strong relations to small farms. No relations between single habitats and landscape structures and presence of single bird species could be found. This indicates that it was the diversity of habitats, not occurrence of single habitats that was important.

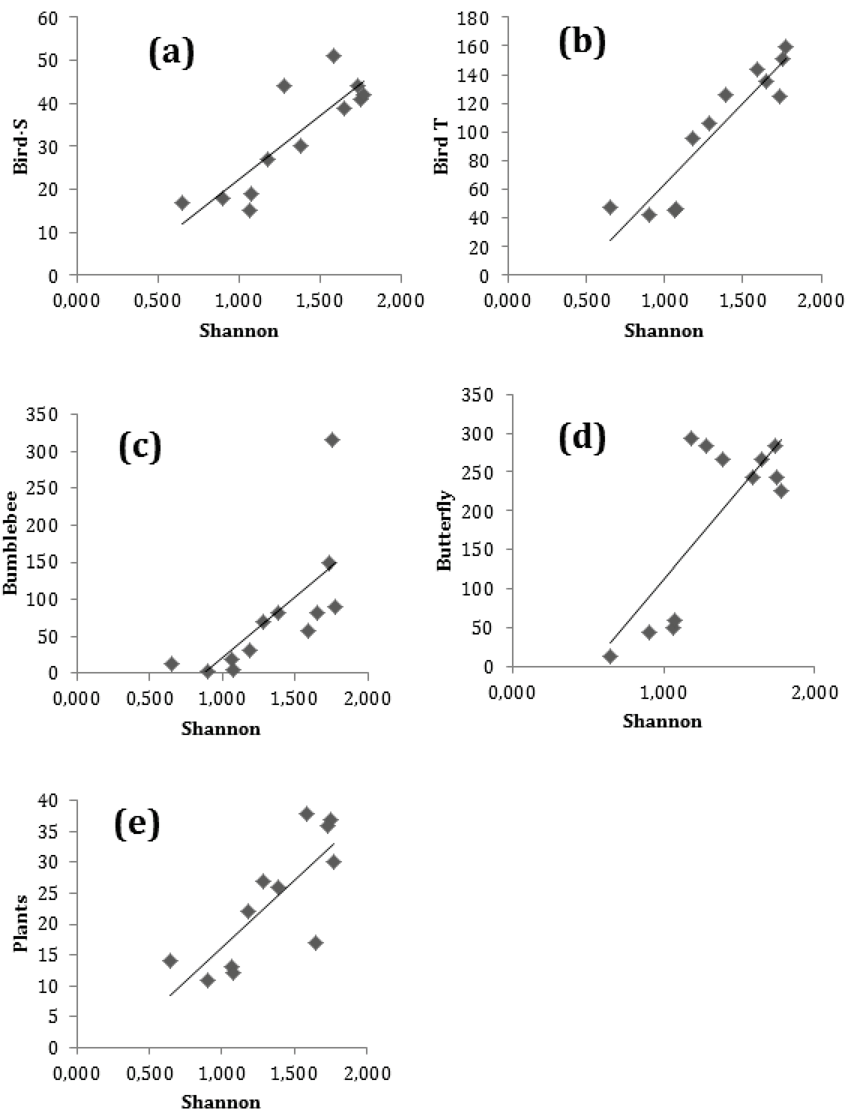

Figure 7. (a) Regression between the sum of breeding **bird species,** identified on each census spot at each farm, and on-farm landscape heterogeneity, measured by Shannon-Wiener diversity index (r = 0.87 ***). (b) As for (a), but for the numbers of **bird territories** (r = 0.94 ***) and (c) for the numbers of **bumblebees** (r = 0.69 *), (d) **butterflies**, (r = 0.77 **), and (e) herbaceous non-crop **plant species** (r = 0.83 **).

5.4 Production of biofuels and their impact on food production and nutrient fluxes

As previously mentioned, based on the food needs of the world population, our basic prerequisite was that every ha of land on the case study farm had to feed at least five people. The results from Papers III and IV indicate that it was possible to achieve this on the case study farm. The results further indicate that the case study farm's capacity to provide people's food needs was strongly dependent on which type of biofuels were chosen, because the different biofuels interacted more or less with food production (Table 2). The diesel scenario was used as a reference scenario to measure how much the different biofuels decreased food production when part of the crop production was used as fuel.

Table 2. Impact of the choice of fuel on the number of people the case study farm of 11.5 ha could supply with food, expressed as number of people and in % of the diesel scenario.

	Diesel	Rapeseed oil/ horse draft	Wheat ethanol	Potato ethanol
Number of people	69	65	53	57
% of diesel scenario	100	94	77	82

The "worst" scenario, from a food supply perspective, was the wheat ethanol scenario, which lowered the calculated number of people fed by the farm by 23% or 16 persons, compared to the diesel scenario. The rapeseed oil/horse draft scenario was the best biofuel solution considering the number of people that could be supplied with food. It only reduced the number of people fed by 6% or four persons, compared to the diesel scenario. Since the yield of rapeseed was not enough to cover the whole fuel demand on the farm, the rapeseed oil-fuelled tractor was combined with one workhorse. The calculated number of people fed, 65 persons, is larger than the number needed to fulfill the share of the global food producing capacity, 58 persons.

5.4.1 Nutrient fluxes

All biofuel scenarios in the study showed a nutrient balance at the farm level that was positive for nitrogen but negative for phosphorus and potassium. The best scenario in terms of nutrient recycling was the potato–ethanol scenario. The wheat ethanol scenario had a larger deficit of phosphorus compared to the other biofuels because the low number of people provided with food meant less urine and feces as input.

5.4.2 Animal combinations

The interdependencies between the different species of animals at the farm were many. For example, the number of horses limited the number of cows and sheep, and the number of slaughtered animals affected the number of poultry as they ate slaughter waste. Some computed mixtures of livestock and their influence on number of people provided with food are shown in Table 3. The cases include scenarios with largest possible amount of large cows (case 1) and small cows (case 3). Also scenarios with no cows, only sheep (case 2) and better balance between the different livestock (case 4) were computed. The cow breeds included in the scenarios were Large and Small Swedish Mountain Cow. They are breeds that are able to maintain themselves and produce milk on low-energy feed, like forage and grass from semi-natural pastures and forests. The sheep included were crossbreeds between different mutton breeds, which are all able to maintain themselves from grazing pastures and forests for large parts of the year (Fig. 8).

Table 3. Computed numbers of persons whose food needs were met with different mixtures of livestock in two different fuel scenarios. Scenario I, with diesel, was used as reference scenario. Scenario II includes a tractor fuelled with crude rapeseed oil, plus one workhorse. Large cows=Large Swedish Mountain Cows. Small cows=Small Swedish Mountain Cows

Case	Case description Scenario I Diesel	Scenario I No. of people fed	Case description Scenario II Rapeseed oil/horsed draft	Scenario II No. of people fed
1	19 large cows, 7 sheep, 67 hens	69	18 large cows, 8 sheep, 67 hens	65
2	0 cows, 183 sheep, 70 hens	35	0 cows, 175 sheep, 70 hens	33
3	25 small cows, 5 sheep, 65 hens	51	24 small cows, 4 sheep, 65 hens	48
4	18 large cows, 16 sheep, 69 hens	67	17 large cows, 17 sheep, 68 hens	62

From the computed examples in Table 3, it is obvious that it is the number of large cows with high milk production that is decisive for the large number of people that can be fed in case 1. A change to only sheep production, case 2, decreases the number of people whose food needs can be met by around 50% in both scenarios, due to loss in milk production. On the other hand, this scenario gives much more wool, which can be used for e.g., clothing. Dairy sheep could have been an alternative that would give some milk even in case 2 and increase the number of people provided for in all cases where sheep are included. However, all sheep holders we contacted gave their sheep concentrate and it was difficult to find any figures about how much milk we could expect in our case scenarios. Consequently, dairy sheep were not included in the study.

Figure 8. Large Swedish Mountain Cows and sheep at the case study farm.

5.4.3 Diet

The crops cultivated on the farm were decided entirely from a sustainable crop rotation perspective where yield, weed pressure, nutrient circulation, and disease control were among the most important parameters acknowledged. However, we found it important to determine the diet that emerged from the different foodstuff produced from the crop rotation used. In the wheat-ethanol scenario the buckwheat was replaced by wheat and all wheat was used as feedstock for ethanol production. In the potato-ethanol scenario the vegetables were replaced by potatoes and all potatoes produced were used as feedstock for ethanol production. Since both ethanol scenarios would give poor diets we selected scenario II, case 1 in Table 3, the combined rapeseed oil/horse draft scenario, as a base for calculations of a possible weekly diet (presented in Table 4).

Table 4. Possible weekly diet from scenario II, case I in Table 3.

Product	Quantity per week
Rapeseed oil	66 g
Wheat flour	622 g
Oat meal	320 g
Buckwheat	348 g
Potato	1.9 kg
Vegetables	6.1 kg
Lamb meat	46 g
Veal	221 g
Poultry (meat)	13 g
Egg	252 g = 3.5 eggs
Milk	11 L

The milk consumption might seem rather large in this diet, however, the present Swedish consumption of milk products is around 9 L per week (LRF, 2013). 11 liter milk corresponds, e.g., to 400 g cheese and 400 g butter, 1 dl cream, and 5 liter drinking milk or other milk products, such as yoghurt, per person per week. At present, Swedes eat an annual average of 88.5 kg meat per person (Jordbruksverket, 2014). Our scenario using horse draft and a rapeseed oil-driven tractor produces 14.5 kg of meat and edible intestines per person per year. Hence, this type of system requires a significant decrease in meat consumption, more like an ovo–lacto–vegetarian diet. A discussion of whether this diet is suitable for humans or not is not included in this study. The above presented diet is the diet that appears under the specific conditions of this particular crop rotation and animal combination. It is the crop rotation and animal combination that decides the diet. Other crop rotations and animal combinations would give other diets.

6 Discussion

The higher biodiversity found on organic farms compared to conventional farms is in line with most research regarding effects of organic farming practices on biodiversity (see, e.g., Tuck et al., 2013; Geiger et al., 2010; Mondelaers et al., 2009; Bengtsson et al., 2005). However, despite the fact that neither the small nor the large organic farms in our study used any pesticides or artificial fertilizers, the number of breeding bird species on the small organic farms was one and a half times that on the large organic farms. This suggests that organic agriculture, *per se*, is not enough to achieve high on farm biodiversity; size also has to be taken into consideration. One reason why the small farms harbored much higher biological diversity compared to the large farms could be the higher on farm landscape heterogeneity found on the small farms. Another reason could be the higher crop diversity found on the small farms, indicating that multifunctionality was a common strategy among the farmers included in our study to find an earning on their small farms, i.e., by cultivating a number of different crops and keeping a large diversity of livestock species and breeds. Such multifunctionality has been shown to increase both social and economic resilience (Tengö and Belfrage, 2004; Van der Ploeg and Renting, 2000). In line with other research regarding relation between biodiversity and crop diversity from a landscape (Wretenberg, 2006) and farm (Björklund et al., 2009) perspective, we found statistically significant correlations between crop diversity and abundance of two of the assessed biodiversity indicator groups; birds and butterflies. Additionally, our results suggest that the smaller field sizes found on the small farms can be supposed to be even more important to achieve high on-farm biodiversity. Statistically significant correlations were found between field size and all assessed biodiversity indicator groups; birds, bumblebees and butterflies. The small fields, surrounded by field edges and open ditches, created a patchy landscape rich in wild flora, surface water, and screes. Several studies illuminate the importance of field edges and open ditches for biodiversity at different spatial scales (Vickery et al., 2009; Östman et al., 2001; Weibull et al., 2000; De Snoo, 1999; Tucker, 1997).

Our attempts to find out which specific habitat was especially important for different bird species were almost fruitless. The results indicate that no particular landscape structure in isolation could be considered as especially important. This lack of correlation suggests that it is the total landscape heterogeneity on the farm that decides the number and diversity of breeding birds. For example, where the northern wheatear was found, screes and stone walls were always present. However, presence of screes and stonewalls did not necessarily mean that northern wheatear was present. As a matter of fact, none of these habitats had a strong impact on the number of northern wheatear. For this species, as for most of the species investigated, it seems that it is not just the preferred nesting habitat that decides whether a species is present, but the mix of many different habitats used for feeding and shelter. This indicates that not only suitable nesting sites, but a large variety of insects and seed are needed to support a high abundance of birds. Hence, in line with other research (Benton et al., 2003, Östman et al., 2001; Donald et al., 2001; Weibull et al., 2000), the more habitats per area, the higher the biodiversity. In this perspective, it is easily understood why the small farms were superior to the large farms regarding biological diversity since not only birds, but also insects, require non-cultivated habitats for foraging and nesting.

The interviews showed that grazing of livestock more commonly occurred on the small farms. Research has shown that grazing animals are an important contributor to high biodiversity, not only because grazed pastures attract a variety of insects and plants that constitute a valuable food resource for e.g., birds, but the grazing animals themselves attract insects that, in turn, can be caught by the birds (Kasprzykowski and Golawski, 2012; Ahnström et al., 2008; Evans et al., 2007; Buckingham et al., 2006; Bruun and Smith, 2003; Ambrosini et al., 2002). Starlings, pied wagtails, swifts, and swallows can serve as examples of bird species especially dependent on grazing animals for catching insects.

The strong relation found between on farm landscape heterogeneity and abundance of breeding birds, a relation that was not found between single habitats and single bird species, suggests implications for future development of the EU's CAP. Our results indicate that agricultural subsidies supporting single habitats in an otherwise homogenous landscape, as in the current CAP, will not succeed in increasing biodiversity to any major degree. Instead, management regimes that, as a by-product, generate high on farm biodiversity should be supported. Based on the results of this thesis, it could be emphasized that small-scale farms belong to this category.

It is perhaps tempting to believe that the negative effects of field enlargement, in an otherwise small-scale landscape mosaic, can be counteracted by the presence of all naturally occurring non-cultivated habitats in the surrounding landscape. However Figure 9 illustrates what happened when small-scale farms were converted into large-scale farming in an otherwise heterogeneous landscape, in this case Roslagen, the research site in this thesis. For example, the conversion included enlargement of the small fields into larger, more rectangular fields with fewer field margins per area, loss of grazed areas around the fields and conversion of several open ditches to subsoil drainage. Several habitats within or close to the fields, e.g., dwellings, ponds, and screes, were also lost. Additionally the farmsteads, known as biodiversity hot-spots (Hiron et al., 2013), disappeared. Hence, not only the field sizes changed, but the whole landscape structure was simplified.

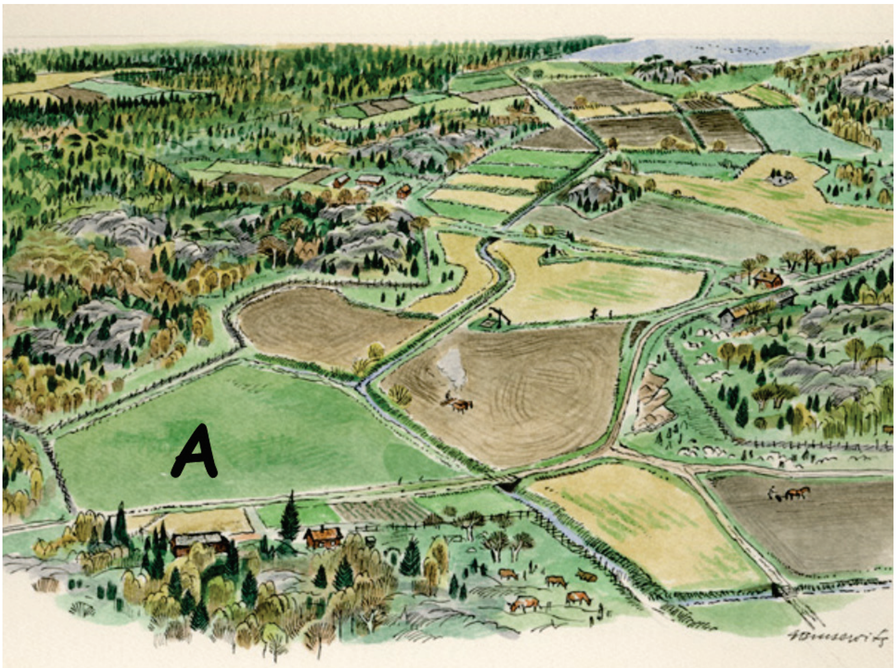

Figure 9. Impact of management on landscape and heterogeneity, painted by Gunnar Brusewitz (reprinted with kind permission of Gunnar Brusewitz). A = small-scale farming; B = large-scale farming.

Intensively managed farms that, for one reason or another, have to convert to rely mostly or entirely on local renewable resources will, regardless of size, have to design the farm in such a way that the generation of ecosystem services is large enough to replace external inputs in the form of fossil fuels, artificial fertilizers, and chemicals; otherwise the production will drop. Since the ecosystem services used in such production are generated by the different underground and aboveground species that make up the biodiversity on the farm, the management regimes will increase biodiversity as a by-product of the food production practices. This connection between biodiversity and food production is important to emphasize, especially because biodiversity conservation is often regarded as contradictive to high food production and, in the end, to our capability to feed a growing world population.

The results from the studies on the case study farm, presented in Papers III and IV, show that a very small farm (for Swedish conditions), with high on farm biodiversity and managed without any use of chemicals, artificial fertilizers, or fossil fuels, was able to contribute its share of the global food production necessary to feed the current and even a slightly larger world population. But was it because of the high biodiversity on the farm or in spite of the high biodiversity? Judging only from the results presented in this thesis, it is of course not possible to answer this question. However, many studies have shown that biodiversity plays a key role in the resilience of ecosystem functions, something that could be considered to have a positive effect also on food production capacity (Elmqvist et al., 2013; Rockström et al., 2009; Bengtsson et al., 2003; Kinzig et al., 2002; Loreau et al., 2001; Peterson et al., 1998). Additionally, in line with several studies (Kleijn et al., 2007; Costamagna and Landis, 2006; Schmidt et al., 2003; Östman et al., 2003), the high food production may also have been enhanced by efficient pest control and pollination generated by all wild predators, parasitoids and pollinators.

The results from the case study farm are also in line with some researchers arguing that small-scale farming has higher food production output compared to large farms. The multifunctionality and intense land use found in many small-scale farming systems, much like a larger scale of gardening, is one of the main arguments for the larger productivity observed in small-scale farms, also known as "paradox of the scale" or "inverse farm size–productivity relationship" (Horlings and Marsden, 2011; De Schutter, 2011; Barrett et al., 2009; Halweil, 2006; Rosset, 2000; Cornia, 1985). For example, Rosset (2000) argues that the habit of concentrating on measuring yield as the production per unit area of a single crop biases the results towards large-scale agriculture. The intercropping and multifunctionality on small farms results in the yield not being based on one single crop, but being distributed between different crops with, logically, lower yields for each one of these crops. For example, on the case study farm, cereals were intercropped with clover. Since the clover enriched the straw it could be used as fodder for, e.g., dry cows and sheep and the discard could be used as litter. After harvesting, the clover was grazed and thereby the grazing season was extended with nutrient-rich fodder, decreasing the need for supplementary feeding. Hence, grains, litter, and fodder are harvested on the same plot, but only the grain yield "counts." Rosset (2000) shows that when measuring total output, as opposed to measuring the yield of one single crop, the smaller farms are two to ten times more productive than the larger farms. Large-scale farms tend to have larger labor productivity, while smaller farms tend to have a more multifunctional land use which eventually gives higher total yield output per area. Likewise, Tscharntke and coworkers (2012) state that small-scale, diversified farms show higher productivity per area compared to large, less diversified, farms. Hence, the small farm size in itself may have contributed to the high food production achieved.

Today, the largest loss of energy in the global food system is through feeding cereals to livestock for meat production (Misselhorn et al., 2012;

Johansson et al., 2010). Therefore, another reason why the case study farm could feed so many people is that the animals did not eat what humans can eat. Instead, they grazed extensive land and converted crops that are inedible to humans into valuable food sources, such as milk and meat. Livestock grazing pastures and forests are not only able to produce food from land types that are difficult or undesirable for crop cultivation; they also release arable land, previously used for fodder production, to food production for humans, or biofuel production.

As mentioned previously, the number of people calculated to be supplied with food from the case study farm in the scenario including one rapeseed oil-driven tractor and one workhorse, 65 persons, was larger than the number needed to fulfill the share of the present global food-producing capacity, 58 persons. Thus, our results suggest, in contrast to other research (JTI, 2013), that even in a future with no access to fossil fuels, we will not necessarily have to starve. It should be noted that the number of people needed to be supplied with food, 58 persons, is a gross generalization since there are large regional differences in food producing capacity between e.g., extensive farming in Australia or Namibia versus intensive farming in for example central Europe. Not every ha is able to produce equally. Taking the enormous land tracts of extensive farms in arid and semi-arid regions into consideration, surely this pushes the requirement per ha up for farms in climatically more favourable regions. This suggests that the case study farm should supply more than 58 persons with food. On the other hand, Sweden has rather cold climate and comparably short growing season therefore it could be stressed that the production requirement should be reduced. However, to in detail decide the exact number of people needed to be supplied is outside the scope of this thesis. The number illuminates the fact that it is not a big deal for a farm to be self-sufficient of fuels if it does not have to produce food and it is not a big deal for the Swedish agriculture to supply the society with bioenergy as long as it does not have to fulfil its share of the global food production necessary to feed the world population. It is when these two goals are linked that the real challenge begins. Judging from the results from this thesis, if these two goals are to be fulfilled, it is very unlikely that the Swedish agriculture will be able to supply the society with any energy at all.

Additionally, with our scenario with horse draft and rapeseed oil-driven tractors as substitution for diesel, many social challenges will need to be faced, such as where to get labor cheap enough to enable food production at reasonable prices, and how to educate all the people that will be needed in the food production. As the scenario includes several animal species, cultivation of various crops, and horse draft as biofuel, it is very likely to require significantly more labor compared to more specialized farms. The horses must be trained and groomed, the cows milked, the sheep regularly shorn, and the wool taken care of. All fences have to be maintained, as does the tractor and all other machinery and equipment. At slaughter, the meat has to be distributed and the slaughter waste and, ideally, also the hides and feathers have to be taken care of. Considering all different tasks that must be managed, even a small farm, like the case study farm, easily becomes a large operation in terms of labor. It should also be noted that the self-sufficiency in energy included in our study, as in most other studies regarding bioenergy, only concerns fuel for tractive power. All other energy usage, e.g., milking machines, milk cooling tanks, hay and grain-drying plants, auxiliary engines, crushing machines, thermal lamps, electric fences, and frost protection of water pipes and drinking bowls, has not been included. If all, or some, of the tasks performed by all these machines would be done entirely by humans, the labor demand would further increase.

The increase in labor demand if all Swedish farming would be done by horse draft and tractors fuelled with vegetable oils is of course impossible to quantify as we do not know the future contribution of, e.g., wind and sun power to the energy sector. However, studying some historical data could give us some clues about what is to be expected. From 1900 to 2012, the number of people working in the agricultural sector in Sweden decreased from 1.3 million to 156 000 (SCB, 2012). In 1960, 540 000 persons, or 7% of the Swedish population, worked in agriculture (SCB, 2012). If we assume that agriculture will be supplied with electricity even in the future, the same percentage as in 1960 could perhaps be an appropriate prediction for the post-carbon era. With a Swedish population of 9 million people, this would mean that 630 000 persons will be needed in the food production sector, that is, almost a fourfold increase compared to the number working in agriculture today. This indicates drastic challenges for rural development processes and policies.

To include horse draft among the biofuels is definitely a slightly new approach. There is of course a range of parameters that distinguish the living system from the technological system. One of them is that "techno" biofuels are storable, which makes it possible to gather a large amount of energy for power outtake when wanted. Horses demand care every day, even when not working. They demand skilled labor and they need to operate slowly and regularly. If we calculate that the horse needs energy for maintenance even when not at work, then it needs to be at work every day to reach an energy efficiency of 17%. A tractor is an all-round equipment that not only can exert tractive power, but is also able to, e.g., lift heavy loads. Horses work more slowly than the tractor and have a lower power output, a fact that is a large problem in agriculture where timeliness is very important in obtaining high yields.

However, horse draft also has some advantages compared to tractors. Horses do not depend on fossil fuels for lubrication of engine, transmission and hydraulics, as do tractors. This, often neglected, oil consumption corresponds to about 100 liters of oil per year per tractor. Neither do horses depend on spare parts derived from, or manufactured by, fossil fuels for their maintenance. The yearly energy cost for spare parts is estimated to be, in diesel equivalents, 750 liters (Svensson, 1987). While tractors exhaust two-thirds of the energy used as fumes and heat, horses "exhaust" one-third of the energy consumed in the fodder, as reusable manure (Morrisey, 2009). Horses can gather their fuel by themselves for large parts of the year and in contrast to tractors, they have a balanced carbon budget since the crops used as fodder sequester carbon via photosynthesis. A horse manufactures its own replacement even while at work, a process that tractors cannot attempt. A mare can give birth to at least ten foals during her lifetime, that is, not only her own replacement is secured, but so is also a substantial amount of meat, and bones and slaughter waste, which can be recycled to the fields.

The deficits of phosphorus that occurred in all biofuel scenarios presented could, at the farm level, be reduced by half if bones and slaughter wastes were recycled. If, in addition to this, also 80% of the human excreta were recycled, the phosphorus deficits would be almost eliminated. For the time being, it is prohibited to recycle bones and slaughter wastes on farms, due to concerns about mad cow disease. However, this study shows that, for long-term sustenance of nutrients, it is vitally important to find ways to recycle these products in a safe way.

All scenarios also showed large deficits of potassium. However, when the nutrient balance was modeled only for the arable land, the hay from the lowland meadows was regarded as a nutrient input. In this case, the calculations showed a positive balance for potassium in all scenarios. This implies that the nutrient balance can be maintained on arable land if nutrients (in hay) are moved from meadows to arable fields (through manure) and bones and slaughter waste is recycled. However, this will inevitably lead to nutrient losses from the meadows. On the other hand, lowland meadows are typically situated on lands that receive runoff water from surrounding land. This, in turn, might enable trapping of elements like potassium in the meadow soil through sorption processes. Harvesting these meadows returns some of the nutrients that were previously leaked from the fields and forests at higher altitudes. In addition, sorption processes in recharging areas, followed by plant uptake and removal by harvest, might be an effective way to mitigate eutrophication of lakes and seas, similar to riparian areas (Baker et al., 2006).

However, as mentioned previously, leakage of potassium was not included in our calculations. Therefore, the potassium deficits could be assumed to be even larger than those presented in Paper IV. On the case study farm the soils are rich in sedimentary clay; hence, the potassium deficits are likely to be compensated through weathering. However, in the long run and especially at lighter, more sandy, soil conditions, the weathering rate might not be fast enough to compensate losses, and some solution for potassium recycling must be found.

Since the nutrient balance is very specific to the production and local conditions on this particular farm during these particular circumstances it is hard to generalize the results to other parts of Sweden or even to other farms in the same region. However, the results high-light the fact that nutrient circulation is a forgotten aspect of biofuels. The choice of biofuel does affect not only the number of people supplied with food, but also the long-term sustenance of the whole production system. A biofuel that drains the ecosystem too much on nutrients, like the wheat–ethanol scenario in our study, simply is not viable in the long run.

Moving the "window of interest" back and forth between arable land and the whole farm made it apparent that the studied agrarian system drains all support areas – not only the meadows, but also the forests and pastures – of nutrients. These nutrients are accumulated on the fields. From a landscape perspective, it might be questionable if this could be regarded as sustainable land use. The views on this may vary between researchers, but I would argue that it is sustainable, at least under the conditions prevalent on this particular farm. Forest grazing is a very extensive type of grazing and nutrients drained as a result of this grazing system are most certainly replaced by weathering and atmospheric depositions (Olsson, 2014). The pastures, on the other hand, suffer from severe export of nutrients, not least nitrogen and phosphorus. The grazing intensity has to be fairly high to prevent bushes from invading and the grazing period corresponds with the period of highest milk production and growth increment of the animals; hence, large amounts of nutrients are moved from the pastures by milk and meat, including bones. However, the successive depletion of nutrients has the effect that, at least up to a certain threshold, there is an increase in biodiversity. Flowering plants will no longer be outcompeted by aggressive grass species. Hence, there will be an increase in the number of plant species, and in the number of insects, including pollinators (Öckinger et al., 2006). The higher insect abundance will in turn increase the number of birds (Söderström and Pärt, 2000). Accordingly, abandonment and fertilization of pastures are, at least in Europe, considered a large threat to biodiversity (Krauss et al., 2010; EEA, 2004). Hence, the uneven allocation of nutrients in the studied system could be considered to increase, more than decrease, the whole system's resilience (Dahlin et al., 2005).

One advantage of grazing pastures and forests, as on the case study farm, is that the livestock are able to produce food from land types that are difficult or undesirable to cultivate for crops. As mentioned above, one reason why the case study farm could feed so many people is that the animals did not eat what humans can eat. However, not only did they allocate and convert for humans inedible food into nutritious food sources, but they also allocated nutrients. This often forgotten ecosystem service is of great importance for sustaining high yielding and resilient agricultural systems.

There are plenty examples of extremely efficient crop rotations in the literature, which could perhaps have been implemented on the case study farm. For example, already in the early 20th century, the Swedish research farm Ugglehult performed trials on fish production in the crop rotation (Edling, 1921). The water from flooded meadows was trapped by embankments and the annual fish production was estimated to be about 100 kg per ha. Together with 80–90 geese per ha, such a crop rotation would have given more meat and eggs in the diet and most certainly increased both the number of people supplied and the biodiversity. However, it should be stressed that in the area where the Ugglehult farm was situated, precipitation strongly exceeded evapotranspiration, resulting in a large amount of runoff water. This is not the case in the region where the case study farm is situated; on the contrary, in this area long drought periods are common.

According to Odum and Odum (2008), sustainable use of agricultural land demands some kind of long-term fallows during which the land can regain some of the mature stage crops, like trees and woody bushes, and rebuild a stock of nutrients to the topsoil by reallocating these from greater depth of soil levels. Additionally, tree vegetation normally does not lead to the same export of nutrients from the site as agricultural crops do, hence, during a tree fallow, not only is nutrient export mitigated, but input rates increase. As a consequence, the soil structure improves in the subsoil, and soil carbon content increases (Olsson, 2001). In analogy with this reasoning, 10 year fallows with fruit and nut trees and berry bushes included in the crop rotation on the case study farm could have enriched the diet even more. These orchards could be used for raising geese, turkeys, and even more laying hens than in our scenarios, providing more meat and eggs to the diet. Also, all uncultivated field margins and edges of forests, pastures, and field islets could be used for cultivating perennial woody fodder crops, e.g., gorse (*Ulex europaeus*), roses (e.g., *Rosa rugosa*), and buckthorn (*Hippophae rhamnoides*). These plants can be grazed by sheep and horses during late autumn and early winter, extending the grazing season with nutrient-rich fodder and decreasing the amount of harvested winter fodder needed. All these crop rotations could be assumed to also increase the number and diversity of wild flora and fauna by giving even more heterogeneity to the landscape.

Innovative crop rotations and multifunctional land use strategies are surely something we will have to test in the future, whether we want to or not. If there are to be 9 billion people on Earth 2050, globally on average 6.4 persons will have to be supplied with food per ha (UN, 2012). Consistent with this figure, our case study farm would need to be able to support at least 74 persons. This is impossible in the current scenarios under current conditions, but with extremely high yielding and labor-intensive crop rotations, it might be achievable. However, meeting the challenge will not be easy. There is an urgent need for increased knowledge of how to sustain large yields even during hard stress in more extreme weather and with more insects and weeds that are able to survive, and even thrive, under warm and wet conditions. Also, having livestock breeds that manage to give high yields on forage and grazing will be important in the future if this type of multifunctional farms is to become important in the food system.

A solution often mentioned when it comes to the question of how to feed the world population is veganism. Maybe a global transition towards a vegan diet would make the goal of supplying 6.4 capita/ha more achievable? Not diving too deep into the divergent attitudes regarding different diets, a vegan transition at farm level may not be that simple. The first question is how to replace the soil nutrients that are lost through harvest. In a vegan scenario, recirculation of human urine and feces is absolutely crucial. Ideally, the people consuming the food produced on the farm should also return the excreta to fertilize the crops during the next growing season. However, there are large uncertainties in terms of the amount that can be recycled in reality. Also the urine and feces must be sanitized so as not to spread parasites and diseases, and cleansed so as to prevent accumulation of pharmaceuticals, heavy metals, and other unwanted substances in the soils. However, studies concerning local recycling systems at farm and community level show that there are possibilities for success in using nutrient recycling from human excreta (Winker et al., 2009; Tidåker et al., 2007; Tidåker et al., 2006).

Another difficulty is that ley in the crop rotation is no longer needed from a food production perspective in a vegan diet production, since no animal feed needs to be produced. However, from an agrarian perspective, leys have several advantages. Ley in crop rotation is crucial to control weeds; it helps the soil to recover from soil-borne diseases; and last, but not least, it accumulates carbon and thereby increases the soil carbon content (Davis et al., 2012; Mäder et al., 2002; Paul et al., 1997). If horses are used in agriculture, leys can be used as forage for them. On the other hand, to keep only one livestock species will most certainly give problems with parasite infestation. This is why mixed grazing systems with different species have been in use for quite a while, as an alternative to pharmaceuticals to control parasites (Antell, 2005; Nolan and Connolly, 1977). If no, or very few, animals are kept on the farm, this will mean that grazed pastures will be overgrown by shrubs and, eventually, forest. Several studies have suggested that semi-natural pastures are an important factor for bird and insect abundance in the agricultural landscape (Öckinger et al., 2006; Söderström and Pärt, 2000). Most certainly, the biodiversity would decrease if no animals were kept on the farms and the decreased biodiversity, in turn, would decrease the resilience of the agriculture (Elmqvist et al., 2013; Rockström et al., 2009; Kinzig et al., 2002; Loreau et al., 2001; Peterson et al., 1998). Furthermore, integrated crop and animal production facilitates nutrient recycling since the animals collect nutrients from vast areas by grazing. This is an ecosystem services that is difficult to cope without, especially in organic agriculture (Mäder et al., 2002; Lampkin, 2002; Wolfe, 2000).

When we performed the field trials to find suitable crop rotations for the farm, we considered testing a purely vegan alternative with fertilizers such as human urine (which is less complicated to sanitize compared to human feces), ash, stone meal, and seaweed. Several studies have shown high concentrations of cadmium in seaweed from the Baltic Sea (Broman et al., 1991; Söderlund et al., 1988) and we decided to analyze the seaweed we had harvested before spreading it on the fields. The cadmium content of the seaweed was 6.8 mg/kg dry matter, which is far above the permitted cadmium administration to arable land (European Commission (EC) 629/2008). Cadmium is a heavy metal that causes severe health effects when accumulated in the body. Since the half-life of cadmium in the body is between 20 and 30 years, accumulation can cause health problems with, e.g., renal stones and osteomalacia, even at low exposure level, and women are especially vulnerable (EU, 2007; Åkesson et al., 2006). Since we would not be able to use seaweed as a fertilizer, we abandoned a pure vegan diet scenario. However, this illustrates another challenge when it comes to the question of how to feed the world. This is not just a question for agronomists and engineers; it affects every single part of our society. If we withdraw useful sources of soil fertilizers, like seaweed and sewage sludge, because we have polluted them with chemicals and heavy metals from traffic, industry, and daily life, we surely make things worse. What we put into the ecosystem will sooner or later reach us again, this time possibly as a food contaminant.

In conclusion, working with real conditions on a farm has many practical and methodological limitations and uncertainties. On the other hand, working on a farm in close contact with other farmers and incorporating their points of view has the advantage that miscalculations are recognized fast and that solutions which, from practical viewpoints, are difficult to implement, can be identified and ruled out. I would argue that it is vitally important to conduct research under real conditions, on farms, rather than relying solely on more or less trustworthy theoretical calculations, when deciding the pathway of how to break the fossil fuel dependency of the Swedish agriculture. Ideally, the research should span at least 7–8 years, i.e., one crop rotation. During this longer time span, it would be possible to capture more of the complex interactions connected to choice of different management regimes and different biofuels than those included in this thesis.

Despite all the practical limitations and challenges connected with the studies presented in this thesis the fact remains; the results show that the case study farm could fulfil its proportionate share of the global food production necessary to feed the current world population without using any inputs in the form of artificial fertilizers, chemicals, and fossil fuels. Large-scale industrialized agriculture has for a long time been regarded as the only way to feed the growing world population (Giampietro et al., 1997). The results from this thesis indicate that small-scale, organic farming could be a more appropriate way to produce food in the future compared to continuing on the current pathway and facing even bigger problems with environmental degradation and pollution and a defective food security. Biodiversity and high production of food are often regarded as opposites. However, this thesis shows that high biodiversity and high production of food and biofuels can be combined on the same farm and piece of land. The results also suggest that this combination of high biodiversity and high production is enhanced by small-scale farming.

7 Conclusion

The results from this thesis can be summarized as follows:

1. There is a strong correlation between farm size and biodiversity, with small farms supporting the highest biodiversity (*Objective 1*).
2. Many studies show that organic agriculture is superior to conventional agriculture regarding biodiversity, which is in line with the findings in this thesis. However, our results suggest that there is a large difference in biodiversity also between small and large organic farms, despite the fact that neither of them used any pesticides. Farm size could therefore be considered as just as important to include in agri-environmental schemes, as organic farming.
3. There is a strong correlation between farm size and on farm landscape heterogeneity, with small farms harbouring the highest on farm landscape heterogeneity. There is also a strong correlation between high on farm landscape heterogeneity and high on farm biodiversity (*Objective 2*).
4. When investigating if any habitats are especially important to conserve in order to enhance high abundance of birds, we could find no such habitats. The total habitat heterogeneity seemed to be the most important factor deciding high abundance of birds.
5. The results indicate that it is possible to combine high on farm biodiversity and high on farm productivity, measured as the number of people supplied with food, on the same piece of land. Small-scale farming seems to be a win–win solution in terms of both biodiversity and food production, since it enhances high on farm biodiversity, but not at the expense of the food production rate (*Objective 3*).
6. A combination of horse draft and tractor(s) fuelled with crude vegetable oils, e.g., rapeseed oil, seems to be an appropriate way to achieve both

self-sufficiency in fuel for tractive power, sustainable nutrient circulation, and food production output large enough to fulfill the proportionate share in feeding the current world population (*Objective 4*).

7. An important insight from this thesis is that a seemingly simple choice – deciding what biofuel to produce on a farm – affects very many parameters, including food production, crop rotations, and nutrient levels.
8. The results from this thesis indicate, in line with many studies, that conversion to small-scale agriculture is one way to achieve high food production output per area; however, at the cost of higher labor demand.

8 Future research

It has already been mentioned that the high on farm biodiversity on the case study farm is suspected to have contributed to the high total food production output per ha achieved in this study. To examine how strong this relation between high on farm biodiversity and food production is, it is important to conduct further research to test differences in total yields between larger numbers of high and low biodiversity farms in several parts of Sweden and globally. A strong correlation between high biodiversity and high food production would hopefully increase the "market value" of biodiversity conservation.

The results from this thesis show that there are correlations between farm size and biodiversity, between crop diversity and biodiversity, and between field size and biodiversity. However, in order to isolate these relations, another research design is needed since all these parameters covaried in this thesis. The small number of farms included in the studies presented in this thesis prevents generalization of the results. Hence, I encourage other researchers to continue the research, not only using different research designs, but also including a larger number of farms of different sizes in different regions and countries.

To manage a complex ecosystem, such as the agricultural ecosystem, without any help from fossil fuel-derived products takes extraordinary expertise. Hence, to develop highly productive, multifunctional farming systems will require knowledge transfer between farmers and the scientific world. Today, these worlds are to a large extent separated from each other. More research needs to be done in collaboration between farmers and scientists and performed under real conditions where all the complex interactions between every change in management regimes and the surrounding agricultural system become apparent.

The results from this study indicate that on farm landscape heterogeneity and high biodiversity were characteristic features found on the small farms. If high on farm biodiversity is prioritized and farm size is of minor interest, it would mean that also a large scale farm could be “small scaled” if dividing the fields into smaller units and creating non-cultivated habitats like field islets and open ditches. However, and this stresses why “small scaled” large farms are so rare, by this, the very meaning of growing bigger and being large disappears when all economies of scales are lost. Research that deals with these complex relations and interactions between society, economy, policies, food production and ecosystems is urgently needed in order to find ways to convert the Swedish agriculture into sustainable direction.

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