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Land savings potential of pea/barley intercropping and the resulting biofuel potential in Europe

Master's Thesis

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ABSTRACT

Greenhouse gas emission (GHG) reduction targets have led to an increased demand for bioenergy. One way to increase bioenergy production is through intensification of agriculture, and use of the surplus land area for biofuel cultivation. Intercropping has been theorised to lead to such intensification. Therefore, a literature review was executed to identify the potential benefits of intercropping over sole cropping, to estimate the land savings potential from pea/barley intercrops, to calculate the resulting biofuel potential, and to approximate the difference in fertilizer needs between pea/barley sole and intercrops. The focus of the study was on pea/barley, because of their complementarity indicated in literature. Finally, a sensitivity analysis was conducted to illustrate a reliable range of results instead of a singular value.

Intensification of pea/barley cultivation through intercropping constitutes a considerable land savings potential. As much as 50 thousand hectares of land might be freed up for other purposes in the 15 European countries within the scope of the current study, which is the approximate size of the 'Noord-Oost polder' in the Netherlands. If this land would be utilized for biofuel production, 7,32 PJ could be generated each year, providing the same amount of energy as the heat demand of roughly 175 thousand Dutch households. European countries could increase their renewable energy production from biomass and waste by .184%. Emission abatement from biofuel production was up to 522 kt CO_{2eq}. Intercropping did not seem to contribute to a lower N fertilizer need, although this was almost impossible to conclude due to the large variance in the result.

PREFACE

In front of you lies the result of my Master's Thesis Project Sustainable Development. The goal of this project is to let students gain their first experience in conducting independent research as a sustainable development analyst. In doing so, I've learned to write a research proposal, formulate aims, analyse literature and write academically. I was given the chance to write my thesis at the Copernicus Institute for Sustainable Development, which is ranked as the 'Best Research Institute for Environmental and Sustainability Sciences' in the Netherlands. I feel very lucky to have had the opportunity to write my thesis at such a prestigious institute, with supervisors like Birka Wicke and Ingeborg Kluts.

CONTENTS

1. INTRODUCTION

Greenhouse gas emission (GHG) reduction targets have led to an increased demand for bioenergy. The European Union (EU) has set the so called "20-20-20" target: A commitment was made by the EU to reduce its overall emissions to 20% below 1990 levels, and increase the renewable energy share to 20% by 2020 (European Commission, 2014). A significant portion of renewable energy comes from biomass, and governments often set specific quota for biofuel. An example is the current 5% biofuel quota for petrol products within the EU, which is to increase to 10% by 2020 (European Commission, 2009). At the same time, food production has steadily increased over the past decades and is expected to increase further in the future (FAO, 2012).

Both energy biomass and food crops compete with each other, and with nature areas for land. This is often at the expense of forested areas, causing direct land use change (DLUC) or indirect land use change (ILUC) (Wicke, Verweij, Meijl, Vuuren, & Faaij, 2012). In the last decade, each year around 13 million hectares of forest has been destroyed or converted to other uses, compared to 16 million hectares per year in the 1990s. Other uses include industrial estates, mines, and agricultural (food and biofuel production) land uses. Despite the recent decrease, deforestation rates are still alarmingly high (Food and Agriculture Organisation of the United Nations, 2010; Geist & Lambin, 2001).

The sustainability of bioenergy and biomass products has often been questioned (Fargione, Hill, Tilman, Polasky, & Hawthorne, 2008; Searchinger et al., 2008). This was due to land use changes and the competition for land, water and nutrients between biomass production, food production and nature areas. Producing large amounts of sustainable biomass is therefore a major challenge, that requires an increase in the total agricultural production. One way of doing this is by enlarging the agricultural area. However, the unused land suitable for agriculture is limited, and the worldwide agricultural area has not increased since the early 90's (FAO, 2012). Another way to increase agricultural outputs is by increasing the productivity of land.

One way of potentially increasing the productivity of land is through intercropping systems, where multiple crops are cultivated on the same piece of land. In some cases, these systems were able to increase production, enhance nutrient cycling, and/or reduce the need for pesticides, making them an interesting subject of research (Anex, Lynd, Laser, Heggenstaller, & Liebman, 2007; Heggenstaller, Anex, Liebman, Sundberg, & Gibson, 2008; Malézieux et al., 2009).
A large number of studies has been conducted in the field of intercropping systems. Many studies describe the productivity of particular intercropping systems (Anil, Park, Phipps, & Miller, 1998; Cenpukdee & Fukai, 1992; Gesch, Archer, & Berti, 2014; Graß, Heuser, Stülpnagel, Piepho, &

Wachendorf, 2013; Olasantan, 1988; Reynolds, Simpson, Thevathasan, & Gordon, 2007; Schittenhelm, Reus, Kruse, & Hufnagel, 2011; West & Griffith, 1992), others focus on the effects on nutrient sequestration (Anex et al., 2007; Gooding et al., 2007; Heggenstaller et al., 2008). Another study provides an overview of techniques and practices commonly used in intercropping systems (Malézieux et al., 2009). A large scale project has been conducted in the EU that surveys the parameters that play a role in successful implementation of intercropping systems in the EU (4FCrops, 2010).

In recent years, little research has been aimed at providing a more extensive overview of different benefits of intercropping systems. Only limited study has been conducted towards integrating biofuel crop production into food production systems. One such study does show promising results, with successful intensification through mixed production systems (Heaton et al., 2013). De Wit (2014) uses a method that integrates food production and biofuel crop production by intensifying the food production, and utilizing the freed land for biofuel cultivation. A similar approach will be used in the current report (see method section). The land that would become available after a successful intensification of the production is called the land savings potential.

No attempts have been made to estimate the land savings potential and biofuel yield potential of implementing intercropping systems in a particular area. Furthermore, many studies are focused on the United States or South East Asia, rather than Europe. No studies have assessed the potential of intercropping for Europe or the EU as a whole. This would be an interesting scale, as many significant policy decisions are made at this level. Meeting the policy goals concerning renewable energy and biofuels specifically calls for European-scale information to base this policy on. The lack of research at this level results in the absence of a valid method of estimating the potential of intercropping systems for Europe in terms of land savings and biofuel production. For this reason, the current study has four aims:

- To identify the different potential benefits of intercropping systems
- To estimate the land savings potential of one particular intercropping combination
- To estimate the biofuel potential on the resulting freed up land
- To estimate the difference in fertilizer needs between this intercropping combination and its component crops.

In order to address these aims, first, a theoretical section will be constructed describing the potential benefits of intercropping and their underlying mechanisms. Field studies are then analysed to collect more detailed characteristics of intercropping from literature, namely their yield, weed suppression ability, nutrient dynamics and disease/pest effects in comparison to monocultures. This will be carried out with special interest in pea/barley intercrops, as these have shown high complementarity in previous studies (Anil et al., 1998; Hauggaard-Nielsen et al., 2009b; Malézieux et al., 2009). An attempt will be made to somewhat quantify these benefits, and to provide typical examples of their magnitude. A second part of the current study will be to perform a case study where a particular intercropping system is applied in a European context to partially replace the existing agricultural array. The effects of using intercropping systems on land use will be examined to determine the land savings potential. Thirdly, the biofuel potential resulting from the land savings potential will be calculated along with the emission abatement potential, and lastly the different fertilizer needs of sole crops and intercrops will be examined.

Environmental effects of the use of intercropping systems, GHG emissions caused by the use of machinery and fertilizers among others, and effects on biodiversity are all important factors in decision making about intercropping systems. These factors do not fall within the primary scope of the study, which is aimed at land savings and biofuel potential.

2. THEORY

2.1. INTERCROPPING SYSTEMS

A mixed cropping system is any form of agriculture where two or more species of crops are grown on the same piece of land during a period of time. Species can be combined spatially, temporally or in a combination of both. This means that species are either grown simultaneously in short succession of each other, or overlapping in time. Combining species spatially is called intercropping, whereas combining species temporally is called crop rotation (Malézieux et al., 2009). See figure 1 for examples of different kinds of spatial species mixing. Similar to Malézieux et al. (2009), Andrews & Kassam, (1976) categorize intercropping into four principal types:

1. Mixed intercropping – growing two or more crops simultaneously with no distinct row arrangement;
2. Row intercropping – growing two or more crops simultaneously with at least one planted in rows;
3. Strip intercropping – growing two or more crops simultaneously in different strips wide enough to permit independent cultivation, but narrow enough for the crops to interact agronomically;
4. Relay intercropping – growing two or more crops in relay, but with the growth cycles overlapping to some degree

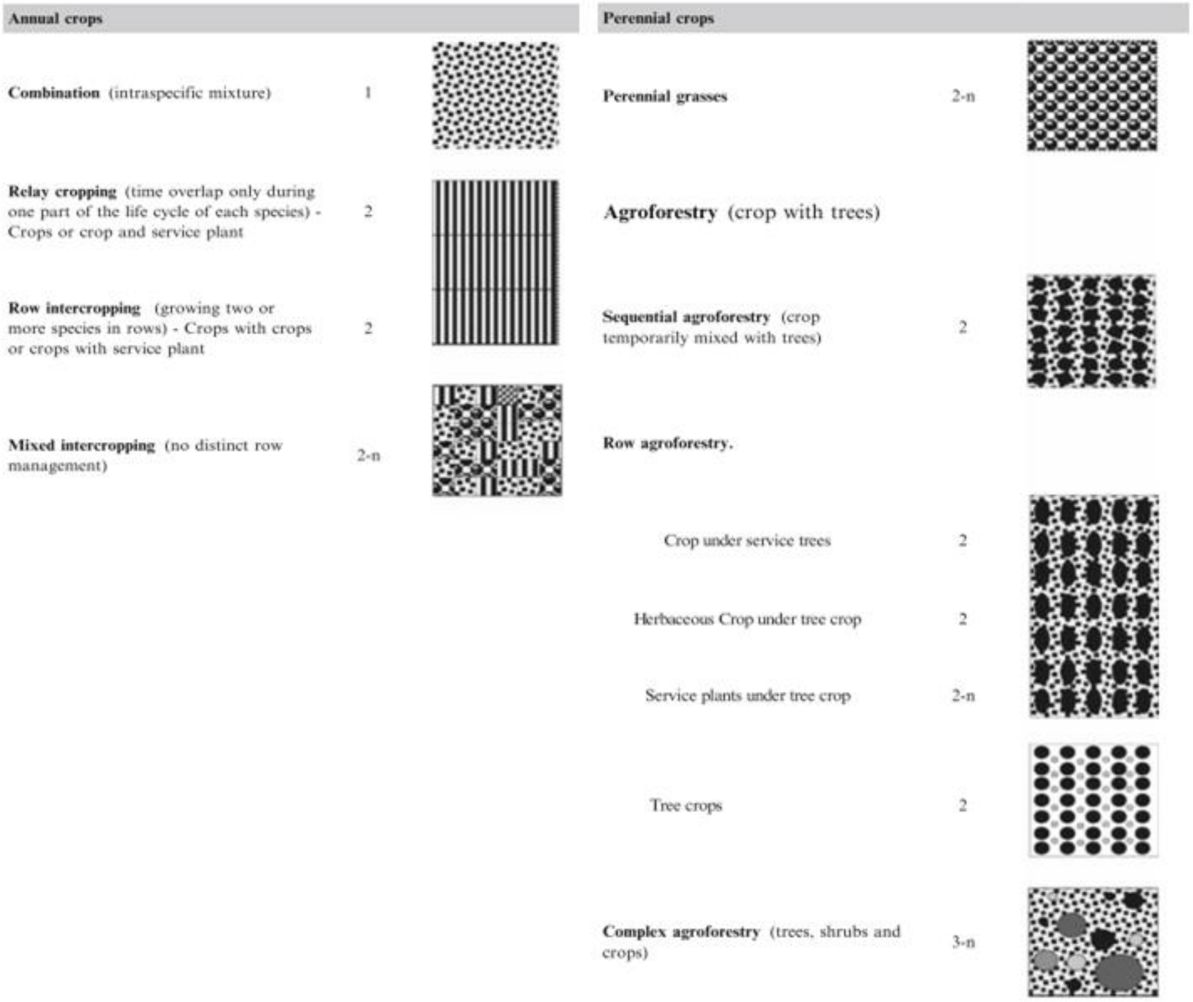

Figure 1: Examples of different kinds of species mixtures in mixed production systems (Malézieux et al., 2009).

Because of its closer match to current agricultural methods, strip intercropping will be the focus of this report. Current intensive agricultural systems are often based on optimising the productivity of monocultures. Monocultures are known for their low biodiversity, homogeneous genetic make-up, and high need for external inputs.. Such systems are widely criticised today for their negative environmental impacts, such as soil erosion and degradation, chemical contamination, loss of biodiversity, and high fossil fuel use (Giller, Beare, Lavelle, Izac, & Swift, 1997; Tilman, Cassman, Matson, Naylor, & Polasky, 2002). Conversely, multispecies cropping systems may often be considered as a practical application of ecological principles based on biodiversity, plant interactions and other natural regulation mechanisms. They are assumed to have potential advantages in productivity, stability of outputs, resilience to disruption and ecological sustainability, although they are sometimes considered harder to manage (Van der Meer, 1989). The major advantage of monocultures is that they lend themselves to large scale, streamlined, and low labour forms of agriculture. The whole chain of soil tillage, planting/seeding, growing, harvesting, and processing is recurrent and can therefore be optimized for efficiency, whereas a changing system requires more inventive and flexible management (Gurr, Wratten, & Luna, 2003).

There are several reasons for which intercropping systems could be applied, and examining which reasons prove the most relevant for farmers is part of the study. Increased outputs, reduced inputs, spread of income over the year, security of income, culture or tradition, soil quality, biodiversity or pollution might all be relevant for the decision to apply intercropping on one's land.

2.2. EFFECTS OF INTERCROPPING

In this section, four potential effects of intercropping practices that are often described in literature and their underlying mechanisms will be discussed. These benefits are by no means universally applicable to all intercrops, but are dependent on the specific cultivar combination, availability of environmental resources, and manage intensity. Because the specific differences between inter- and sole cropping systems such as plant height and soil micro-environment are impossible to isolate, it can be difficult to measure the individual effects of each factor (Fukai & Trenbath, 1993). Still, it could provide insight to examine which processes might influence intercrop benefits, should they occur. Several researchers have found a variety of benefits from intercropping in comparison to a monoculture system; research from a variety of geographical locations shows increased yield and/or monetary returns, reduced incidence of weeds, pests and diseases, improved nitrogen relations in legume intercrops, and higher land use efficiency per unit land area (Anil et al., 1998; Fukai & Trenbath, 1993; Ijoyah, 2012). Special interest will be paid to the different pea/barley intercropping systems, as they are the focus of the current study. In the results section, the benefits of intercropping pea/barley intercrops in particular will be further examined on a more quantitative level.

2.2.1. YIELD/PRODUCTIVITY BENEFITS

The terms yield and productivity are used interchangeably in both literature and in this report, both indicate the amount of product that a piece of land generates (t ha^{-1}), most often grain. The advantages of intercropping in comparison to sole cropping are often assimilated to a higher productivity of the mixture (Malézieux et al., 2009), meaning that intercropped land produces more than the same amount of sole cropped land. A higher yield is the result of many advantageous and disadvantageous characteristics of intercropping, including the ones mentioned individually below. These characteristics interact with environmental factors such as temperature, humidity, precipitation etc., making yield an umbrella concept in a way. Generally, high crop yield is obtained when particular cultivars are grown in such a way that they utilize limiting resources more thoroughly, and they mature before the resource limitation or environmental factor becomes too severe (Fukai & Trenbath, 1993).

Cereal/legume intercrops have consistently been shown to increase yield and resource utilization in various locations and under a variety of growing conditions; significantly more land is needed under sole cropping conditions compared to intercropping conditions to produce the same outputs (Banik, Midya, Sarkar, & Ghose, 2006; Gooding et al., 2007; Hauggaard-Nielsen & Jensen, 2001; Hauggaard-Nielsen et al., 2009b; Hauggaard-Nielsen, Andersen, Jørnsgaard, & Jensen, 2006; Jensen, 1996; Rao & Singh, 1990; West & Griffith, 1992). In one a sorghum/pigeon pea experiment in India, Ranganathan, Fafchamps, and Walker (1991) found that as much as 61% more land was needed to produce the same outputs when sole cropping compared to intercropping, though such results are not typical.

2.2.2. WEED SUPPRESSION

Crop-weed competition differs substantially between sole crop and intercrop combinations and is mainly determined by the growth habit of crops (Dimitrios, Panyiota, Aristidis, & Aspasia, 2010) Higher plant density in intercropping systems and resulting leaf cover help to reduce weed populations once the crops are established (Hauggaard-Nielsen et al., 2006). According to Ijoyah and Dzer (2012), okra and leafy greens can be intercropped with maize to reduce weeds and increase productivity. Weed density was reduced considerably compared to the sole cropped maize when intercropping maize with vegetables by decreasing the available light for weeds (Ijoyah, 2012).

One of the major advantages in cereal/legume intercropping over legume sole cropping is the increased competition with weeds. This is largely attributed to the population density of intercrops and the poor competitive ability of legume sole crops. Banik et al. (2006) showed that in wheat/chickpea intercropping systems, weed population and biomass were reduced by 70% compared to monocropping.

Pea/barley intercrops show high advantages in suppressing weeds when compared to pea sole crops, regardless of the particular weed infestation (species and productivity), the crop biomass or the soil nitrogen availability; Corre-Hellou et al. (2011) found that in pea/barley intercrops, weed biomass at maturity was, on average, one-third the amount found in pea sole crops. This finding is consistent with other studies, where weed biomass was reduced by 27 and 55% respectively compared to pea sole crops (table 1).

Table 1: Weed biomass in pea sole crops, barley sole crops, pea/barley intercrops, and % reduction.

Study	**Weed biomass (t ha^{-1})**			**% reduction**	
	Pea	Barley	Intercrop	Pea ~ IC	Barley ~ IC
(G. Corre-Hellou et al., 2011)	.99	.26	.28	73%	- 8%
(Hauggaard-Nielsen et al., 2006)	.82	.51	.37	55%	27%
(Hauggaard-Nielsen, Jørnsgaard, Kinane, & Jensen, 2008)	.70	1.05	.51	27%	51%

2.2.3. FERTILIZER NEEDS AND NUTRIENT CONTENT

Legumes have the ability to fixate atmospheric nitrogen (N_2) through a symbiotic relation with bacteria called rhizobia that become established in the plant's root nodules. This makes them suitable as 'green manure' plants and a potential organic fertilizer in systems with low inputs, such as in organic farming. Alternatively they could reduce the need for synthetic fertilizers (Jensen et al., 2012). In cereal/legume intercropping systems, the cereal plant is generally a much stronger competitor over soil N than the legume plant, likely as a consequence of the cereal's faster and deeper root growth (Bellostas, Hauggaard-Nielsen, Andersen, & Jensen, 2003). Because of this, when intercropped with legumes, cereals take up a much larger proportion of the soil N than would be expected based on sowing density. This forces the legume to be more reliant on atmospheric N_2 fixation, increasing the fertilizing quality of legumes. Systems that increase below-ground levels of C and N through inclusion of legume crops in rotations often increase microbial populations and activity to greater extent than conventional systems using commercial fertilizers (Altieri, 1999). In cases where biodiversity has been increased by the introduction of a leguminous plant, atmospheric nitrogen will be fixed. This important plant nutrient will be available to the intercrop or to the next crop in the rotation (Gurr et al., 2003).

Besides reducing the need for fertilizer, intercropping might also raise the quality of harvested products in terms of a higher nutrient content. Gooding et al. (2007) found that intercropping wheat with grain legumes increased the N concentration of cereal grain, regardless of design or location. Sulphur concentration of the cereal was also increased by intercropping, but less regularly and to a lesser extent compared with effects on nitrogen concentration.

When comparing pea and barley sole crops and pea/barley intercrops, the N accumulation can most often be ranked pea sole > pea/barley > barley (Corre-Hellou et al., 2011; Hauggaard-Nielsen & Jensen, 2001; Hauggaard-Nielsen et al., 2009b). Even though pea sole crops yield the most total N, several studies report substantially more efficient use of N resources in intercropping systems, leading to a relatively high grain N yield with improvements of 30-40% (Chapagain & Riseman, 2014; Hauggaard-Nielsen et al., 2009b; Hauggaard-Nielsen, Ambus, & Jensen, 2003; Hauggaard-Nielsen et al., 2008; Jensen, 1996). This improvement is mainly caused by a relatively high nitrogen content in the intercropped barley, as would be expected from its strong competitive ability for N compared to pea.

2.2.4. DISEASE/PEST MANAGEMENT

Intercropping reduces the incidence and severity of pests and diseases in the component crops when compared to each sole crop (Gurr et al., 2003; Ijoyah, 2012; Malézieux et al., 2009; Trenbath, 1993). Trenbath (1993) explains three main mechanisms by which this reduction might occur, these are discussed below.

The first way in which intercropping might affect pests and diseases is indirectly, by influencing the host plant. Conditions might be less favourable for the host plant in intercropping systems, causing it to be suppressed, and form a less attractive food source for pests and disease. However, when the health of the plant is impaired by this suppression, it might actually lead to an increase in certain fungus attacks. The host plant might be surrounded by taller plants, making it a less efficient trap for passively dispersing attacking organisms.

Intercropping also directly influences the spread of pest and diseases. Having non-host plants in a field can provide a visual and olfactory (smell-based) barrier for pests, making it harder for them to find host plants. Pests also tend to stay for less time due to the disruptive effect of landing on non-host plants, and have lower survival and reproductive rate; many fungus spores and some weak-flying pests die when they land on a non-host, this is called trapping. The overall idea is that a lower concentrations of host plants, diluted by non-host plants, form a constraint on pest and disease population growth.

A third way in which intercropping might contribute to a lower incidence of pests and diseases is by increasing the prevalence of their natural predators and parasites, the so called “natural enemies hypothesis”. Many species of predator show higher populations in more diverse agroecosystems. This is attributed to a greater range of available microhabitats, of alternative prey for unspecialised predators and parasites, and of nectar sources as supplements to the diet of parasites.

In pea/barley intercrops, three diseases are reported to affect the crops: pea is affected by ascochyta, a fungus that causes brown spots on the leafs, pods, and stems; barley is affected by brown rust, a fungus that is characterized by small brown pustules on the plant’s leafs; barley also suffers from net blotch, a fungus that is visible by brown stripes on the leafs, that cause senescence, and even leaf death (figure 4). The severity of each of these three afflictions is reduced in intercrops when compared to sole crops by 10 – 32% (table 2).

a B c

Figure 2: Ascochyta lesions on a pea pod (a), brown rust in a barley leaf (b), and net blotch on barley leafs (c)

Table 2: Disease severity in pea sole crops, barley sole crops, and pea/barley intercrops.

Disease	**Sole crop** Sole Pea	 Barley	**Intercrop** Pea	 Barley	Reduction	
Disease severity (% leaf covered by disease; Pea: Ascochyta blight, Barley: net blotch, brown rust)	9.50		6.50		32 %	(Hauggaard-Nielsen et al., 2008)
		23.3		15.9	32 %	
		10.0		7.70	23 %	
Disease severity (Pea: no. of Ascochyta blight lesions, Barley: no. of net blotch lesions, % of leaf covered by brown rust)	1.50		1.19		21 %	(Kinane, 2002)
		2.73		1.92	30 %	
		16.3		14.6	10 %	

2.2.5. COMPETITION BETWEEN CROPS

Besides potentially providing benefits, intercrops can also cause adverse to their component crops. The most important inhibiting effect of intercrops is the competition over resources such as soil nitrogen, water, and light (Corre-Hellou, Fustec, & Crozat, 2006; Hauggaard-Nielsen, Ambus, & Jensen, 2001; Nassab, Amon, & Kaul, 2011).

2.2.6. INCREASED MANAGEMENT COSTS

Although not the focus of this study, it is worth mentioning that generally, it is more management-intensive and more costly to produce crops with a system of intercropping, when compared to sole cropping. This is mainly due to the need for different types of agricultural machinery (Schittenhelm et al., 2011).

2.3. INTERCROPPING RESEARCH

2.3.1. FIELD STUDIES

Most of the data collected about intercrops is gathered from field studies. Researchers control or document the characteristics of the soil, solar irradiance, climate, and the plant's genetics. During one or several growing seasons, they measure the effects of one or more variables in plots of land like those in figures 3 and 4. This has the advantage of being able to compare many different variables and growing conditions without needing large amounts of land, it is also easier to determine the environmental conditions at the exact location of the plants.

Figure 3: Experimental plots in a field study with varying crop combinations (Chapagain, 2011).

Figure 4: Sole cropped legume (left), cereal/legume intercrop (middle), and sole cropped cereal (right) at early (top) and late (bottom) growth stages (Chapagain, 2011).

When harvesting the crops, not the whole plot is harvested. Only several rows from the centre of the plot are analysed for data. This is done because the edges of plots often show different characteristics than the centres, and since farm-scale plots consist of almost exclusively non-edge plants, these are more representative.

In order to determine the biomass of crops, weeds or grain, the dry matter (DM) is often determined. Researchers mean to correct for any differences in moisture content that may occur because of precipitation shortly before harvest, time elapsed between harvest and analysis, etc. The DM is generally determined by drying the biomass in question in an oven heated to 70-80 °C for one or two days.

2.3.2. NUTRIENT DYNAMICS

In order to monitor the nutrient dynamics in a field study and to be able to distinguish a plant's soil-N uptake from its atmospheric N fixation, researchers use either the isotope dilution principle or the natural abundance method. With the isotope dilution principle researchers enrich the soil with a known amount of nitrogen-containing fertilizer such as KNO_3 that has been labelled with the isotope ^{15}N. This isotope is stable and occurs naturally, generally making up less than 1% of the natural soil N composition, ^{14}N accounting for the other 99%. After treatment, the soil has a $^{14}N : {}^{15}N$ ratio that deviates significantly from the natural occurring ratio. When harvesting, the ratio found in the plant's biomass can be used to derive how much of the total N originates from the soil and the atmosphere, respectively. With the natural abundance method, the soil's ^{15}N content is already relatively high (>3%) compared to the occurrence in the atmosphere (<<1%) (Shearer & Kohl, 1988).

3. METHODS

3.1. LITERATURE REVIEW

Literature study played a central role in the current report. It was used as a main source of both qualitative and quantitative data about the potential benefits of intercropping. Literature review has revealed what the most important potential benefits of intercropping are, and what their underlying mechanisms are. These potential benefits and their mechanisms were reported in the theory section.

An appeal to literature was also made when attempting to evaluate the magnitude of each benefit. In order to do this, intercropping field studies such as described in the theory section were analysed, and their results summarised. In order to keep this magnitude study manageable, only cereal/legume intercrops were included because of their complementarity indicated in literature.

Furthermore, one promising crop combination was chosen to examine in-depth. This combination, namely pea/barley intercrops, served as the 'case study' of this report and was the subject of the estimations of land savings potential, biofuel potential, and fertilizer needs. Pea/barley intercrops were chosen because of its strong presence in literature, and the fact that both crops are specified individually in Eurostat data.

Weed suppression data of pea/barley intercrops was taken from relevant literature in the form of the total aboveground weed dry matter(DM) that was harvested from sole crop and intercrop plots. To illustrate the relative (dis)advantage of intercrop plots compared to plots of each sole crop, each value of aboveground weed was divided by the intercrop value. This results in two figures that indicate the relative severity of weed infestation in sole crops compared to intercrops, where values above 1.0 indicate a more severe infestation in sole crops, and values below 1.0 indicate a larger weed population in intercrops.

Data on nutrient dynamics of pea/barley intercrops was collected in two areas. Firstly, the grain N yield, the amount of nitrogen in the crop grain (kg ha^{-1}), is an indicator of the protein content of the grain. This measure is especially important in livestock feed markets where high protein products are preferred (Gesch et al., 2014). The LER was calculated for the grain N in the same way as for yield, with the grain yields replaced by grain N yields. Secondly, the N balance was collected from literature and used to estimate the N fertilizer needs. This is explained in-depth in the relevant chapter of the method section.

Information about the disease management of pea/barley intercrops and sole crops was reported in literature by describing the severity of several diseases that affect pea and barley plants. Severity was either expressed by the percentage of lead surface covered by the disease, or by the number of lesions caused by the disease.

3.2. LAND SAVINGS POTENTIAL

In order to retrieve yield data from literature, studies that focus at least in part on yield effects from intercropping were examined. Because intercropping systems often grow two crops with widely varying (grain-) yields, it can become difficult to compare the total productivity of intercropped land directly to that of sole cropped land. Also, field studies tend to have high levels of maintenance and therefore higher yields than real life scale agriculture (van de Ven, personal communication, March 9, 2015). For these reasons, yields from field studies cannot be used directly, and only the ratio of sole cropped yields compared to intercropped yields within one study can be used. A measure that compares the performance of intercropping systems to a monoculture is the measure of Land Equivalent Ratio (LER). The LER is the ratio between the sole cropping and intercropping area needed to produce the same outputs. The calculation of LER is the most commonly used method in intercropping studies (Anil et al., 1998) and is shown in equation 1.

When LER > 1, a beneficial effect from intercropping is observed, because less land area is needed to produce the same outputs compared to sole cropping (figure 5). For this relation to land area, the LER will play a central role in calculating the land savings potential.

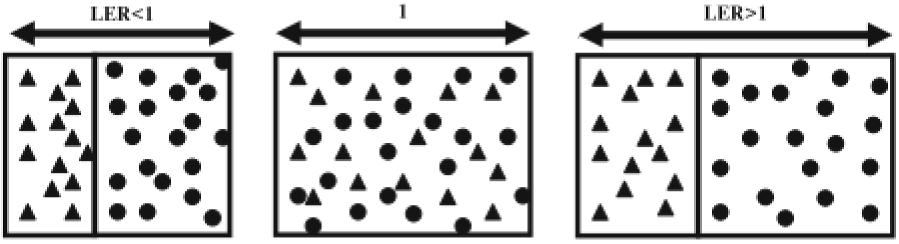

Figure 5: Illustration of Land Equivalent Ratio (LER); the LER of an intercropping system is the ratio between the area needed for the same outputs with a pattern of either intercropping or sole cropping (Malézieux et al., 2009).

The LER can be calculated by looking at the productivity of a set amount of land area, instead of the land needed for a set amount of production. Because the individual performance of crops in intercrop and sole cropping systems is relevant, LER will be calculated using the following equation:

$$LER = pLER_1 + pLER_2 = \frac{intercrop\ yield_1}{sole\ yield\ _1} + \frac{intercrop\ yield_2}{sole\ yield_2} \quad (1)$$

pLER$_1$ and pLER$_2$ represent the partial land equivalent ratios of crop 1 and 2, respectively. This is the land equivalent ratio for one individual component crop. Sole yield is the yield (t ha^{-1}) of an area of land that contains only one species of crop, and mixed yield is the yield of that same crop when grown together with another crop. An LER greater than 1.0 indicates intercropping systems are advantageous, whereas a LER less than 1.0 shows a yield disadvantage.

Measures for comparing yield and land use of mixed production systems to those of monocultures, such as LER, are oftentimes mentioned in studies. When no such measures were mentioned, these were calculated based on available grain yield data from the study in question.

To get an idea about the maximum potential of pea/barley intercrops in Europe, the maximum amount of agricultural production of these two crops in each country was virtually ‘replaced’ by intercropping practices. However, in determining the size of the intercropped area, a limit was set so that a country's production of either component crop would not be exceeded by the production of the theoretical intercropped land. In each country, this limiting crop was pea as barley production always far exceeded that of pea (table 3).

The land savings potential is calculated by the difference between the land area needed for production by intercropping and by sole cropping. The area needed to supply a country's pea production with intercropping is calculated by equation 2. Pea is chosen because it is the limiting factor when applying the restriction that a country's production of either component crop may not be exceeded by the intercropping production.

$$Area_{\ IC} = \frac{Prod_{\ pea}}{pL\ ER_{pea} * \ Yield_{SCpea}} \tag{2}$$

Where Area$_{IC}$ is the needed intercropped (IC) area in a country, Prod$_{pea}$ is the harvested production of a country, and because pea is always the limiting factor it is the same as the IC production. LER$_{pea}$ is the average partial land equivalent ratio for pea found in literature, and Yield$_{SCpea}$ is the the pea sole crop yield of a country.

The pea production from intercropping is the same as Prod$_{Pea}$ in equation 2. Barley production from the intercropped area is calculated by equation 3.

$$Prod_{\ ICbarley} = \ Area_{\ IC} * \ (pLER_{\ barley} * \ Yield_{SCbarley}) \tag{3}$$

Here, Prod$_{ICbarley}$ is the intercropped barley production. Note that for pea, being the limiting factor, the country's production and the intercropped production are the same, but for barley they are not. Area$_{IC}$ is the intercropped area in a country, LER$_{barley}$ is the average partial land equivalent ratio found in literature, and Yield$_{SCbarley}$ is the barley yield in a country.

The sole cropping area needed for the determined intercropped production is calculated by:

$$Area_{\ SC} = \frac{Prod_{\ ICbarley}}{Yield_{SCbarley}} + \frac{Prod_{\ pea}}{Yield_{SCpea}} \tag{4}$$

Finally, the land savings potential in a country is the difference between sole cropping area and intercropping area.

$$Land\ savings\ potential\ = \ Area_{\ SC} - \ Area_{IC} \tag{5}$$

Data

In order to make an order-of-magnitude estimation of the land savings potential in Europe and the following potential for biomass cultivation, data from years 2003 through 2012 about the recent agricultural array was collected from Eurostat (2015). This data is derived from '*Surveys, administrative data and estimates based on expert observations are the main data sources. The sources are not the same for every Member State but are adapted to national conditions and statistical practices. For the data governed by the regulation, the quality level is indicated in the legislation. Yields are calculated in the same way as in the Member States: by dividing production by area'* (Eurostat, 2014). The Eurostat data is combined with findings in literature about the yields of intercropping systems. Calculations and variance analyses were conducted in Microsoft Excel according to the description above.

For all countries represented in the Eurostat data, barley production was significantly larger than pea production, ranging from six times to a few hundred times more barley production. Therefore, in selecting countries that could make a considerable contribution to the impact of pea/barley intercropping in Europe, the 15 European countries with the largest pea production were selected (table 3). Pea production ranged from 6,34 kt to 214,78 kt. Pea production of countries that produced less was negligible, the included countries accounted for 97 and 84 percent of pea and barley production in Europe, respectively.

Table 3: Area harvested, harvested production, and yield for pea and barley in the 15 European countries with the highest pea production. Data are averages from 2003 to 2012 (Eurostat, 2015).

	Pea			**Barley**		
Country	**Area Harvested (1000 ha)**	**Harvested production (kt)**	**Yield (100 kg ha^{-1})**	**Area Harvested (1000 ha)**	**Harvested production (kt)**	**Yield (100 kg ha^{-1})**
France	29,09	214,78	73,77	1685,20	10634,09	62,02
United Kingdom	31,90	128,32	40,22	986,84	5722,01	58,08
Hungary	16,57	90,02	54,04	307,11	1096,55	35,79
Turkey	9,43	88,29	92,74	3258,67	7925,56	24,26
Italy	14,16	80,60	58,61	301,61	1102,77	36,53
Spain	10,96	72,80	66,75	3064,77	8483,15	27,6
Belgium	9,64	64,40	66,62	45,69	357,72	77,88
Serbia	6,43	37,83	58,81	91,33	297,27	32,55
Poland	6,16	34,30	56,00	1111,29	3565,93	31,84
Netherlands	5,21	30,85	58,63	43,44	270,85	62,81
Germany	5,06	27,91	55,14	1869,99	11126,03	59,56
Denmark	3,01	15,40	51,41	663,44	3461,60	52,23
Greece	1,56	10,20	63,93	104,93	263,00	25,07
Austria	1,59	7,92	49,63	183,52	859,66	47,07
Romania	3,27	6,34	19,91	421,93	1045,63	24,42

3.3. BIOFUEL POTENTIAL

The land savings that were found for each country were used to estimate the maximum energy potential from biomass cultivation on the saved land according to equation 6. Predicted biomass yields (GJ biofuel ha^{-1}) from European countries were taken from the European refuel program (Fischer, Hizsnyik, Prieler, & Velthuizen, 2007). These values were predicted using the agro-ecological zones (AEZ) modelling framework which uses a range of climate and soil data to model the suitability and potential productivity of crops in a certain area (Fischer, Velthuizen, Shah, & Nachtergaele, 2002).

$$Biofuel\ energy_{country} = Land\ savings\ potential * Biofuel\ yield \tag{6}$$

In retrieving biofuel yields from the database, values were grouped into five main land utilization types (feedstocks), each with specific biofuel production pathways. These were: herbaceous lignocellulosic plants (miscanthus, switchgrass, and reed canary grass), a 2nd generation source of biofuels; woody plants (poplar, willow, eucalypt), a 2nd gen. source of biofuels; oil crops (sunflower, rapeseed), a 1st gen. source of biodiesel; starchy crops (wheat, rye, triticale, maize), a 1st gen. source of bio-ethanol; and sugar crops (sugar beet, sweet sorghum), a 1st gen. source of bio-ethanol (table 4). Biofuel yields are typically ranked herbaceous > woody > starchy > sugar ≈ oil crops.

Using the average biofuel yields per country partly accounts for variation in suitability of land for biofuel cultivation through the agro-ecological zones (AEZ) method. This method estimates the typical yields in a country by characterizing the relevant climate, soil and terrain conditions for cultivation (Fischer et al., 2007). It doesn’t, however, account for the suitability of the specific land areas that are currently occupied by pea or barley, and that would be occupied by biofuel crops instead. Generally speaking, both herbaceous and woody type biofuel crops can be grown successfully in a wide variety of ecologies and soil types, as well as being highly productive in lignocellulose. This means they are widely employable and yield high amounts of biofuel in their production pathway (Fischer et al., 2007). Therefore, when estimating the maximum potential of intercropping for biofuel production, either of these types will most likely be suitable for such an estimation.

Table 4: average biofuel yields in 15 European countries for different types of biofuel crops.

Typical biofuel yield (GJ biofuel/ha) **Country**	**Herbaceous**	**Woody**	**Oil**	**Starchy**	**Sugar**
France	167	118	32	43	34
United Kingdom	111	85	29	38	32
Hungary	202	114	39	54	40
Turkey	147	107	36	45	38
Italy	154	124	28	38	34
Spain	103	119	21	26	21
Belgium	162	125	44	52	54
Serbia	147	107	36	45	38
Poland	154	101	43	52	47
Netherlands	134	91	39	48	48
Germany	150	104	41	51	44
Denmark	101	66	32	39	30
Greece	157	118	34	42	32
Austria	139	107	44	54	43
Romania	177	120	38	53	36

3.4. EMISSION ABATEMENT

An indication of the CO_2-abatement potential through biofuel production for each country was found by multiplying biofuel production (GJ) with each biofuel crop's corresponding typical European CO_2 abatement value (g CO_2 MJ^{-1}), listed in table 5, see equation 8. According to the EC, "*A 'typical value' means an estimate of the representative green-house gas emission saving for a particular biofuel production pathway*" (European Commission, 2009). The EC directive also states that these values may be used in order to determine the estimated net greenhouse gas emission saving due to the use of energy from renewable sources. This typical abatement value was found by multiplying the typical % emission reduction reported in the EC´s renewable energy directive with the associated reference emission value for fossil fuel alternatives of 83.8 gCO_2 MJ^{-1}, see equation 7.

$$Abatement\ value = GHG\ abatement\ \% * reference\ fossil\ emissions\ value \qquad (7)$$

$$GHG\ abatement_{country} = abatement\ value\ *\ biofuel\ energy_{country} \qquad (8)$$

The EU renewable energy directive reports its abatement value based on a sum of 9 possible sources of CO_2, N_2O, and CH_4 emissions. These include extraction and cultivation of raw materials, processing, transport and distribution, etc (European Commission, 2009). Emission abatement resulting from land use change was not included in the current study.

Table 5: Typical GHG abatement values for different types of biofuel crops. The fossil fuel comparator for the percentages is 83.8 g CO_2 MJ^{-1}.

Type of biofuel crop	**Typical GHG abatement (%)**	**Typical GHG abatement (g CO_2 MJ^{-1})**
Herbaceous	85%	71
Woody	85%	71
Oil	45%	38
Starch	45%	38
Sugar	61%	51

3.5. NITROGEN CONTENT AND FERTILIZER NEEDS

3.5.1. NITROGEN CONTENT

In order to retrieve data on N content from literature, studies that focus at least in part on nutrient effects from intercropping were examined. Similar to yield effects, the relative difference in N content in intercrops compared to sole crops is expressed in a land equivalent ratio. This LER_N shows the ratio between the area needed by sole and intercropping systems to produce the same amount of grain N (equation 9). As mentioned before, grain N is a relevant measure for livestock feed markets where high protein products are preferred (Gesch et al., 2014)

$$LER_N = pLER_{N\,pea} + pLER_{N\,barley} = \frac{intercrop\ \mathrm{N}\ yield_{pea}}{sole\ \mathrm{N}\ yield_{\ pea}} + \frac{intercrop\ \mathrm{N}\ yield_{barley}}{sole\ \mathrm{N}\ yield_{barley}} \tag{9}$$

Where $pLER_{N\,pea}$ and $pLER_{N\,barley}$ represent partial LER_N values for pea and barley, respectively. If $LER_N > 1$, a beneficial effect from intercropping is observed, because less land area is needed to produce the same outputs compared to sole cropping. LER_N values below 1 indicate a less efficient utilization of N resources in intercrops compared to sole crops.

Measures for comparing yield and land use of mixed production systems to those of monocultures, such as LER_N, are oftentimes mentioned in studies. When no such measures were mentioned, these were calculated based on available grain N yield data from the study in question.

3.5.2. NITROGEN FERTILIZER NEEDS

In order to investigate whether there are differences between intercropping and sole cropping in their need for N fertilizer, two components of fertilizer needs were determined: the N fertilizer applied during the growing season, and the N fertilizer that is either superfluous or deficient at the end of the growing season. The latter factor is represented by the nitrogen balance, and functions as a measure of the change in N stock of soil-systems. This figure for both sole cropping and intercropping systems was either retrieved from literature or calculated by equation 10.

$$N_{balance} = N_{applied} + N_{fixed} - N_{grain} \tag{10}$$

$N_{applied}$ is the N that was added to the soil by fertilizer during the growing season,. N_{fixed} is the amount of N entering the system from symbiotic N fixation in pea, and N_{grain} is the amount of N leaving the system through harvest. All values were reported in -or calculated from figures within- the same field studies so that eventually one figure for $N_{fertilizer}$ could be determined per study. Note that it is assumed that the land is utilised in a crop rotation system, and that all N from the 'body' of the plant, the roots and shoots, remains available for subsequent cultivation.

The N balance indicates the net amount of N that enters or leaves the system in the cultivation period. The assumption is that a negative N balance represents a deficit that will need to be replenished with fertilizer before the next crop in the rotation, and that a positive N balance indicates a surplus, which will deduct from the fertilizer needs in the next season. In this way, the N balance represents the fertilizer left over after cultivation, with a high $N_{balance}$ resulting in a lower fertilizer need to restore the soil's N stock. To obtain the total fertilizer needs, the N balance was deducted from the fertilizer that was already applied during the season so that:

$$N_{fertilizer} = N_{applied} - N_{balance} \tag{11}$$

The same cultivated surface areas for sole crops and intercrops that follow from the land savings calculations are used to calculate the N balance of a country. The N fertilizer needs (per hectare) of sole pea, sole barley, and of pea/barley intercrops is multiplied with each respective cultivated surface area, leading to a total N fertilizer need for the two sole crops, and for the intercrop. The difference between these two will indicate whether an intercropping strategy requires more or less N in comparison to a strategy where both crops are grown separately. It will also provide an order of magnitude of the size of this effect.

3.6. SENSITIVITY ANALYSIS

Many figures in the current study are calculated from certain parameters or data from literature. These all have underlying assumptions that may be more or less in accordance with reality, and each has a variance or spread. Rather than only give a single value for each measure and give a false idea of accuracy, it is better to indicate in which range a value can reasonably be assumed to lie. This gives the reader a better handle on the topic at hand and provokes more thought.

For this reason, several main figures in the current study are shown in relation to one or more of their underlying figures to show what the main figures would be, if the underlying figures were different, and to show the impact of these differences. This is done as much as possible with variations of the underlying figures that are likely to occur by using the standard deviation of the data they are based on. The data on which the standard deviation is based will be specified in the relevant subchapter.

3.6.1. Land savings potential

The most important precursor of land savings potential is the LER. Together with its pLER components, this largely determines how much land can be saved by intercropping systems. To give an impression of the magnitude of the influence of LER variance on land savings potential, the standard deviation (SD) was calculated of the different values for LER taken from literature. Then, the land savings potential of each country was adjusted to fit the alternative LER values, namely the average LER minus or plus 1 SD. This adjustment is done according to equation 12.

$$Land\ savings_{LER_{\pm SD}} = Land\ savings_{LER_{avg}} * \frac{LER_{\pm SD}}{LER_{avg}} \tag{12}$$

Another factor that is likely to influence the land savings potential besides the total LER is the proportionality of the two pLER values. Without changing the total LER, the ratio between the pLER values influences the land savings potential. This is mostly due to the limitation that the total production of either component crop in a country should not be exceeded by the intercropped production. The effect of this is that when the intercropped yield of the limiting crop (pea) is lower, more land can be assigned to intercropping before this limit is reached, and more intercropped land leads to more total land savings. The values that were chosen to illustrate this effect spring from a serendipitous coincidence; two studies (Corre-Hellou et al., 2006; Jensen, 1996) report equal total LER values, but one being 'pea heavy', with a high pea yield and low barley yield, and one being 'barley heavy', with a high barley yield and low pea yield. The land savings potential resulting from each set of pLER values is calculated with the same method as described in section 3.2, only using different values for $pLER_{pea}$ and $pLER_{barley}$.

3.6.2. Biofuel potential

The biofuel potential (TJ) is dependent on the biofuel yield (GJ ha^{-1}) and the quantity of land that theoretically becomes available for biomass cultivation (ha), the latter being equal to the land savings potential (see equation 6).

To illustrate the impact on biofuel potential of variations or uncertainty in these two factors, biofuel potential was recalculated for each biomass crop using different values for land savings potential and again with different values for biofuel yield, while keeping all other variables constant. These values were chosen based on the variance of the source data because it gives an idea of the variation that is plausible to occur.

For the factor land savings potential, the source data are the LER-values found in literature. The standard deviation of these LER values was used to recalculate the biofuel potential for when the LER values(and therefore the land savings potential) would be 1 SD higher or lower.

In order to recalculate the biofuel potential with a varying biofuel yield, the average biofuel yield for each production pathway in each country (table 4) was increased or decreased by 1 SD. This SD is derived from the spread in biofuel yields within a country for one production pathway that was found in the refuel programme data (Fischer et al., 2007). This data for biofuel yield was classified according to different land cover classes (e.g. forest, wetlands, urban & industry). The suitable land cover classes for oil crops, starchy crops, and sugar crops were only arable land cover classes (named: arable land, permanent crops, and heterogeneous agriculture). For woody and herbaceous plants, the suitable classes also included natural grassland and pastures.

The refuel study estimates the suitable area (ha) and the average biofuel yield (GJ biofuel ha^{-1}) of each individual land cover class. These two figures were used to calculate the weighted mean and the weighted SD of the average biofuel yield in a country of a single production pathway. The weighted mean is calculated according to equation 13 and is used when some data values contribute more than others.

$$\bar{x} = \frac{\sum_{i=1}^{N} w_i * x_i}{\sum_{i=1}^{N} w_i} \tag{13}$$

In equation 13, N is the number of suitable land cover classes. w_i is the weight of each land cover class, represented by the suitable area of that class. x_i is the average yield of a land cover class and $\bar{x}$ is the weighted average of the biofuel yields in all land cover classes.

As with the weighted mean, the weighted SD is calculated when some data values contribute more than others. Once again, the surface area of a land cover class is regarded as the frequency with which their biofuel yields occur. The weighted SD is presented in equation 14, and the results of its calculation are given in table 6.

$$SD = \sqrt{\frac{\sum_{i=1}^{N} w_i * (x_i - \bar{x})^2}{\sum_{i=1}^{N} w_i}} \tag{14}$$

Symbols in equation 14 represent the same concepts as in equation 13. Using this SD provides an idea of the spread of biofuel yields in the selected European countries across different land cover classes. This might be relevant, as it is uncertain which land cover classes will be utilized for biofuel production, once land becomes available due to intercropping.

Table 6: Standard deviations of average biofuel yields in 15 European countries.

	Herbaceous	Woody	Oil	Starchy	Sugar
France	9,6	7,6	2,8	2,9	2,9
United Kingdom	14,8	21,7	1,5	2,0	1,7
Hungary	5,2	5,0	0,4	0,9	1,3
Turkey	11,9	9,8	2,0	2,7	2,8
Italy	12,9	8,6	1,4	3,0	4,1
Spain	6,4	9,8	1,0	1,9	0,6
Belgium	9,6	10,5	2,5	2,9	3,3
Serbia	11,9	9,8	2,0	2,7	2,8
Poland	7,3	8,6	2,1	2,5	2,7
Netherlands	8,5	2,6	5,3	5,4	5,7
Germany	6,4	6,1	0,8	1,0	1,1
Denmark	6,4	6,5	2,5	3,2	2,5
Greece	11,8	10,5	1,2	3,6	3,8
Austria	45,4	25,0	1,8	3,7	3,3
Romania	10,0	4,5	2,9	1,4	3,3

3.6.3. EMISSION ABATEMENT

The potential emission abatement from pea/barley intercropping in a country is determined by the biofuel production of that country, and the abatement value of each type of biofuel production pathway (see equation 8). This abatement value is calculated according to equation 7 using a reference value for fossil fuel emissions. The impact of variations or uncertainties of these factors on emission abatement potential will be approximated by recalculating the abatement potential with varying underlying figures.

The impact of a different biofuel potential will be estimated in the same way as in section 3.6.1., by varying either one of its two determining factors, LER and biofuel yield. These factors were in turns decreased or increased by their standard deviation. Then, this new value was used to recalculate the biofuel potential, and subsequently the abatement potential, while keeping all other variables the same.

For the abatement value, the reference value with which this is determined, was examined. The European Commission reports three reference values of fossil fuel emission for different fuel uses (table 6), this is a result of the different efficiencies with which the fuels can be used. It also reports a fourth value, which is advised to be used when the use of the fuel is unknown. This was the case in the current study, and this aggregate reference value of 83.8 g CO_{2eq} MJ^{-1} was used to produce the results. However, it might be valuable to see what influence the eventual use of biofuel has on its emission abatement potential. Therefore, the standard deviation of the three reference emission values given will be deduced from and added to the aggregate value to produce a spread in emission abatement potential following from differences in end-use of biofuels.

Table 7: Reference emission values (g CO_{2eq} MJ^{-1}) for different uses of biofuels (European Commission, 2009).

Biofuel use	**Reference emission value (g CO2eq MJ-1)**
Electricity production,	91
Heat production	77
Cogeneration	85

3.6.4. NITROGEN FERTILIZER NEEDS

Nitrogen fertilizer needs of 15 countries were calculated using nitrogen balance data from literature (equations 10 and 11) . The variance of the values found in literature will cause variation in the resulting nitrogen fertilizer needs of countries. The magnitude of this effect is evaluated by calculating the standard deviation of the different fertilizer need values for pea sole crops, barley sole crops, and intercrops. The total nitrogen fertilizer need of a country was then recalculated using the average fertilizer need per hectare of each cropping system, reduced or increased by the SD. This way, an image is created of the influence of variance in values found in literature on the estimated nitrogen fertilizer needs of sole pea , sole barley and intercropping systems.

4. RESULTS

4.1. LAND SAVINGS POTENTIAL

Partial land equivalent ratios reported in literature for pea and barley grown in intercrops varied between 0,47 and 0,74 for pea, and between 0,30 and 1.01 for barley. Mean values were 0,54 and 0,64, respectively, with a mean total LER of 1,17 (table 7).

Table 8: Grain yield (t ha^{-1}) of pea and barley sole crops, pea/barley intercrops, and the corresponding LER values from various studies.

Study	Wet / dry base yield	Sole yield (t ha^{-1})		Intercrop yield (t ha^{-1})			pLER pea	pLER barley	LER
		Pea	Barley	Pea	Barley	Total			
(Chapagain & Riseman, 2014)	Wet	5,30	4,00	2,50	2,70	5,20	0,47	0,68	1,15
(Corre-Hellou et al., 2006)	Wet	4,91	4,35	3,49	2,14	5,63	0,71	0,49	1,20
(Hauggaard-Nielsen et al., 2001)	Dry	2,63	3,92	,60	3,97	4,58	0,23	1,01	1,24
(Hauggaard-Nielsen et al., 2006)	Wet	4,76	4,39	3,53	1,30	4,83	0,74	0,30	1,04
(Hauggaard-Nielsen et al., 2008)	Wet	4,75	2,68	2,90	1,60	4,50	0,61	0,60	1,21
(Jensen, 1996)	Dry	5,67	3,93	2,59	2,93	5,52	0,46	0,75	1,20

The largest land savings potential was estimated to be in the United Kingdom, with 10.29 thousand hectares potentially being saved by applying intercropping methods to pea/barley production. Intercropped and sole cropped areas, and the land savings potential are shown in table 8. The total land savings potential for the included 15 countries was 49.67 thousand hectares, which equates to approximately 75 thousand football fields, or roughly the size of the 'Noord-Oost polder'-area in the Netherlands (46,03 kha).

Table 9: Characteristics of intercropped pea and barley production, and equivalent sole production areas in the 15 European countries with the highest pea production (Eurostat, 2015).

Country	IC area (1000 ha)	P production (1000 t)	B production (1000 t)	SC P area (1000 ha)	SC B area (1000 ha)	Total SC area (1000 ha)	Land savings (1000 ha)
France	54,19	217,55	214,78	34,48	29,09	63,57	9,38
United Kingdom	59,42	219,22	128,32	37,81	31,90	69,71	10,29
Hungary	30,87	70,12	90,02	19,64	16,57	36,21	5,34
Turkey	17,56	27,17	88,29	11,17	9,43	20,60	3,04
Italy	26,37	61,34	80,60	16,78	14,16	30,93	4,56
Spain	20,42	35,96	72,80	12,99	10,96	23,95	3,53
Belgium	17,96	89,45	64,40	11,43	9,64	21,07	3,11
Serbia	11,98	24,82	37,83	7,62	6,43	14,06	2,07
Poland	11,47	23,41	34,30	7,30	6,16	13,45	1,98
Netherlands	9,70	38,50	30,85	6,17	5,21	11,38	1,68
Germany	9,43	35,68	27,91	6,00	5,06	11,06	1,63
Denmark	5,61	18,63	15,40	3,57	3,01	6,58	0,97
Greece	2,91	4,63	10,20	1,85	1,56	3,41	0,50
Austria	2,96	8,83	7,92	1,88	1,59	3,47	0,51
Romania	6,09	9,60	6,34	3,88	3,27	7,15	1,05
Total	**286,92**	**884,92**	**909,96**	**182,56**	**154,03**	**336,59**	**49,67**

A visual representation of the current situation and a scenario in which intercropping was implemented is shown in figure 6. Both situations have the same outputs, but the intercropping scenario can produce these outputs using a smaller land area. The resulting surplus area is the land savings potential.

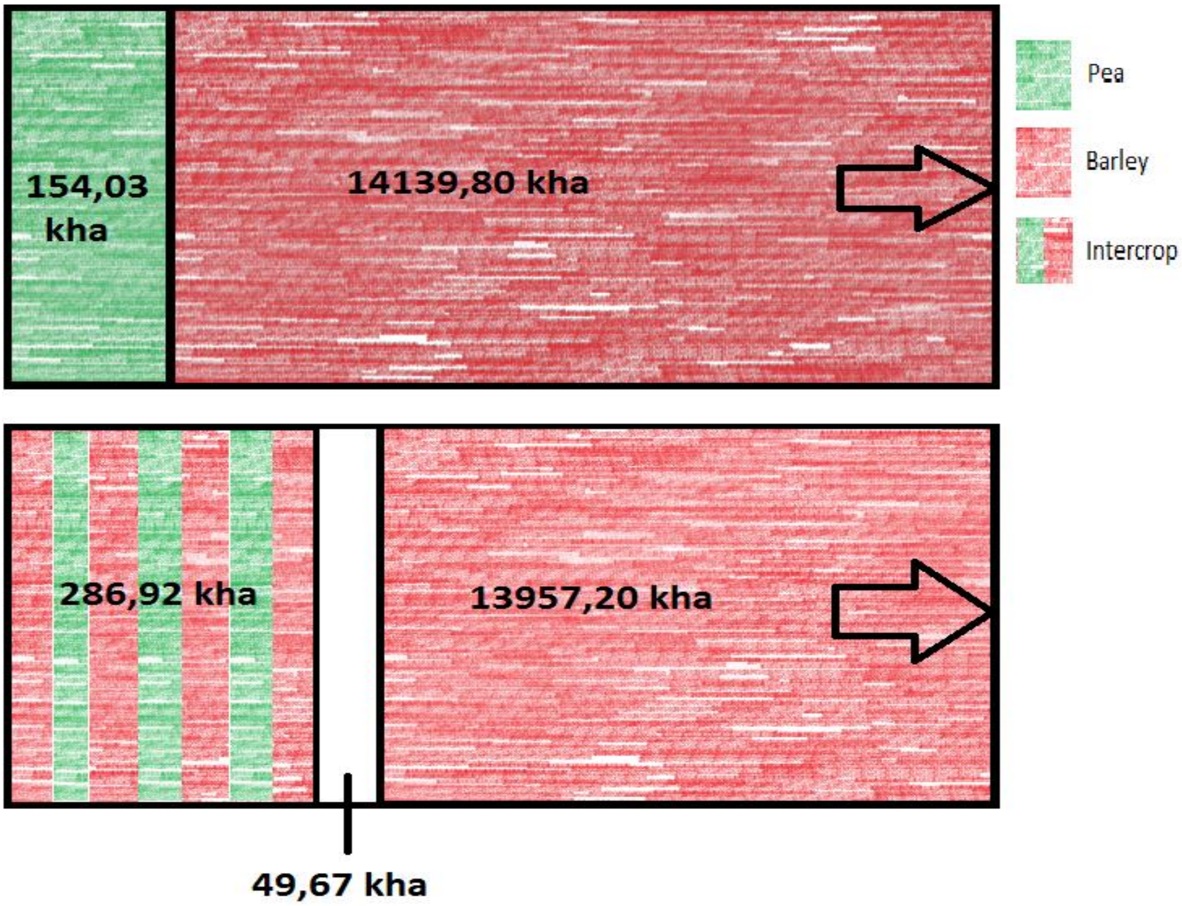

Figure 6: Visual representation of implementation of pea/barley intercropping. The arrow indicates that barley sole cropping covers a much larger area than is shown in this figure.

4.2. BIOFUEL POTENTIAL

There is a significant potential for biofuel production from feedstocks grown on land that becomes available as a result of intercropping pea and barley. The highest total biofuel potential across 15 European countries is achieved by herbaceous plants, at 7,32 PJ per year. Oil based plants produced the least, at 1,65 PJ per year. Biofuel potentials for production pathways the different feedstocks typically ranked herbaceous > woody > starchy > sugar > oil and are shown in table 9.

The maximum biofuel potential of 7,32 PJ per year equates to the heat demand of roughly 175 thousand Dutch households (CBS, 2014). The total production of renewable energy in 2013 from biomass and waste in the 15 countries included in the current study was 3,98 EJ (Eurostat, 2013). This means that these countries could increase their bioenergy production by anywhere between .041% (oil) and .184% (herbaceous) if they would be able to implement the amount of biofuel cultivation described in the current study.

Table 10: Biofuel energy potential per country (TJ per year) from biofuel cultivation on saved land using biofuel production pathways with one of five feedstocks: herbaceous lignocellulosic plants, woody plants, oil crops, starchy crops, and sugar crops.

Country	Herbaceous	Woody	Oil	Starchy	Sugar
France	1565	1106	297	406	323
United Kingdom	1146	873	298	387	333
Hungary	1078	607	206	287	214
Turkey	447	325	109	138	116
Italy	705	567	127	172	157
Spain	362	419	76	94	73
Belgium	502	387	138	163	169
Serbia	305	222	74	94	79
Poland	305	201	86	104	93
Netherlands	225	153	66	81	80
Germany	245	170	67	84	71
Denmark	98	65	31	38	29
Greece	79	59	17	21	16
Austria	71	55	22	28	22
Romania	187	126	40	56	38
Total	**7322**	**5336**	**1654**	**2154**	**1813**

4.3. EMISSION ABATEMENT

CO_2 reduction potentials from biofuel cultivation on land that becomes available due to agricultural intensification through intercropping practices are shown in table 10. With 522 kt CO_{2eq} per year, herbaceous biofuels have the largest potential for CO_2 abatement. This is due to their high biofuel yield combined with a high typical abatement value per unit of energy. This difference in abatement value contributes to a widening of the gap between the different feedstock that was already present in the biofuel production. Oil crops perform the least well in terms of abatement, at as 62 kt CO_{2eq} per year, or less than 1/8th that of herbaceous lignocellulosic plants.

522 kt CO_{2eq} is equivalent to the emission of 206 thousand Dutch households. The total CO_2 emission in the Netherlands in 2013 was 166400 kt (CBS, 2015). This means that anywhere between 0,04% (oil) and 0,33% (herbaceous) of the Dutch CO_2 emission could be abated by implementing biofuel cultivation in 15 European countries, such as described in the current study. In terms of European emissions, the percentage would be negligible.

Table 11: Greenhouse gas emission abatement as a result of biofuel cultivation on land that comes available through pea/barley intercropping.

Country	Herbaceous	Woody	Oil	Starchy	Sugar
France	112	79	11	15	17
United Kingdom	82	62	11	15	17
Hungary	77	43	8	11	11
Turkey*	32	23	4	5	6
Italy	50	40	5	6	8
Spain	26	30	3	4	4
Belgium	36	28	5	6	9
Serbia*	22	16	3	4	4
Poland	22	14	3	4	5
Netherlands	16	11	2	3	4
Germany	17	12	3	3	4
Denmark	7	5	1	1	2
Greece	6	4	1	1	1
Austria	5	4	1	1	1
Romania	13	9	2	2	2
Total	**522**	**380**	**62**	**81**	**93**

4.4. NITROGEN CONTENT AND FERTILIZER NEEDS

4.4.1. NITROGEN CONTENT

Intercrops outperformed sole cropping systems in terms of grain N yield, according to literature. Intercrops used N resources 16 to 40 per cent more efficiently with LER values ranging from 1,16 to 1,40. Typically, grain N yield ranked cropping systems pea SC > pea/barley IC > barley SC (see table 11).

Notable is the relatively low grain N yield in intercropped pea, sometimes even being outperformed by both IC and SC barley. This large difference between pea/barley intercrops and pea sole crops can largely be attributed to growth suppression of pea plants when intercropped with barley, causing pea to fix significantly less nitrogen than would be expected from the relative plant density (data not shown). The growth of pea plants is inhibited due to the strong competition of barley for soil N; barley is up to 30 times more competitive than pea for inorganic N (Jensen, 1996). This same competition leads pea plants in intercrops to rely more heavily on their nitrogen fixing ability, and therefore acquire a greater percentage of their total N through symbiotic N fixation with rhizobia. Because of its strong competition over soil N, barley plants in intercrops performed relatively well compared to barley sole crops based on their plant density, with partial LER values for grain N yield averaging 0,86 (table 11). In some cases intercropped barley even outperformed performed sole cropped barley in terms of grain N yield (Hauggaard-Nielsen et al., 2001).

Table 12: Grain N yield and LER values from literature for pea sole crops, barley sole crops, and pea/barley intercrops.

Nutrients (kg ha^{-1})	**Sole**		**Intercrop**			**LER**
	Pea	**Barley**	**Pea**	**Barley**	**Total**	
(Hauggaard-Nielsen et al., 2001)	104	49	25	54	78	1,34
(Hauggaard-Nielsen et al., 2008)	166	37	101	28	129	1,35
(Hauggaard-Nielsen et al., 2009a)	108	46	67	32	99	1,31
(Chapagain & Riseman, 2014)	192	47	87	45	131	1,40
(Hauggaard-Nielsen et al., 2003)	143	31	63	23	86	1,18
(Jensen, 1996)	210	85	50	78	128	1,16

4.4.2. NITROGEN FERTILIZER NEEDS

Fertilizer needs in sole and intercrops reported in literature were generally ranked barley SC > pea/barley IC > pea SC (Chapagain & Riseman, 2014; Hauggaard-Nielsen et al., 2001, 2003, 2008; Jensen, 1996). Barley sole crops needed an average of 49 kg ha^{-1}, pea/barley intercrops required 29 kg ha^{-1} on average, and pea sole crops produced an average surplus N of 10 kg ha^{-1} (data not shown). Values for N fertilizer needs in literature greatly varied, with standard deviations for barley SC, pea/barley IC, and pea SC of 21.2, 32.4, 40.2, and respectively. This high standard deviation is discussed in the sensitivity analysis under section 4.5.4.

The total yearly N fertilizer needs for the calculated intercropped area, and for the areas of sole cropped pea and barley needed to produce the same outputs are shown in table 12. The data showed that pea sole crops add nitrogen to the soil, and reduce rather than increase the fertilizer needs of cultivated land. Barley sole crops had the largest fertilizer needs, followed by pea/barley intercrops. This implies that when pea and barley sole crops are grown in the ratio that produces the same grain as the intercrop, the sole crops require slightly less N fertilizer inputs than the intercrop. This is explained in part by the fact that pea/barley intercrops yield more N-rich grain, and therefore have higher N outputs (table 11). After all, the N that leaves the system must be replenished afterwards by fertilizer N. In total, an additional 1184 t N is needed when implementing pea/barley intercropping practices instead of sole cropping to the extent described in the current study in section 4.1.

Table 13: Fertilizer needs (t N / year) of pea and barley sole crops and pea/barley intercrops in 15 European countries.

Country	Pea SC	Barley SC	SC total	Intercrop
France	-283	1595	1313	1536
United Kingdom	-310	1750	1439	1685
Hungary	-161	909	748	875
Turkey	-92	517	425	498
Italy	-138	776	639	748
Spain	-107	601	495	579
Belgium	-94	529	435	509
Serbia	-63	353	290	340
Poland	-60	338	278	325
Netherlands	-51	286	235	275
Germany	-49	278	228	267
Denmark	-29	165	136	159
Greece	-15	86	70	82
Austria	-15	87	72	84
Romania	-32	179	148	173
Total	**-1498**	**8448**	**6950**	**8134**

4.5. SENSITIVITY ANALYSIS

4.5.1. LAND SAVINGS POTENTIAL

Different recalculations of land savings potential using varying LER values are shown in figure 7. Recalculations of land savings potential with either a 'pea heavy' or a 'barley heavy' ratio of pLER values are shown in figure 8. Note that the 'Average' value for the 'Total LER' graph is slightly lower than for the 'Pea or barley heavy' graph. This is because the average LER is 1,17, while the LER in each of the 'Pea or barley heavy' studies is 1.20.

Variations in LER, being fairly constant across values found in literature, had a marginal effect on land savings potential, with the +1SD value being only 13% higher than the -1SD value. The SD of the total LER values found in literature was 0,07. pLER values had a much larger SD of 0,19 and 0,24 for pea and barley, respectively. This difference in variance can be explained by a trade-off of success of component crops. Apparently, if one crop performs poorly, the other crop has high yields and vice versa, causing the total LER to be fairly constant. This effect could either illustrate a competition between component crops, or a different suitability for the climatic conditions under which they were grown, meaning that conditions that favour barley hurt pea, and vice versa. The effect seems so support the risk-reducing quality that is sometimes attributed to intercropping systems (Rao & Singh, 1990), as one low performing component crop might be compensated by a better performing second component crop.

The 'Pea or barley heaviness' had a large effect on land savings potential, with the barley heavy distribution resulting in a 52% higher land savings potential compared to the pea heavy alternative.

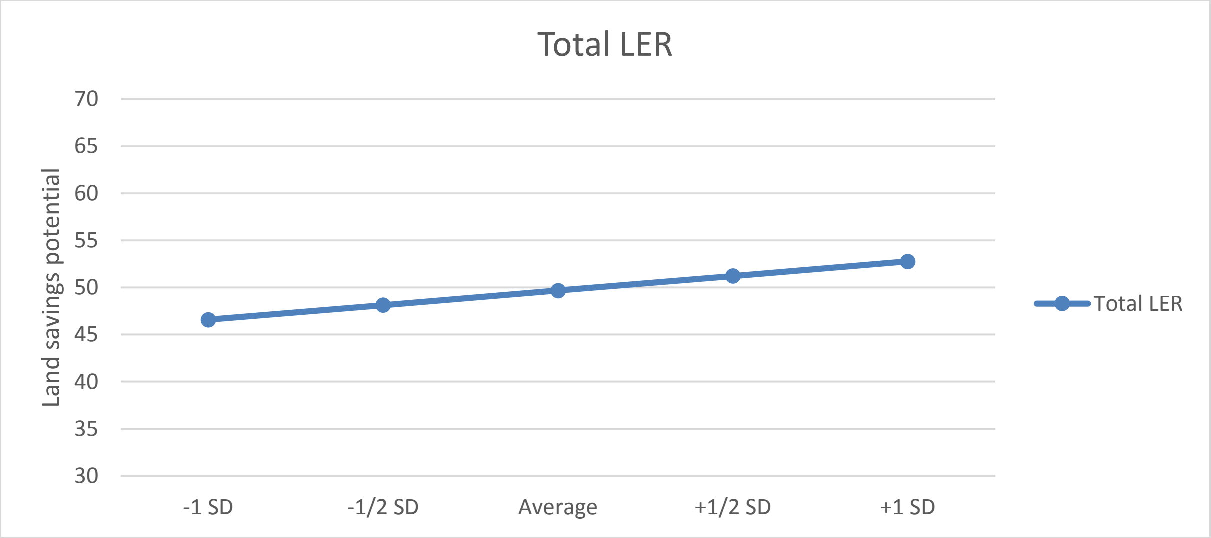

Figure 7: Land savings potential from pea/barley intercropping in 15 Europnean countries for varying total LER values.

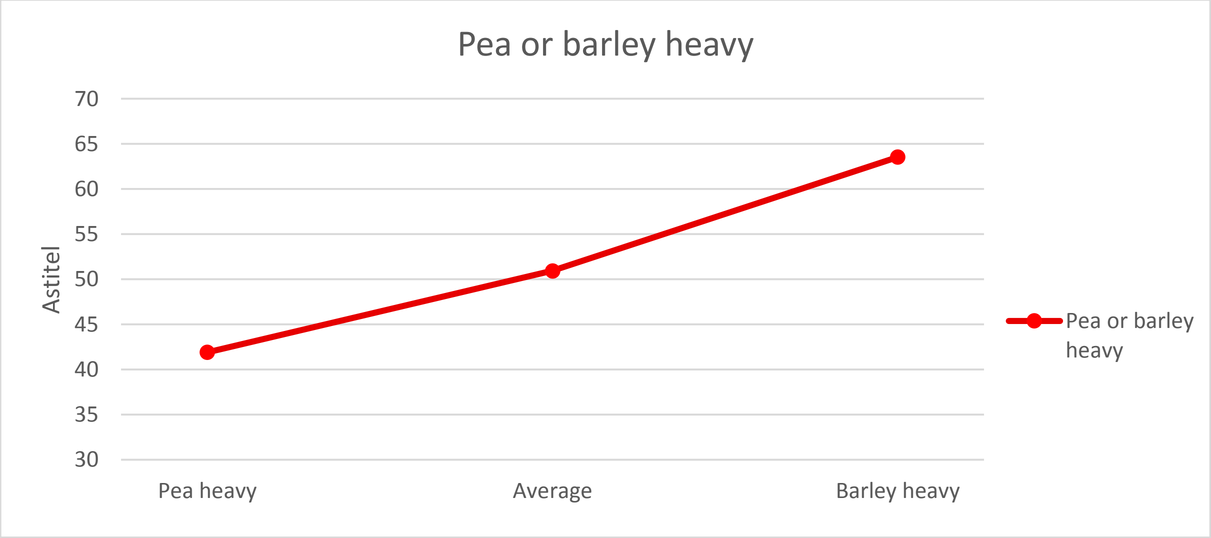

Figure 8: Land savings potential from pea/barley intercropping in 15 European countries for a pea heavy or barley heavy distribution of pLER values.

4.5.2. BIOFUEL POTENTIAL

Different calculations of the biofuel potential, caused by variations in LER and biofuel yields, are shown in figure 8. This figure shows the large differences between biofuel, as were reported in section 4.2. Herbaceous lignocellulosic plants outperform the other feedstocks, and oil crops perform the least well. For all feedstocks, variations in biofuel yield had similar impact on the biofuel potential compared to the variations in total LER value. The relative differences between the high and low estimates based on biofuel yield ranged from 12% for starchy crops to 22% for woody plants (data not shown), where this effect from LER values was 13% for all feedstocks.

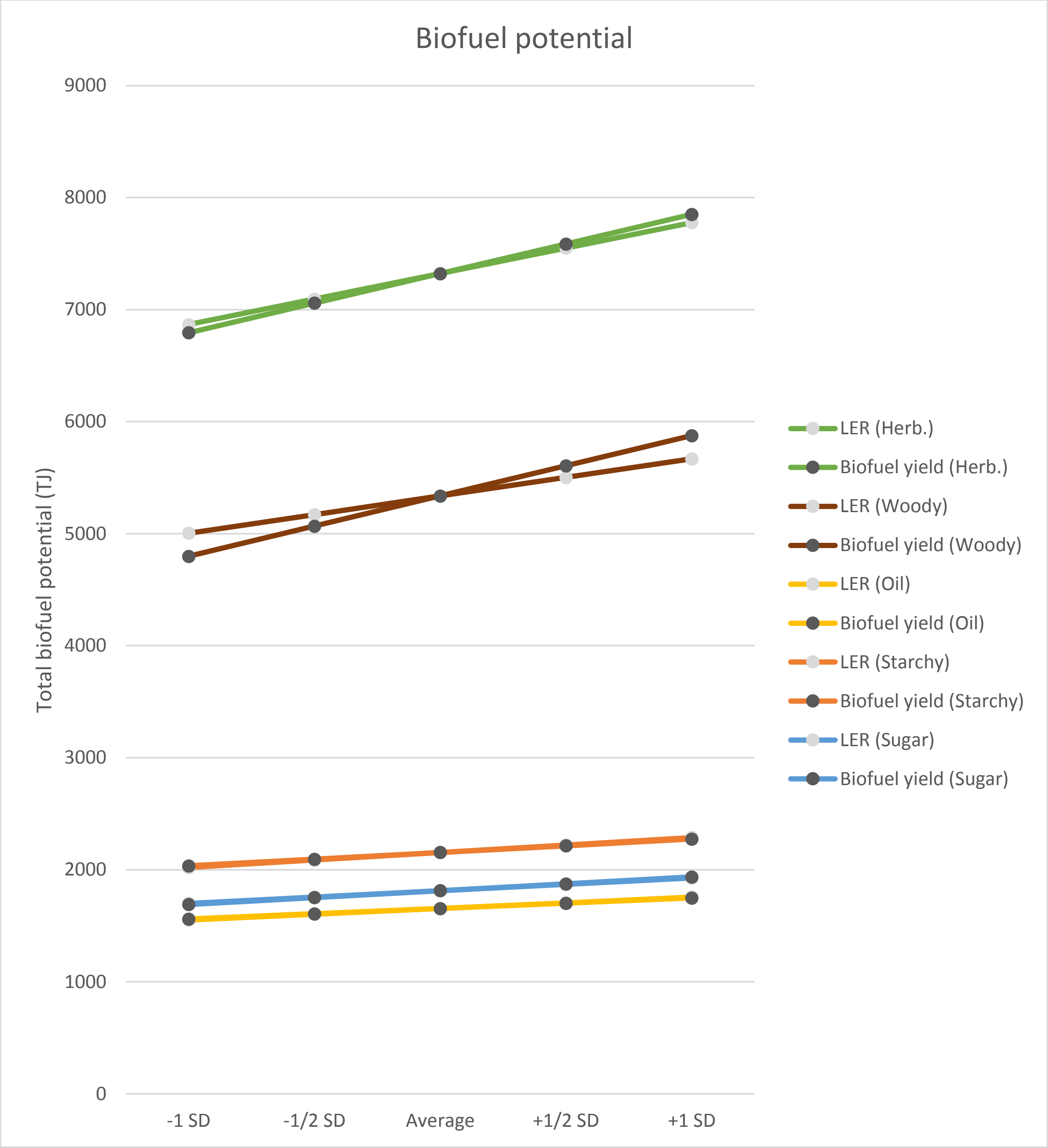

Figure 9: Total biofuel potential of 15 European countries (TJ per year) of different biofuel feedstocks and their production pathway (herbaceous lignocellulosic plants, woody plants, oil crops, starchy crops, and sugar crops) for varying total LER values and biofuel yields.

4.5.3. EMISSION ABATEMENT

The potential emission abatement from cultivating biofuel feedstocks on land that comes available by applying pea/barley intercropping practices in 15 European countries was recalculated with varying underlying figures, namely the total LER, the biofuel yield, and the abatement value. The results are shown in figure 9. Herbaceous lignocellulosic plants perform the best, and are estimated to abate anywhere between 484 and 559 kt CO_{2eq} per year. Oil crops perform the least well, with an abatement potential between 57 and 68 kt CO_{2eq} per year.

As the emission abatement potential follows directly from the biofuel potential, the graph's slopes are identical to the biofuel potential graphs when it comes to LER and biofuel yield. This is because the biofuel potential is multiplied by a constant, changing the height, but leaving the shape intact. This also means that the relative effect of LER and biofuel yield is the same as for biofuel potential. The third factor that was added to this analysis, the variance in abatement values, has an effect that is slightly larger than that of LER, with an 18% increase from the low value to the high for all biofuel feedstocks, compared to 13% from LER.

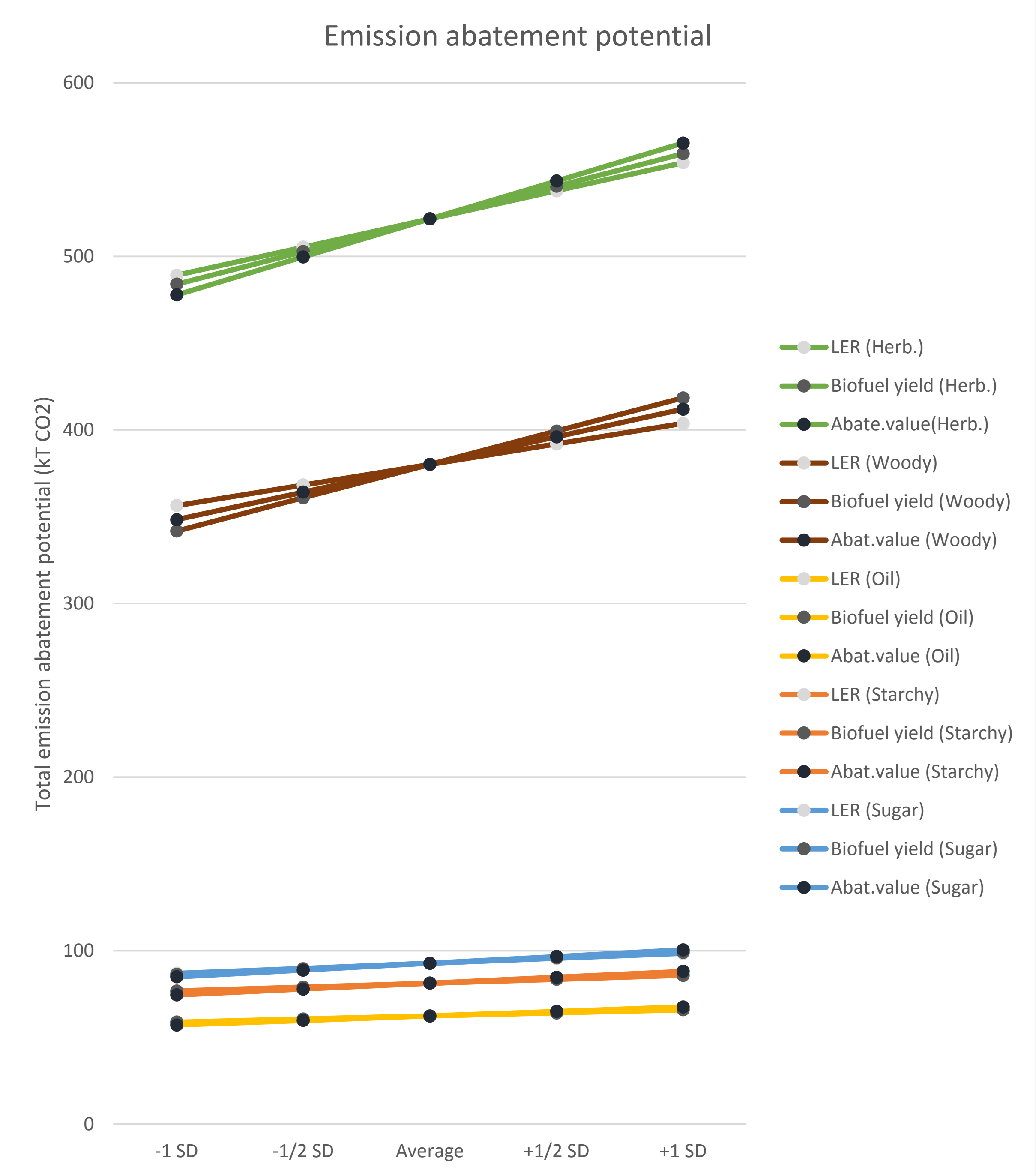

Figure 10: Total emission abatement potential of 15 European countries (TJ per year) of different biofuel feedstocks and their production pathway (herbaceous lignocellulosic plants, woody plants, oil crops, starchy crops, and sugar crops) for varying total LER values, biofuel yields, and abatement values.

4.5.4. Nitrogen fertilizer needs

The total nitrogen fertilizer needed to for the intercropped area that was calculated in the current study, and for the areas of sole cropped pea and barley needed to produce the same outputs was recalculated using the SD of the fertilizer values found in literature, and the results are shown in figure 10. It immediately stands out that the impact of the variation of underlying values is very large. The difference between SC total and IC values seems insignificant compared to effect from variance. For SC total, the relative difference between the average and the highest and lowest values is +134% and -134%. This shows that pea and barley's nitrogen fertilizer needs are highly influenced by differences in cropping conditions which would occur across field studies. The most important of which likely being the nitrogen content of the soil, the soil type, and how overall favourable the growing conditions are for pea and barley crops. An explanation could also be noise: legumes are known as a 'risky' crop because they are sensitive to weed infestations and other harmful influences, causing incidental drops in grain (N) yield and thus lowering fertilizer needs (Banik et al., 2006). More support for this explanation is that variance was also large within studies (data not shown).

It is very difficult to draw general conclusions about nitrogen fertilizer needs of pea/barley intercrops based on the current study, as it seems to depend too heavily on the specific field study. Depending on the conditions, the fertilizer needs could either be quite high, or negative.

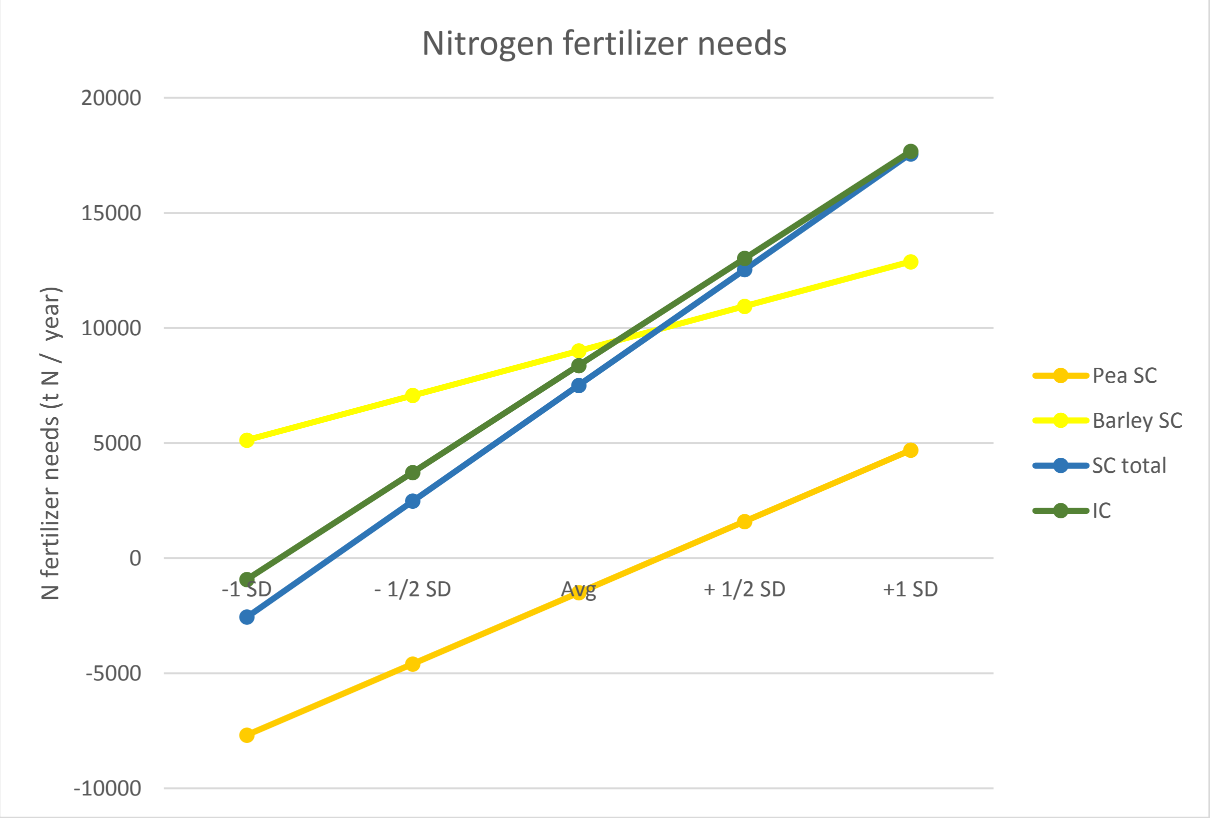

Figure 11: Nitrogen fertilizer needs (tonne nitrogen per year) of pea sole crops, barley sole crops, sole crop total, and intercrops for varying levels of biofuel need values (kg ha^{-1}).

5. CONCLUSIONS

The main aims of the current study were to identify the potential benefits of intercropping over sole cropping, to estimate pea/barley land savings and biofuel potential, and to approximate the difference in fertilizer needs between pea/barley sole and intercrops. The results of the literature review in the current report support claims that intercropping systems have significant benefits in comparison to sole cropping systems. Yields, weed suppression, nutrient utilization and disease management are positively influenced by intercropping practices when compared to sole cropping systems. These benefits have been shown to occur in pea/barley intercrops in particular in studies across Europe with different management practices, soils and climates. Numerous studies have shown that pea/barley intercrops can improve land use efficiency through increasing yield. Yield improvement in terms of LER typically ranges from 5 to 25% above unity. This effect is highly stable across sites in different countries, and under different growing conditions and management intensities.

Intensification of pea/barley cultivation through intercropping constitutes a considerable land savings potential. As much as 50 thousand hectares of land might be freed up for other purposes in the 15 European countries within the scope of the current study. If this land would be utilized for biofuel production, 7,32 PJ could be generated each year using the most favourable production pathway. This would provide the same amount of energy as the heat demand of roughly 175 thousand Dutch households. Compared to the 2013 production of renewable energy from biomass and waste the relevant countries of 3.98 EJ, the biofuel potential seems quite modest.

The amount of CO_2 emissions that could be abated by herbaceous biomass cultivation when utilizing the land savings potential of pea/barley intercropping was found to be 522 kt CO_{2eq} per year. For other feedstocks, the amount was lower. 522 kt CO_{2eq} amounts to 0.33% of the Dutch CO_2 emissions, and a negligible percentage of the total CO_2 emissions of Europe.

No real conclusions could be drawn about the influence of intercropping practices on the N fertilizer needs compared to sole cropping practices. The sensitivity analysis showed that the variance in N fertilizer needs within sole crops and intercrops was much larger than the difference between the sole crops and intercrops. This means that very different results were found in different studies, and no definitive pattern can be discerned. Apparently, the fertilizer N needs of crops were mostly determined by the specific conditions under which the field study was executed, and less by whether they were grown in a sole cropping or intercropping pattern.

A sensitivity analysis was conducted to illustrate a reliable range for the found results. This analysis showed that the land savings potential was influenced by the distribution of pea and barley pLER values, and to a lesser extent by variations in total LER values. Furthermore, biofuel potential was shown to be affected the most by variations in biofuel yield, and to some degree by LER values. Emission abatement potential was influenced strongly by the same factors as biofuel potential, and additionally by the spread in fossil fuel reference emission values. Finally, nitrogen fertilizer needs were very strongly affected by variance in the literature data on fertilizer needs per hectare. Therefore, the results on this topic should be interpreted with some caution.

6. DISCUSSION

A limitation of the current study comes from the fact that the main sources, field studies, don't all apply the same standardized methods. Every piece of literature executes its research in a slightly different way. Different researchers make different choices concerning plant cultivars, sowing densities, pea/barley ratios, fertilizer amount, management intensity, organic/inorganic practices etc. to best suit the specific goal of their studies. Not to mention the inevitable fact that different growth conditions arise in different years and locations. This makes it hard to aggregate the results of these studies into one figure to use in calculations and to regard as 'the result'. Having such an unstandardized source for the final result has the disadvantage that it is somewhat unclear under which exact circumstances this result is achieved. However, the data gathered from literature for the current study showed a highly robust effect of intercropping, despite the studies being somewhat heterogeneous. It could be viewed as an advantage of data aggregation that it shows more convincingly that the effect of intercropping stays prevalent across different times, locations and cropping conditions.

The land savings potential was calculated using yield data from literature, which doesn´t take into account the fact that Europe is not a homogeneous region. Pea/barley intercrop yield advantages were highly robust, but a large percentage of the field studies was conducted Denmark, with others taking place in other north-western European or Canada. Yields will likely differ across different locations and climatic conditions, especially compared to warmer climates such as the Mediterranean. For this reason, the relative measurement LER was used, as it only compares sole- and intercropping results within studies, and not between studies. This way, the effect of site-specific characteristics on research results is minimized, as only the ratio between sole cropped and intercropped results is taken into account; different circumstances would have to favour either cropping system in order to influence the end result. This is much less likely than site-specific circumstances influencing the growth of either or both of the component crops, which is practically inevitable. Still, it cannot be ruled out that the effects of intercropping might be different in other (particularly warmer) climates. It might be expected that intercropping provides additional benefits in systems where it causes greater ground cover, as this might provide some protection against torrefaction, though this is speculative and the exact effects are impossible to predict.

The assumption was made that all pea in the 15 included countries would be grown under intercropping practices. Although this suits the goal of the current study to find the *potential* land savings, it most likely causes an overestimation, as a full transition to 100% intercropped pea is a rather steep expectation. Similarly, when calculating the biofuel potential, the assumption was made that all freed land will be utilized for biofuel cultivation. This also causes an overestimation of the biofuel and subsequently the emission abatement potential, as 100% biofuel utilization on freed land is unlikely. These assumptions were made because the goal of this study was to estimate a maximum potential, and the adoption rate was not part of the scope. Of course it would be interesting for future research to investigate the rate of adoption of intercropping practices over time, and predict this for the future. Finally, the assumption was made that each of the land uses (pea, barley, pea/barley, and all biofuel feedstocks) can be grown on all land areas that are currently occupied by pea or barley monocrops. For the biofuel feedstocks, this assumption is justified, as the AEZ method predicts that this arable land is suitable for each biofuel crop cultivation. It also takes into account how much of the land in a country is more suitable or less suitable for biofuel crop cultivation in the average biofuel yields. In regards to pea and barley, it is also safe to assume that both pea and barley can be grown on the arable land where the other was previously grown, as this is common practice in crop rotation systems (Karpenstein-Machan & Stuelpnagel, 2000), and it shown that both crops can even be grown on the same land at the same time by intercropping.

The extreme variance in N fertilizer needs reported in literature makes it difficult to make meaningful statements about the total N fertilizer need in 15 European countries. One way to cope with this was to provide a lower and upper limit instead of a mean only. Furthermore, the lack of data on N leaching might have contributed to the uncertainty of the outcomes. Although a broad base of literature was used to draw conclusions about intercropping, the special focus on pea/barley might make conclusions about intercropping in general somewhat premature.

No research has like the current study has been done previously, and the results of the current study could provide scholars with a workable body of literature on the subject of intercropping. This might help future research by supplying a starting position with information that otherwise would have to be gathered by the researchers. Also, it might be useful to have a method of determining the land savings potential of intercropping in a certain country for a certain crop combination, as well as being able to determine the resulting biofuel potential and GHG abatement potential.

Policy makers are provided with handles with which they might improve policies specifically targeted at enlarging the energy biomass production within the European Union in a sustainable way. Informing/encouraging farmers regarding the potential benefits of intercropping might be a way to increase agricultural productivity in Europe. Policy makers could also choose to stimulate the development of intercropping practices' knowledge and scale. This could go hand in hand with stimulating biofuel cultivation, thus helping to reach CO_2 emission reduction targets and to lessen foreign dependence on energy supply.

In future research, a point of interest would be to examine other crop combinations in-depth besides pea/barley to discover their potential benefits. It would also be interesting to see optimization studies that don't simply compare sole crops and intercrops, but try to find the best practices for intercropping in order to maximize its benefits. Furthermore, an interesting approach would be to highlight the management costs of intercropping in order to study its economic performance compared to sole cropping. These studies do exist, but they are few and far in between. A good way to truly find out if the benefits of intercropping compared to sole cropping hold up in a non-experimental setting is through farm scale trials. These would be able to demonstrate how intercropping fits into a commercial farming environment. Lastly, a more thorough examination of the suitable areas for intercropping, based on their current agricultural occupation, climate, soil, etc. and the resulting potential would be recommended.

Intercropping practices potentially offer many advantages, but improved understanding is needed of the suitable crop combinations, economics, and best practices to truly make an impact on the European agricultural sector.

7. REFERENCES

4FCrops. (2010). Future Crops for Food, Feed, Fiber, and Fuel. Retrieved from http://www.4fcrops.eu/

Altieri, M. a. (1999). The ecological role of biodiversity in agroecossystems. *Agriculture Ecosystems & Environment*, *74*, 19–31. Retrieved from d:\biblio\a\15480.pdf

Andrews, D. J., & Kassam, A. H. (1976). *The importance of multiple cropping in increasing world food supplies.* Madison, Wisconsin, USA: American Society of Agronomy.

Anex, R. P., Lynd, L. R., Laser, M. S., Heggenstaller, A. H., & Liebman, M. (2007). Potential for Enhanced Nutrient Cycling through Coupling of Agricultural and Bioenergy Systems. *Crop Science*, *47*(4), 1327–1335. doi:10.2135/cropsci2006.06.0406

Anil, L., Park, J., Phipps, R. H., & Miller, F. A. (1998). Temperate intercropping of cereals for forage: a review of the potential for growth and utilization with particular reference to the UK. *Grass and Forage Science*, *53*(4), 301–317. doi:10.1046/j.1365-2494.1998.00144.x

Banik, P., Midya, A., Sarkar, B. K., & Ghose, S. S. (2006). Wheat and chickpea intercropping systems in an additive series experiment: Advantages and weed smothering. *European Journal of Agronomy*, *24*(4), 325–332. doi:10.1016/j.eja.2005.10.010

Bellostas, N., Hauggaard-Nielsen, H., Andersen, M. K., & Jensen, E. S. (2003). Early Interference Dynamics in Intercrops of Pea, Barley and Oilseed Rape. *Biological Agriculture & Horticulture*, *21*(4), 337–348. doi:10.1080/01448765.2003.9755277

CBS. (2014). Energieverbruik particuliere woningen; woningtype en regio's. Retrieved November 27, 2015, from http://statline.cbs.nl/StatWeb/publication/?DM=SLNL&PA=81528NED

CBS. (2015). Emissies van broeikasgassen berekend volgens de IPCC-voorschriften. Retrieved January 21, 2016, from http://statline.cbs.nl/StatWeb/publication/?DM=SLNL&PA=70946ned&D1=a&D2=a&D3=a&HDR=G2&STB=T,G1&VW=T

Cenpukdee, U., & Fukai, S. (1992). Cassava/legume intercropping with contrasting cassava cultivars. 1. Competition between component crops under three intercropping conditions. *Field Crops Research*, *29*(2), 113–133. doi:10.1016/0378-4290(92)90082-K

Chapagain, T. (2011). Cereal:legume intercropping trials under low input organic systems | Flickr foto sharing. Retrieved October 21, 2015, from https://www.flickr.com/photos/cereal-legume_intercropping_ubc/sets/72157627403445066

Chapagain, T., & Riseman, A. (2014). Barley–pea intercropping: Effects on land productivity, carbon and nitrogen transformations. *Field Crops Research*, *166*, 18–25. doi:10.1016/j.fcr.2014.06.014

Corre-Hellou, G., Dibet, A., Hauggaard-Nielsen, H., Crozat, Y., Gooding, M., Ambus, P., … Jensen, E. S. (2011). The competitive ability of pea–barley intercrops against weeds and the interactions with crop productivity and soil N availability. *Field Crops Research*, *122*(3), 264–272. doi:10.1016/j.fcr.2011.04.004

Corre-Hellou, G., Fustec, J., & Crozat, Y. (2006). Interspecific Competition for Soil N and its Interaction with N2 Fixation, Leaf Expansion and Crop Growth in Pea–Barley

Intercrops. *Plant and Soil*, *282*(1), 195–208. doi:10.1007/s11104-005-5777-4

Dimitrios, B., Panyiota, P., Aristidis, K., & Aspasia, E. (2010). Weed suppression effect of maize-vegetable in organic farming. *International Journal of Pest Management*, *56*, 173–181.

European Commission. (2009). *Directive 2009/28/EC of the European Parliament and the Cousil of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC*.

European Commission. (2014). The climate action and renewable energy package, Europe's climate change opportunity. Retrieved from http://ec.europa.eu/clima/policies/package/index_en.htm

Eurostat. (2013). Primary production of renewable energy, 2003 and 2013. Retrieved January 23, 2016, from http://ec.europa.eu/eurostat/statistics-explained/index.php/File:Primary_production_of_renewable_energy,_2003_and_2013_YB15.png

Eurostat. (2014). Crops products areas and productions - reference metadata. Retrieved November 1, 2015, from http://ec.europa.eu/eurostat/cache/metadata/en/apro_cpp_esms.htm

Eurostat. (2015). Crops products areas and productions - annual data (Apro_Cpp_Crop). Retrieved from http://appsso.eurostat.ec.europa.eu/nui/submitViewTableAction.do

Fargione, J., Hill, J., Tilman, D., Polasky, S., & Hawthorne, P. (2008). Land Clearing and the Biofuel Carbon Debt. *Science*, *319*(5867), 1235–1238. doi:10.1126/science.1152747

Fischer, G., Hizsnyik, E., Prieler, S., & Velthuizen, H. Van. (2007). Assessment of biomass potentials for bio- fuel feedstock production in Europe : Methodology and results, (July), 75. Retrieved from http://www.google.com/url?sa=t&rct=j&q=&esrc=s&frm=1&source=web&cd=1&cad=rja&uact=8&ved=0CCsQFjAA&url=http%3A%2F%2Fs3.amazonaws.com%2Fzanran_storage%2Fwww.res2020.eu%2FContentPages%2F43315751.pdf&ei=nkxWU9SBEKWCzAPgsIHYDg&usg=AFQjCNGu2K275nslV3U4PfoKzq-bW

Fischer, G., Velthuizen, H. Van, Shah, M., & Nachtergaele, F. (2002). *Global Agro-ecological Assessment for Agriculture in the 21st Century : Methodology and Results*. *Analysis* (Vol. RR-02–02). doi:http://www.iiasa.ac.at/Admin/PUB/Documents/RR-02-002.pdf

Food and Agriculture Organisation of the United Nations. (2010). Global Forest Resources Assessment 2010. *FAO Forestry Paper*, *163*.

Food and Agriculture Organisation of the United Nations. (2012). FAOstat - Net food production index 1992-2012. Retrieved from http://faostat3.fao.org/browse/Q/QI/E

Fukai, S., & Trenbath, B. R. (1993). Processes determining intercrop productivity and yields of component crops. *Field Crops Research*, *34*(3-4), 247–271. doi:10.1016/0378-4290(93)90117-6

Geist, H. J., & Lambin, E. F. (2001). *What Drives Tropical Deforestation? LUCC*.

Gesch, R. W., Archer, D. W., & Berti, M. T. (2014). Dual Cropping Winter Camelina with Soybean in the Northern Corn Belt. *Agronomy Journal*, *106*(5), 1735–1745. doi:10.2134/agronj14.0215

Giller, K. E., Beare, M. H., Lavelle, P., Izac, a.-M. N., & Swift, M. J. (1997). Agricultural intensification, soil biodiversity and agroecosystem function. *Applied Soil Ecology*, *6*(1), 3–16. doi:10.1016/S0929-1393(96)00149-7

Gooding, M. J., Kasyanova, E., Ruske, R., Hauggaard-Nielsen, H., Jensen, E. S., Dahlmann, C., … Launay, M. (2007). Intercropping with pulses to concentrate nitrogen and sulphur in wheat. *The Journal of Agricultural Science*, *145*, 469–479. doi:10.1017/S0021859607007241

Graß, R., Heuser, F., Stülpnagel, R., Piepho, H. P., & Wachendorf, M. (2013). Energy crop production in double-cropping systems: Results from an experiment at seven sites. *European Journal of Agronomy*, *51*, 120–129. doi:10.1016/j.eja.2013.08.004

Gurr, G. M., Wratten, S. D., & Luna, J. M. (2003). Multi-function agricultural biodiversity: pest management and other benefits. *Basic and Applied Ecology*, *4*(2), 107–116. doi:10.1078/1439-1791-00122

Hauggaard-Nielsen, H., Ambus, P., & Jensen, E. S. (2001). Interspecific competition, N use and interference with weeds in pea–barley intercropping. *Field Crops Research*, *70*(2), 101–109. doi:10.1016/S0378-4290(01)00126-5

Hauggaard-Nielsen, H., Ambus, P., & Jensen, E. S. (2003). The comparison of nitrogen use and leaching in sole cropped versus intercropped pea and barley. *Nutrient Cycling in Agroecosystems*, *65*, 289–300. doi:10.1023/A:1022612528161

Hauggaard-Nielsen, H., Andersen, M. K., Jørnsgaard, B., & Jensen, E. S. (2006). Density and relative frequency effects on competitive interactions and resource use in pea–barley intercrops. *Field Crops Research*, *95*(2-3), 256–267. doi:10.1016/j.fcr.2005.03.003

Hauggaard-Nielsen, H., Gooding, M., Ambus, P., Corre-Hellou, G., Crozat, Y., Dahlmann, C., … Jensen, E. S. (2009a). Pea-barley intercropping and short-term subsequent crop effects across European organic cropping conditions. *Nutrient Cycling in Agroecosystems*, *85*, 141–155. doi:10.1007/s10705-009-9254-y

Hauggaard-Nielsen, H., Gooding, M., Ambus, P., Corre-Hellou, G., Crozat, Y., Dahlmann, C., … Jensen, E. S. (2009b). Pea–barley intercropping for efficient symbiotic N2-fixation, soil N acquisition and use of other nutrients in European organic cropping systems. *Field Crops Research*, *113*(1), 64–71. doi:10.1016/j.fcr.2009.04.009

Hauggaard-Nielsen, H., & Jensen, E. . (2001). Evaluating pea and barley cultivars for complementarity in intercropping at different levels of soil N availability. *Field Crops Research*, *72*(3), 185–196. doi:10.1016/S0378-4290(01)00176-9

Hauggaard-Nielsen, H., Jørnsgaard, B., Kinane, J., & Jensen, E. S. (2008). Grain legume–cereal intercropping: The practical application of diversity, competition and facilitation in arable and organic cropping systems. *Renewable Agriculture and Food Systems*, *23*(01), 3–12. doi:10.1017/S1742170507002025

Heaton, E. A., Schulte, L. A., Berti, M., Langeveld, H., Zegada-Lizarazu, W., Parrish, D., & Monti, A. (2013). Managing a second-generation crop portfolio through sustainable intensification: Examples from the USA and the EU. *Biofuels, Bioproducts and Biorefining*, *7*(6), 702–714. doi:10.1002/bbb.1429

Heggenstaller, A. H., Anex, R. P., Liebman, M., Sundberg, D. N., & Gibson, L. R. (2008). Productivity and nutrient dynamics in bioenergy double-cropping systems. *Agronomy Journal*, *100*(6), 1740–1748. doi:10.2134/agronj2008.0087

Ijoyah, M. O. (2012). Review article Review of intercropping research : Studies on cereal-vegetable based cropping system, *1*, 55–62.

Ijoyah, M. O., & Dzer, D. M. (2012). Yield Performance of Okra (Abelmoschus esculentus L. Moench) and Maize (Zea mays L.) as Affected by Time of Planting Maize in Makurdi, Nigeria. *ISRN Agronomy*, *2012*, 1–7. doi:10.5402/2012/485810

Jensen, E. S. (1996). Grain yield, symbiotic N2 fixation and interspecific competition for inorganic N in pea-barley intercrops. *Plant and Soil*, *182*(1976), 25–38. doi:10.1007/BF00010992

Jensen, E. S., Peoples, M. B., Boddey, R. M., Gresshoff, P. M., Henrik, H. N., Alves, B. J. R., & Morrison, M. J. (2012). *Legumes for mitigation of climate change and the provision of feedstock for biofuels and biorefineries. A review*. *Agronomy for Sustainable Development* (Vol. 32). doi:10.1007/s13593-011-0056-7

Karpenstein-Machan, M., & Stuelpnagel, R. (2000). Biomass yield and nitrogen fixation of legumes monocropped and intercropped with rye and rotation effects on a subsequent maize crop. *Plant and Soil*, *218*, 215–232. doi:10.1023/A:1014932004926

Kinane, J. (2002). Effect of barley-legume intercrop on disease frequency in an organic farming system. *Plant Protection Science*. Retrieved from http://orgprints.org/00001536

Malézieux, E., Crozat, Y., Dupraz, C., Laurans, M., Makowski, D., Ozier-Lafontaine, H., … Valantin-Morison, M. (2009). Mixing plant species in cropping systems: concepts, tools and models. A review. *Agronomy for Sustainable Development*, *29*(1), 43–62. doi:10.1051/agro:2007057

Nassab, A. D. M., Amon, T., & Kaul, H.-P. (2011). Competition and yield in intercrops of maize and sunflower for biogas. *Industrial Crops and Products*, *34*(1), 1203–1211. doi:10.1016/j.indcrop.2011.04.015

Olasantan, F. O. (1988). Intercropping of cassava (Manihot esculenta) with maize or cowpea under different row arrangements. *Field Crops Research*, *19*(1), 41–50. doi:10.1016/0378-4290(88)90032-9

Ranganathan, R., Fafchamps, M., & Walker, T. S. (1991). Evaluating biological productivity in intercropping systems with production possibility curves. *Agricultural Systems*, *36*(2), 137–157. doi:10.1016/0308-521X(91)90020-B

Rao, M. R., & Singh, M. (1990). Productivity and Risk Evaluation in Contrasting Intercropping Systems I, *23*(878), 279–293.

Reynolds, P. E., Simpson, J. A., Thevathasan, N. V., & Gordon, A. M. (2007). Effects of tree competition on corn and soybean photosynthesis, growth, and yield in a temperate tree-based agroforestry intercropping system in southern Ontario, Canada. *Ecological Engineering*, *29*(4), 362–371. doi:10.1016/j.ecoleng.2006.09.024

Schittenhelm, S., Reus, D., Kruse, S., & Hufnagel, J. (2011). Assessment of productivity and profitability of sole and double-cropping for agricultural biomass production. *Journal Für Kulturpflanzen*, *63*(11), 387–395.

Searchinger, T., Heimlich, R., Houghton, R. A., Dong, F., Elobeid, A., Fabiosa, J., … Yu, T.-H. (2008). Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change. *Science*, *319*(5867), 1238–1240. doi:10.1126/science.1151861

Shearer, G., & Kohl, D. H. (1988). Natural 15N abundance as a method of estimating the contribution of biologically fixed nitrogen to N2-fixing systems: Potential for non-legumes. *Plant and Soil*, *110*(2), 317–327. doi:10.1007/BF02226812

Tilman, D., Cassman, K. G., Matson, P. A., Naylor, R., & Polasky, S. (2002). Agricultural sustainability and intensive production practices. *Nature*, *418*(August), 671–677.

Trenbath, B. R. (1993). Intercropping for the management of pests and diseases. *Field Crops Research*, *34*(3-4), 381–405. doi:10.1016/0378-4290(93)90123-5

Van der Meer, J. H. (1989). *The Ecology of Intercropping*. Cambridge, UK: Cambridge University Press.

West, T. D., & Griffith, D. R. (1992). Effect of Strip-Intercropping Corn and Soybean on Yield and Profit. *Journal of Production Agriculture*, *5*(1), 107–110.

Wicke, B., Verweij, P., Meijl, H. Van, Vuuren, D. P. Van, & Faaij, A. P. C. (2012). Indirect land use change : review of existing models and strategies for mitigation Current status of modeling LUC-related GHG emissions, *3*, 87–100.

Wit, M. P. De. (2014). Greenhouse gas mitigation effects of integrating biomass production, 374–390. doi:10.1002/bbb

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