Future-Proof Agriculture

The Lasting Fields concept

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Summary

Current development in conventional arable farming systems in Europe remains faithful to the past, resulting in; increasing soil compaction, inapplicability of new farming methods and an increasing energy demand. The Lasting Fields project aims to design arable farming from scratch. Lasting Fields can reduce the adverse environmental effects of current agriculture by providing small, lightweight machines that are based on a fixed path system with energy efficient rail based transport. In this report literature studies are performed to assess the potential of Lasting Fields in terms of benefits to soil and crop (soil compaction, field applications), technology, and environment (LCA). The results are used to perform an economic analysis. It is estimated that crop yields can be increased up to 20% based on a reduction in soil compaction, which can be partly realized by Lasting Fields. Due to knowledge gaps in the literature and the requirement of site-specific information, no quantitative information is found on increased yields due to reduced soil compaction caused by implementing Lasting Fields. Complete avoidance of soil compaction however, may also decrease crop yields in some cases. Applying controlled traffic farming is therefore not necessarily desirable. The machinery of Lasting Fields could solve the lack of useful machinery for new cultivation systems (e.g. intercropping) which forms the main bottleneck for implementing new cultivation systems in the Netherlands. Based on intercropping it is estimated that crop yields can increase from 10% up to 30% in appropriate intercropping combinations. Due to intercropping the occurrence of pests and diseases could also be reduced within a range from about 10% up to 30%, which stabilizes the financial income. In other fields of application Lasting Fields offers opportunities in decreasing the large demand of human labour. Technically the Lasting Fields project is in an early stage of development. Most of the design decisions considering the key functions of Lasting Fields are not made in this stage of the project. Key functions of lasting field include; small autonomous on-field robots, rail system for farm field logistics and an integrated farm management system. This report analysed autonomous driving pilot studies in agriculture. The technical principles used in these agricultural robots are used in conducting a concept design for the Lasting Fields project. The environmental impact of implementing Lasting Fields on current arable farming is assessed by performing a life cycle assessment. Implementing Lasting Fields results in a decreased environmental impact, mainly due to a lower demand of energy (fuel) per hectare. The yield gains of reducing soil compaction and implementing intercropping, results in financial gains. The feasibility of Lasting Fields cannot be given; therefore more specific information about the costs of implementing Lasting Fields is needed. Lasting Fields is not only interesting for conventional arable farming. If Lasting Fields machinery can replace manual labour in labour intensive crops (vegetables) or labour intensive farming methods (organic farming) a large financial potential is reached. A roadmap indicates the logical order of steps to be taken in order to reach the goal of this Lasting Fields project, specifically; commercially implementing Lasting Fields. In order to reach this goal recommendations for further research are expressed. After all, it can be concluded that the Lasting Field project could offer possibilities for new cultivation systems, like intercropping, while reducing the impact on the soil. Furthermore a decreased energy consumption per hectare decreases the environmental impact, while the economic potential of Lasting Fields will increase. The technologies needed for on-field autonomous driving are already developed, while autonomous operating farm tasks and integrating Lasting Fields in a management system needs further research. Therefore, further developing Lasting Fields could result in an interesting and completely different alternative for conventional arable farming techniques.

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Introduction

During last decade most innovations in agriculture in the Netherlands have been focused on increasing yield, maximizing human labour efficiency and reduce costs. These innovations and the economic pressure pushed farmers to use larger and heavier machines to work more efficiently. As a result, the mass of most agricultural machinery has more than doubled from 1945 to 1985 in the Netherlands (Perdok *et al.,* 1985) and this trend is still continuing (Horn *et al.,* 2006). The intensification of agriculture has mostly been at the expense of soil, environment and economic sustainability.

Wim Steverink, owner of Steverink Techniek B.V., is concerned about the current state of arable farming. According to Steverink, fossil fuel use and soil compaction are important effects of the current mechanisation of agriculture in the Netherlands. Therefore, Steverink developed the concept 'Lasting Fields' which aims to minimize energy use and soil impact in arable farming. The aim of Steverink is to implement 'Lasting Fields', improving the sustainability of farming and to contribute into a reduction of greenhouse gas emissions from agriculture.

Steverink contacted PPO Lelystad as knowledge partner for the Lasting Fields concept. Marcel van der Voort is the representative of PPO regarding the Lasting Fields concept and asked composed an ACT-project to provide more insights for the implementation of the Lasting Fields concept.

Van der Voort is the commissioner of this ACT-project and is interested in the (economic) potentials of the Lasting Fields concept. This reports aims to provide Van der Voort additional background knowledge for approaching new partners in implementing Lasting Fields.

The Lasting Fields concept is a new vision of farming where, through the usage of technological advanced lightweight machinery, the soil and the environment have a primary relevance. This report analyses: 1) the impact of small and light Lasting Fields machinery on soil and crop, 2) opportunities in cultivation systems an application fields, 3) the technology needed for developing Lasting Fields machinery, 4) the environmental impact of Lasting field, and 5) the economic feasibility. These 5 topics examine the Lasting Fields' bottlenecks, benefits and possible alternative or advice.

Chapter 2 discusses about the soil compaction in agriculture that is caused by heavy machinery. To avoid drastic increases in soil compaction, the tire size increased with the weight of the machines, while inflation pressure of the tires decreased. Because the state of the soil is important for crop yield and the environment, preservation of soil quality is essential (Weisskopf *et al.,* 2006). The structure of some soils has already deteriorated to the extent that crop yields have been reduced due to soil compaction (Hamza & Anderson, 2005). The degradation of 33 million ha of soil in Europe is estimated to be caused by compaction (Nawaz *et al.,* 2013). According to another estimate, 17% of the degraded soil surface in Europe is degraded due to soil compaction (Osman, 2013). 'Sustainable' soil management techniques require consideration and respect for site specific properties and functions that soils fulfil in ecosystems (Horn *et al.,*2006), as well as prevention of long lasting damages to soil structure (Weisskopf *et al.,*2006). The latter is nearly impossible in current mechanized agriculture, as all agricultural processes involve some degree of soil compaction (Ryan *et al.,* 1992). However, excessive compaction results in a change of soil physical properties that affects other chemical and biological factors in a negative way, reducing the productivity of the soil. Therefore, minimizing soil compaction is an important aim in making contemporary agriculture more sustainable. These soil compaction issues are the main trigger for developing the Lasting Fields concept.

Chapter 3 discusses the opportunities for intercropping and other cultivation systems. The commissioner was mainly interested in the potentials of intercropping. Intercropping refers to the situation where two or more crops are grown simultaneously on the same field. This technique has several advantages and benefits but also some disadvantages; mechanization is the biggest bottleneck for applying intercropping on large scale farming (Lithourgidis *et al.,* 2011). Some positive environmental effects are explained in the chapter such as symbiosis with nitrogen fixating bacteria in root nodules and when a crop repels pests for the other. Another disadvantage could be the competition if crops are not chosen carefully. There are different methods of intercropping that are analysed and also feasible crop combinations that could fit in the Netherlands. Intercropping may also contribute to a more stable farmers' income over years due to diversification of crops and so reduction in pest diseases.

Finally, other practices in agricultural where Lasting Fields concept could work are discussed. These are orchards, floriculture, forage and organic agriculture. All these sectors have in common, the substantial amount of labour's hours. Lasting Fields with autonomous driving can help in reducing significantly total costs.

Chapter 4 discusses the technology needed for developing 'real' Lasting Fields machinery. The concept, developed by Steverink Techniek BV, aims to solve soil compaction in arable farming by using small, light, autonomous and fixed path driven machinery. A rail system is supposed to energy efficiently transport machinery and products from farm to field and vice versa. A conceptual sketch of the Lasting Fields concept is shown in figure 1. Lasting Fields is currently in the starting phase and a proof of principle potato harvester is built. However, there is currently no commercial machinery. Therefore, the concept is open for discussion, suggestions and improvement.

This chapter specifies the current state of automated agricultural technology considering Lasting Fields characteristics and requirements. The technical principles described in the pilot studies on autonomous driving in agriculture providing suggestions for the detailed Lasting Fields design. Based on these technical principles described in the current state a technological future vision of Lasting Fields is constructed.

In **Chapter 5** the Life Cycle Assessment (LCA) for the Lasting Fields concept is performed. The analysis focuses on the reduction of diesel consumption and weight of machinery. These changes are made directly in the database used and the final results refer to the production of 1 kg of potatoes. Besides the LCA, in the chapter are also discussed other energy improvements that comes with Lasting Fields, but that were not implemented in the simulations. They are about the solar panel implementations, the rail system as a substitute for the truck biomass transport from field to barn. Furthermore also the energy self-sufficiency is discussed.

Chapter 6 discusses the economic potential of Lasting Fields concept and compares it with a conventional system. The basis of this analysis is a standard cultivation system used in the Dutch province of Flevoland. Using the outcome of chapter 5 and chapter 6, an increase in farm revenue is calculated. Machinery costs are left out of this analysis, because the costs of Lasting Fields machinery are unknown. Besides that, the chapter discusses other applications of Lasting Fields, and how this concept could be put on the market.

The chapters above are discussing the concept and suggest improvements. Finally, a roadmap is created, providing a development strategy for the Lasting Fields concept. Besides suggestions for improvement the total report also provides an overview of the advantages of the Lasting Fields concept and the new opportunities enabled by Lasting Fields in the discussion.

Figure 1. *Sketch of the '*Lasting Fields*' concept (Steverinktechniek.nl, 2016).*

1. Methods

This report is conducted after five main literature studies on the Lasting Fields topics: soil compaction, intercropping, technology, life cycle assessment and economy. In this chapter the research methods used to find all the information are described. The analytical methods used to thresh out the information found in literature are also briefly described.

1.1. Soil compaction

The literature study regarding soil compaction started with general keywords like ‘soil compaction’ in combination with ‘machines’, ‘agriculture’ and reading relevant books available in the WUR library. Afterwards several review papers were analysed to get more familiar in the particular subject and to get an overall view on it.

We also interviewed our scientific expert, prof. dr. ir. Liesje Mommer. She is specialized in soil compaction and she is also familiar with intercropping. These review papers were used in for general ‘knowledge-like’ information and to look for more sources that are relevant. For specific facts the papers that are referred to by the review paper were looked into. Beside these referred papers a search engine is used (global search of WUR, Web Of Science, and occasionally Google Scholar) with appropriate keywords. The order of articles is always set on ‘relevance’. Primary sources were used as much as possible.

1.2. Intercropping

At first the relevant topics related to intercropping were determined. It seemed that it was important to search information about the potentials for intercropping. Information about the potentials of intercropping such as yield increase and/or the decrease of agricultural inputs such as fertilizer and crop protection agents was searched. The focus on this search was to quantify these potentials and the mechanisms behind these potentials.

In searching engines such as Google Scholar and WUR library catalogue the key words: intercropping, yield increase, machinery, resource use efficiency, ecology were used. We interviewed our scientific expert, prof. dr. ir. Liesje Mommer. She is specialized in soil compaction and she is also familiar with intercropping. During writing our report she provided us feedback how we can improve our report of the project. Tjeerd-Jan Stomph (WUR chair group Crop Systems Analysis) provided additional relevant publications. At first reviews were used which provided a lot of information about intercropping, relevant cited publications within the review were also used as source for the intercropping part.

1.3. Technology

The technology chapter is written after a literature study regarding autonomy in agriculture. To get general insights in the future of farming this literature study started with finding and analysing peer reviewed articles considering a future vision on arable farming. Autonomous driving vehicles and advanced farm management systems where the mean topics in these studies. Furthermore, Joris IJsselmuiden (Postdoc agricultural robotics at the Farm Technology Group of Wageningen University) is interviewed to reflect on the general insight found in literature and ideas for Lasting Fields implementation.

Further more specific literature research focused on the requirements of future autonomous agricultural vehicles. Thereafter articles about designing and evaluating proof of principle agricultural robots were analysed. Finally, commercial agricultural autonomous vehicles were researched. The specifications of the robots found in the research described above were used to find the advantages and disadvantages of the navigation and positioning solutions used in agricultural robots. The second important topic, farm management information systems, (FMISs) is separately studied. After a look into the future vision on FMISs and research projects about FMISs, commercial FMISs were studied. Dutch governmental information is used to evaluate legislation and safety issues regarding autonomous driving.

Engineering design methodology from the book Engineering Design Methods by Nigel Cross is used to analyse the range of navigation, sensing and management solutions found in the literature study described above. The first step was to set the objective of the idealized future designed solution. Thereafter requirements to fulfil this objective were determined. The concept is divided in several key functions. The technical principles found in literature provide the range of design solutions possible for each key function. A morphological chart is used to order these solutions and key functions. By selecting one path throughout this morphologic chart a design concept is obtained and described.

1.4. Life cycle assessment

In order to conduct the life cycle assessment analysis, OpenLCA software was used. This software is developed by Green Delta, an independent sustainability consulting and Software Company based in Berlin. OpenLCA is open source software able to operate with every database available worldwide. Generally, databases are constructed regarding the same standard, '.zolca'. The databases used in the LCA are the 'ELCD' provided by the European Commission and the 'Agribalyse' provided by the French Environment and Energy Management Agency. Some data for the Lasting Fields concept are provided from Steverink, others from the literature and others were assumed.

1.5. Economy

The economic analysis is conducted using information from information provided by the Centraal Bureau voor de Statistiek, the book KWIN-AGV (2015), and information obtained from Van der Voort. The results of this report regarding yield increase due to intercropping and a lower soil compaction are also used for the economic analysis. Information about the business model that could be used by Lasting Fields is obtained by interviewing Joris IJsselmuiden.

2. Soil compaction

The focus of this chapter is on machine-induced soil compaction. Besides vehicle traffic there are other causes of soil compaction in agriculture. Natural phenomena like the fall of raindrops or freezing and drying of the soil will not be discussed because the Lasting Fields concept does not change the impact of these other causes. The chapter will begin with the definition and description of soil compaction, after which the extend of soil compaction by machinery-induced compaction will be discussed. The overall effects of soil compaction will be elaborated in the physical, chemical and biological consequences. To assess the economic potential for the Lasting Fields concept an estimation of yield reduction due to soil compaction is provided. Lastly, the effect of Lasting Fields on soil compaction will be discussed by comparing the effects of light machines and controlled traffic farming to heavy machines in conventional farming.

2.1. Definition and description

Soil compaction (also called soil structural degradation), is regarded as one of the most important problems in conventional agriculture. Soil compaction is not always directly detectable due to difficulties in localizing compaction and the lack of distinct signs on the surface (Hamza & Anderson, 2005). Soil compaction is reversible, although undoing subsoil (layer beneath the plough layer) compaction is more challenging (McGarry, 2003). In Figure 2.1 the natural susceptibility to soil compaction in West-Europe is shown and it indicates that a large part of The Netherlands has a high natural susceptibility to compaction. Moreover, preliminary research by Van den Akker (2006) found that about 50% of the Dutch sandy and sandy loam soils showed compaction.

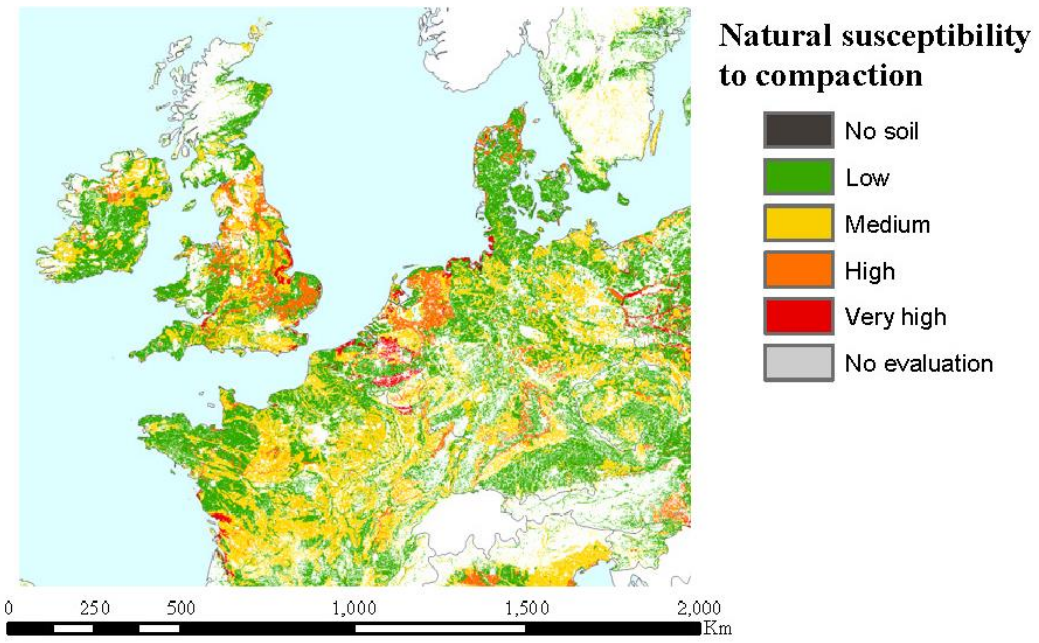

Figure 2.1. *Natural susceptibility of West-Europe to soil compaction.*
(http://esdac.jrc.ec.europa.eu/content/natural-susceptibility-compaction-europe)

Soil compaction is a physical form of degradation, officially defined as the process by which the soil particles are rearranged to decrease void space and bring them closer together (SSSA, 1996; Horn *et al.,* 1995; Soane & Van Ouwerkerk, 1994). This increases bulk density and decreases soil porosity which influences biological and chemical properties. Soil porosity can be expressed in the amount of macropores, water infiltration rate, and permeability of air. Additionally, soil strength is used when the effect of soil compaction on plants is investigated (Nawaz *et al.,* 2013).

In figure 2.2 an overview is given of the initial soil properties which were affected by soil compaction. The effects of soil compaction on soil properties are divided into three groups: 1) Physical soil properties, 2) Chemical soil properties, and 3) Biological soil properties. The soil properties which are affected by soil compaction are described for each group. Most of these soil properties do not show a linear response to soil compaction but depend on other factors as well. For example, higher organic matter content usually decreases the effect of soil compaction, but the effect of organic matter content on compaction is likely greater at a low compaction level with high soil moisture, and depends on the soil texture (Mosaddeghi *et al.,*2000).

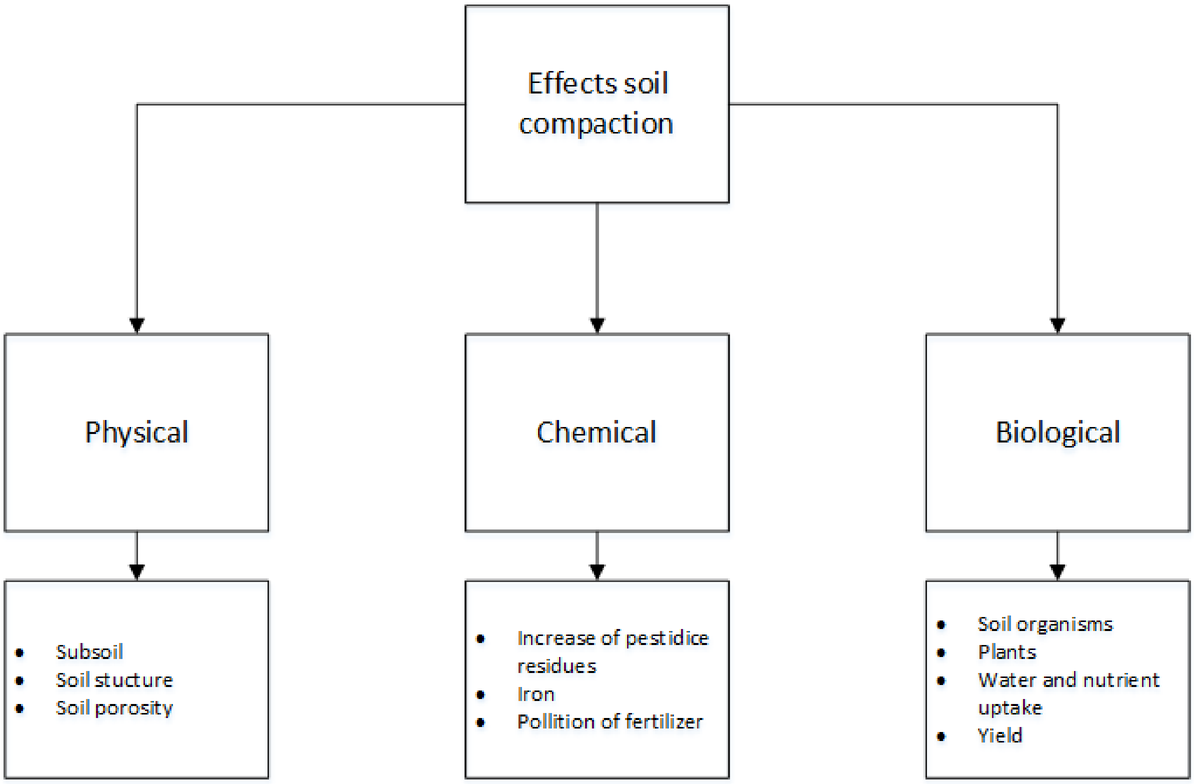

Figure 2.2. *Overview of soil properties which are affected by soil compaction*

2.2. Machine-induced soil compaction

First the used measure will be elaborated so the rest of the paragraph is more clear, after which the difference between tracked and wheeled machines will shortly be discussed. Secondly, current traffic intensity and frequency will shortly be discussed which will enlighten the problem of soil compaction in conventional farming. Thirdly, ground pressures will be elaborated, enabling a comparison between conventional farming and the small lightweight machines of Lasting Fields in the future. Finally, the stress distribution in the soil is illustrated.

2.2.1. Tracked and wheeled machines

The focus will be on wheeled tractors rather than tracked ones (Dutch: 'rupsbanden'), since more information is available for wheeled tractors and tracked machines are not commonly used in the Netherlands. Wheeled and tracked vehicles both cause soil compaction. The exact differences between both types of vehicles are not essential in analysing the effects of soil compaction and how Lasting Fields could solve these issues, because both tracked and wheeled tractors generally have high machine masses. In general, tracks are better than wheels at limiting soil compaction (Erbach, 1994). However, according to Culshaw (1986) and Erbach (1994) they can have negative effects on soil for several reasons: first, although the calculated average contact pressure is smaller than for a wheel, it is applied for longer; second, track belts with inadequate tension may result in a non-uniform pressure distribution; third, vibrations from the engine and other machine parts are more readily transmitted into the soil on tracks because of the reduced suspension effect.

It results from the literature that large differences on soil compaction depend on the tyre inflations pressure (Ansorge D. *et al.,* 2009). Both techniques have advantages and disadvantages and the best solution depends on the type of soil and the type of crop. Increasing width leads generally to a decrease in soil compaction (Ansorge D. *et al.,* 2009). It was also tested from the ministry of agriculture and forestry of Alberta, CA (2004) that a rubber tire tractor to have similar average ground pressures of tracks required triple tires. However, a lower mean ground pressure of tracked vehicles does not directly result in a lower degree of compactness. The track width of wheeled vehicles is often wider than the track width of the tracked vehicles, resulting more compacted tracked zones in case of tracked vehicles. However, a smaller proportion of the field is affected by tracked traffic (Håkansson, 2005).

5.2.2. Measure used

In literature a distinction is made between compressibility (compression index using a simple uniaxial test) and compactibility (maximum bulk density), which are not correlated (Smith, 1967). A commonly used measure of soil compaction is 'the degree of compactness', which is analogous to the compressibility and corrects for soil texture. The degree of compactness is defined as "the dry bulk density of the soil in the field as a percentage of the dry bulk density of the same soil after compaction in the laboratory in a standardized way" (Håkansson, 2005). A force of 200 kPa (1 kilopascal equals 102 kilograms per square meter) is first applied to the soil and this bulk density (the reference state) is measured and used relatively to the bulk density that is measured later when a compaction event has occurred. It is used to determine relative yields of crops and provides an overview of the effects of soil compaction for all soil types. The degree of compactness and the degree of compaction are both used throughout this chapter, the former indicating the definition described above relating to actual measurements of soil compaction while the latter is a more abstract indicator.

5.2.3. Traffic intensity and frequency

In most mechanized farming systems the field is run over by field traffic (wheeled tractors) several times a year. Total annual wheel passes (wheeling frequency) vary from crop to crop. A measure of traffic intensity is the total annual wheel track area per year, which is usually several times the field area. This means that every part of the field is at least run over once a year unless a controlled-traffic farming (CTF) system is used, which is discussed later on. Another measure of the traffic intensity is the weight of the machines multiplied by the distance driven ($tons \cdot km \cdot ha^{-1}$). In cereal production, all field operations equal to about 100 to 150 tons·km·ha-1 while sugar beet production generates nearly twice as much. The importance of wheeling frequency for the degree of compactness is illustrated in figure 2.3.

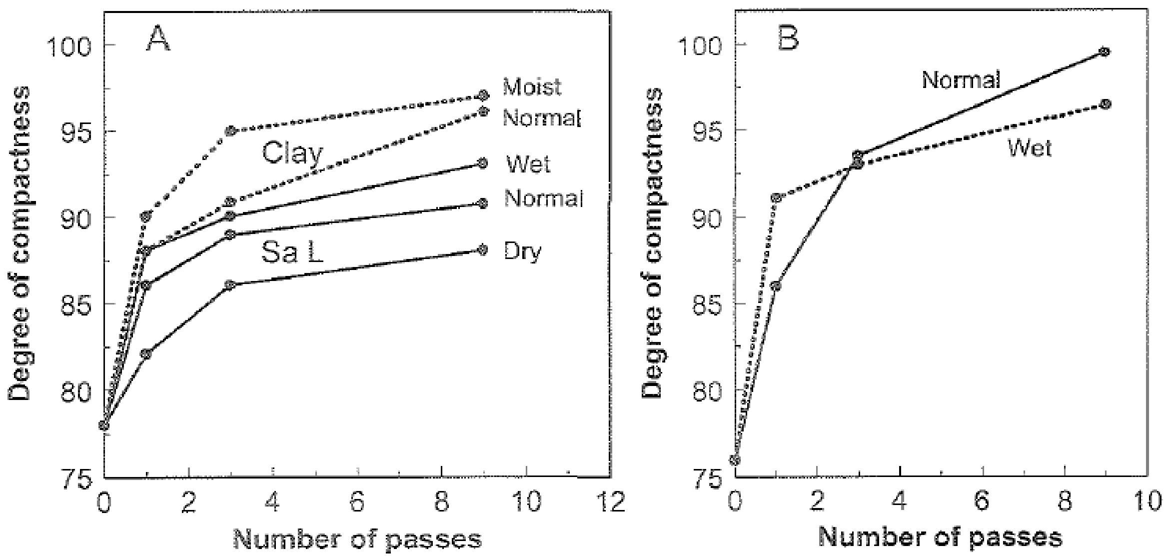

Figure 2.3. *The degree of soil compactness in the topsoil as function the number of passes (a) by relatively light machine for clay and sandy loam texture and (b) relatively heavy machine in normal and wet circumstances (Håkansson, 2005).*

2.2.4. Ground pressure

The ground contact pressure is often used to indicate vertical stress in the ground resulting from contact with a wheel or track. It is often measured by psi (pounds per square inch of pressure that the tire has on the surface of the soil) or in the similar kPa (same as 0,145 psi). Axle load (total weight of machine in kg or Mg) or wheel load (weight of machine per wheel in kg or Mg) in combination with the total contact area is often used to calculate the ground pressure. For the front tires in table 1 the wheel load is divided by the total contact area. The resulting number is then again divided by 102 to reach the ground contact pressure in kPa. From this table it can be seen that not only the wheel load but also the contact area is very important for the ground contact pressure on the soil. The ground pressure is more complicated as the inflation pressure and other tire factors are involved as well. Lowering the inflation pressure results in less severe soil compaction.

Table 2.1. *Relation between wheel load, contact area and ground pressure (rounded numbers). Characteristics are derived from a fully loaded and equipped combine harvester used for the traffic experiments (Schäffer et al., 2007).*

	Wheel load (kg)	**Width contact area (m)**	**Length contact area (m)**	**Contact area (m^2)**	**Ground contact pressure (kPa)**	**Ground contact pressure (psi)**
Front tyres	3455	0.52	0.55	0.2860	119	17
Rear tyres	1410	0.27	0.25	0.0675	205	30

2.2.5. Stress distribution in the soil

Figure 2.4 shows the results of a model that is usually used to illustrate the pressure distribution of wheeled tractors, with stress bulbs showing the major principal stress in the soil acting perpendicular to the surface of the wheel. The stress by compaction increases both with axle load (figure 2.4a and soil moisture (figure 2.4b). Other factors, for example the inflation pressure, do not have a strong effect on the depth of compaction (Schjønning *et al.,* 2006). However, since the stress of compaction on the soil is not the same in all directions, it should be noted that this stress model does not provide complete information on the total stress situation (Håkansson, 2005). An increase in compaction in lower layers of the soil with increased axle load is confirmed by figure 2.5a, which shows that the vertical stress in the soil penetrates deeper with increased axle load when the ground pressure was standardized to 100 kPa. In contrast, an increase in ground pressure with equal axle load mainly results in topsoil compaction (figure 2.6b) (Håkansson, 2005).

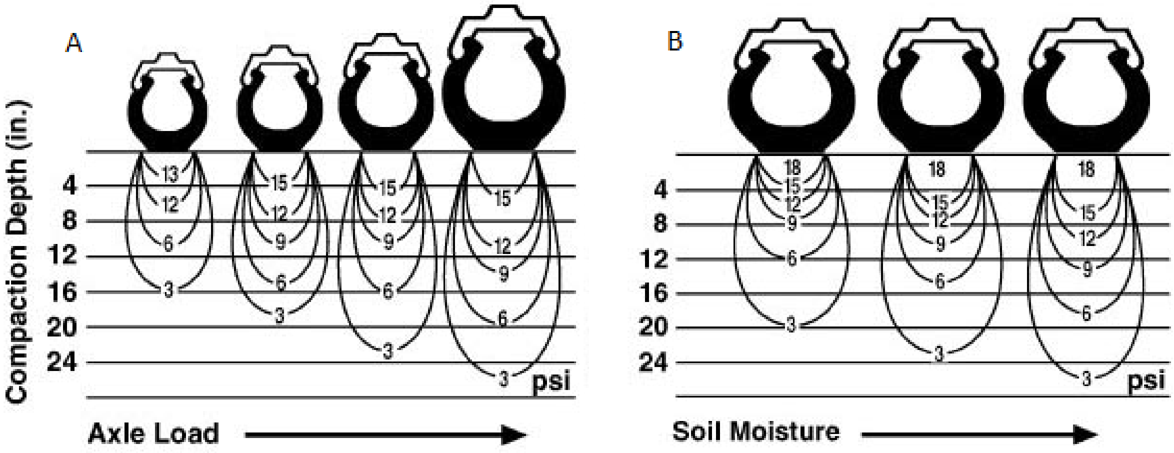

Figure 2.4. *Effect of axle load (A) and soil moisture (B) on compaction depth (University of Minnesota, 2001). Note that the scale is in inch; 24 inch is about 61 cm.*

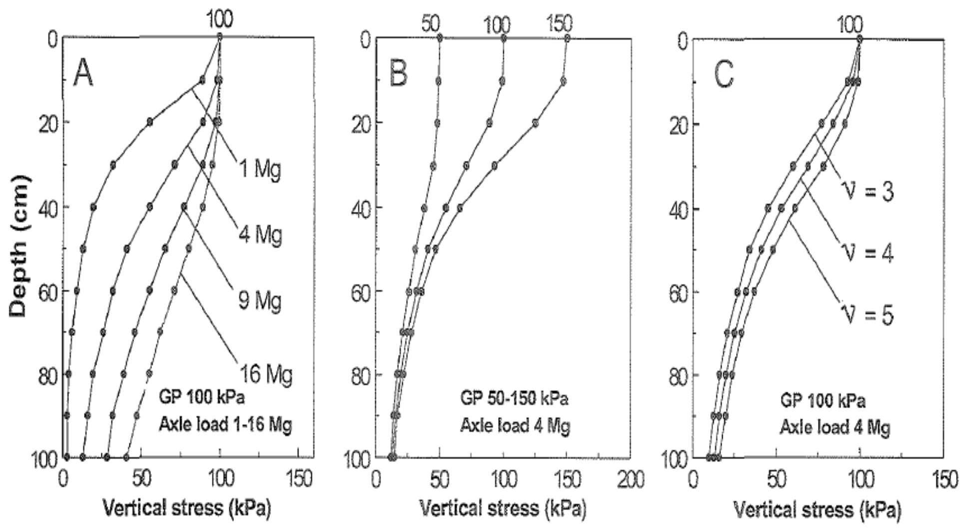

Figure 2.5. *Vertical stress illustrated in the soil profile A) Effect of different axle loads with equal ground pressure. B) Effect of different ground pressures with equal axle load (Håkansson, 2005).*

2.2. Physical soil properties affected by soil compaction

2.3.1. Topsoil, subsoil, and the effect of tillage

From figures 2.4 and 2.5 it is clear that the top 20 to 30 cm of the soil is affected most severely by compaction. This is commonly called the topsoil, often used analogous to the plough layer. The layer between topsoil and subsoil is called the plough pan layer, which is often formed by tractors driving on subsoil during ploughing (Van den Akker, 2006). Subsoil compaction occurs when the soil is compacted below 30 cm.

Machines can compact the soil to a depth of 60 cm (see figure 2.5) or even 90 cm (Voorhees *et al.,* 1986) depending on axle load, tire size and tire pressure. As topsoil is often annually loosened by ploughing it is relatively easy to remedy. Subsoil compaction can be alleviated up to 75 cm depth, but these methods (deep plough of deep spading machine) are expensive and not commonly practised in agriculture (Batey, 2009). In addition, Botta *et al.* (2006) reported that re-compaction may already occur 2 years after loosening the subsoil with deep tillage. As the subsoil is not annually loosened, subsoil compaction is an ongoing cumulative process eventually leading to homogeneously compacted subsoil (Van den Akker, 2006).

Subsoil is mostly compacted due to heavy machines with high wheel or axle loads (see figures 5.4 and 5.5). The soil shows an elasto-plastic response to the stress of soil compaction. This means that the soil can return to its original state up to a certain point. However, when the stress of compaction is increased and repeats in a certain frequency, further damage to the soil becomes more or less permanent (Gallipoli *et al.,* 2003). Studies have shown that deep subsoil compaction can last 11 years (Voorhees *et al.,*1986) or even 14 years or longer with severe compaction (Berisso *et al.,*2012) when the soil is left to recover on its own. Important subsoil functions are negatively affected by compaction, such as a) the provision of water in dry periods, b) retrieving leached nutrients from the topsoil and c) to form new channels to transport water to deeper soil layers (Van den Akker, 2006).

2.2.2. Change in soil structure in relation to other soil physical properties

Soil structure is related to the bulk density and soil porosity. Soil structure is the one of the most important soil physical characteristic for all aspects of soil use and management due to its great impact on other soil physical properties. Reduced aeration (related to reduced soil porosity) and increased soil strength are other physical consequences of soil compaction. As these factors strongly affect soil life they will be discussed in 'Biological consequences'.

2.2.2.1 Bulk density

Soil compaction increases the bulk density, which is defined as "the ratio of the mass to the bulk or macroscopic volume of soil particles plus pore spaces in a sample" (Blake, 1965). It is often used as a measure for soil structure and expressed in $g{\cdot}cm^{-3}$. Figure 2.6 shows the bulk density value above which root growth and function will likely be impaired for different soil textures, also called the critical bulk density. From the figure it can be seen that the critical bulk density is lowest for clayey soils and highest for sandy soils. However, this soil textural classification is only approximate as other factors like particle shape and organic matter content are disregarded (see previous section) (Håkansson, 2005).

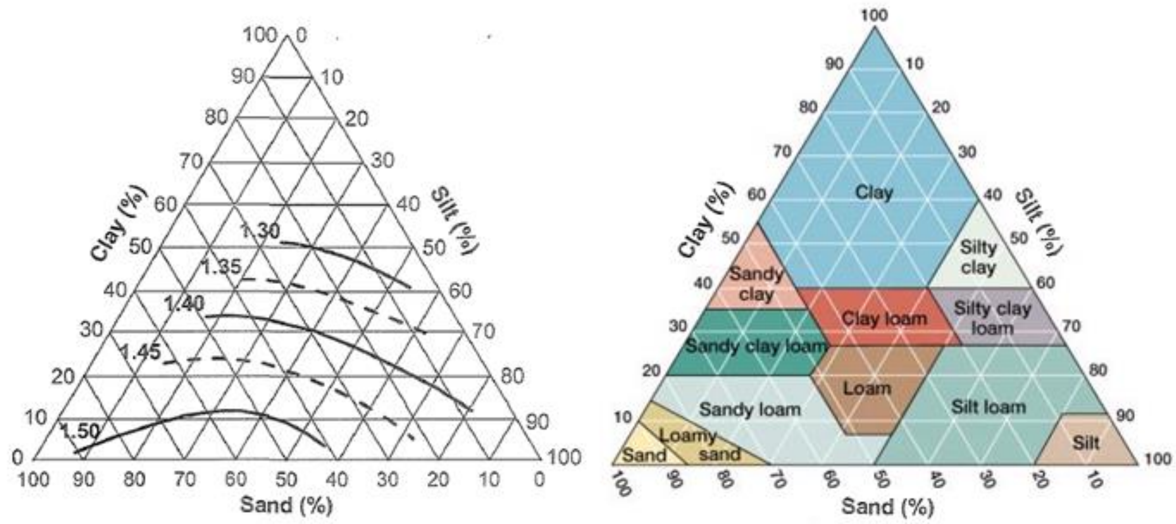

Figure 2.6. *Soil textures and critical bulk density. The left illustration shows the critical bulk density above which root growth and function may be significantly impaired. The values shown here are based on soils with low organic matter content in eastern Germany; the critical bulk densities will be lower in soils higher organic matter content. The right illustration shows the classification of soil textures as a reference (Håkansson, 2005).*

5.2.2.2 Soil porosity

Soil porosity is expressed as the empty space between the soil particles, which decreases with soil compaction. It is related to the bulk density and generally increases with particle size. Reliable measures for a change in soil porosity are the change in the amount of macropores and the decrease in hydraulic conductivity (Schäffer *et al.,* 2007). Soil compaction reduces the amount of macropores in the soil and the connectivity between them (Nawaz *et al.,* 2013). The collapse of macropores depends on the texture of the soil; in finer texture soils mechanical stress results in collapse while macro-pores in coarser soils for the most part remain intact. When a decrease in porosity decreases the hydraulic conductivity, finer textured soils are more prone to a strong reduction in infiltration capacity with compaction (Schäffer *et al.,* 2007).

2.3. Chemical effects

2.3.1. Reductive conditions

Stagnation of water above the compacted layer can be a result of soil compaction. Water stagnation causes more lateral seepage of agrochemicals (pesticides, herbicides), decreased soil buffer of residues/pollutants, increased risk of erosion (particularly phosphorus), an increase in N_2O emissions through denitrification, and an increased risk of flooding (Jones *et al.,* 2003; Batey, 2009). Stagnation of water leads to anaerobic conditions which affects soil life dependent on oxygen (Van den Akker, 2006). Furthermore, an increase in reduced iron forms, increased dissolution of iron hydrates, and an increase in organically complexed iron forms will be a consequence of these anaerobic conditions (Nawaz *et al.,* (2013).

In regions with salt soil water (e.g. Zeeland), the fresh water from rainfall cannot infiltrate into soil to 'wash' the soil is the soil is compacted. This may lead to an increased risk to salinization of the soil. The soil also will have a lower water holding capacity due to compaction.

2.3.2. Carbon and nitrogen cycle

Soil compaction results in reduced water and air permeability, which can cause anaerobic conditions (Berisso *et al.,* 2012). The accumulation of toxic substances and an increase in denitrification is a consequence of reduced oxygen exchange between the atmosphere and the soil. Denitrification leads to increasing or decreasing N_2O emission depending on the residence time, soil conditions, and rainfall. Generally, N_2O emissions increase with soil compaction as the N_2O formation in root environment is enhanced (Horna *et al.,* 1995). Bessou *et al.,* (2010) report an increase in N_2O emissions from 40% up to 50% but decreases CO_2 emissions in compacted soil relative to uncompacted soil.

2.4. Biological consequences

As all life in the soil is affected by compaction to a greater or lesser extent, it can be assumed that all biological processes are affected as well (Håkansson, 2005). In this paragraph however, only the effects of soil compaction on plants and soil fauna are discussed. This will explain most crop yield losses observed with heavy compaction.

2.4.1. Plants

Negative effects of severe soil compaction include restricted root growth, decreased availability of water and nutrients, and an increase in nutrient losses due to leaching, runoff, and gas exchange between soil and atmosphere. Restricted root growth, decreased water and nutrient uptake and reduced aeration will be discussed. Other soil properties of soil degradation amplify the effect of soil compaction on plants. Degradation of salinity was shown to double the effects of soil compaction on plant growth and crop yield (Saqib *et al.,* 2004).

2.4.1.1. Restricted root growth

Restricted root growth is caused by the increase in soil strength, or the penetration resistance, and is related to the soil bulk density. Figure 2.7 depicts the vertical distribution of root biomass in the soil in a non-compacted situation and a compacted situation. It shows that roots on compacted soils are unable to penetrate deeper soil layers, instead focussing more in the topsoil as compared to the non-compacted situation. The penetration resistance at which the relative root growth start to decline depends on the crops and the amount of macropores in the soil. The root growth of crops with soft roots or crops grown on soils with few macropores start declining at 1 MPa, whereas it is 1,5 Mpa for crops with stiff roots or crops grown on soil with a high amount of continuous macropores. Based on these traits plants are unable to grow roots at a penetration resistance of 3 to 4 MPa (Håkansson, 2005). These values also differ for different oil textures. Bengough and Mullins (1991) found that the root elongation rate of

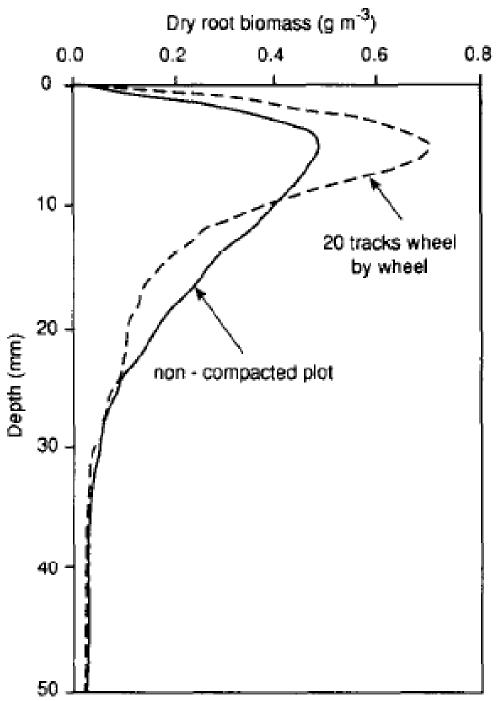

Figure 2.7. *Vertical distribution of dry root biomass of maize in the soil when initially ploughed to a depth of 38 cm. The compacted line is derived from a plot in which a tractor with 179 kPa ground pressure (front wheels) was driven 20 times with high soil water content (Whalley et al.,1995).*

maize was reduced to about 50% to 60% in response to a resistance of 0.26 to 0.47 MPa on sandy loam soils.

Shoot growth may slow down via the direct effect of reduced water and nutrient uptake (because of shorter roots or slowed down uptake). However, hormonal signals from the root induced by a high penetration resistance can also slow the growth of the shoot regardless of water and nutrient uptake (Passioura, 1963). The emergence of seeds in compacted soils, depending on the type of crop, may be significantly reduced because of the increased resistance (Hebblethwaite & McGowan, 1980). Lastly, stress caused by soil compaction (too wet or dry conditions in the soil) can make plants more vulnerable to soil-borne pathogens (Allmaras *et al.,* 1988).

2.4.1.2. Decreased water and nutrient uptake

Soil compaction affects the uptake of water in two ways. Firstly, due to shorter root depths, plants are unable to access water in deeper layers of the soil in dry periods. Secondly, the capacity of the soil to store or hold water diminishes with reduced water infiltration (Unger & Kaspar, 1994).

With heavy soil compaction the uptake of nutrients is reduced due to less dense rooting systems, with fewer roots in the deeper layer (see figure 2.7). Furthermore, the availability of nutrients to plants is diminished as soil compaction also affects transportation of nutrients directly. Nutrients that are taken up by means of diffusion are more affected by soil compaction than nutrients taken by via mass flow, attributed to the dependence of diffusion on functioning roots. Especially nitrogen and phosphorus will become more limited in compacted soils as these nutrients are mainly transported by diffusion (Arvidsson, 1999). Additional nitrogen losses result from decreased mineralization and increased denitrification due to anoxic conditions (see 'Chemical effects'). Nutrient transport by mass flow is also affected as the permeability of water decreases so uptake of dissolved nutrients is diminished (Arvidsson, 1999). Farmers overcome the lower availability and plant uptake of nitrogen with higher application rates of nitrogen which has negative consequences for the environment (Lipiec & Stepniewski, 1995; Soane & Van Ouwerkerk, 1994).

Reduction in nutrient uptake due to subsoil compaction is 12% to 35% for N, 17% to 27% for P and up to 24% for K in wheat. The reduction in nutrient uptake in sorghum due to subsoil compaction was 23% for N, 16% for P, and 12% for K (Ishaq *et al.,* 2001).

2.4.1.3. Reduced aeration

When aeration (often expressed in the oxygen diffusion rate) in the soil is too low, roots growth is impaired. This threshold is called the critical oxygen diffusion rate, and differs between plant species and the growth state of the plant. Values for the critical oxygen diffusion rate range between 25.10^{-8} g cm^{-2} min^{-1} (corn, first five weeks) and 70.10^{-8} g cm^{-2} min^{-1} (peas, entire grow season). The critical index of aeration is 20.10^{-8} g cm^{-2} min^{-1}, below which roots are unable to grow (Letey, 1958). When parts of the soil with roots become anaerobic, root cells can survive for at least several hours, depending on the plant species. However, after prolonged anoxic conditions the roots will likely die off, reducing crop yield (Drew, 1992). Other effects of poor aeration include the accumulation of carbon dioxide and other substances in the. These substances may also cause root death or interfere with other biological processes (Unger & Kaspar, 1994).

2.4.2. Soil fauna

One of the most important organisms affected by soil compaction is earthworms, and is well-studied. Results generally show a strong reduction in the amount of earthworms after compaction, especially in heavy clay soils (Blanchart *et al.,* 1999), even in normal tractor traffic compared to no compaction. The wheels likely injure the earthworm tunnels and kill the earthworms (Whalley, 1995). The resulting compaction can also partly destroy the burrow system and severe compaction hinders the formation of new burrow because the soil cannot be pushed aside anymore.

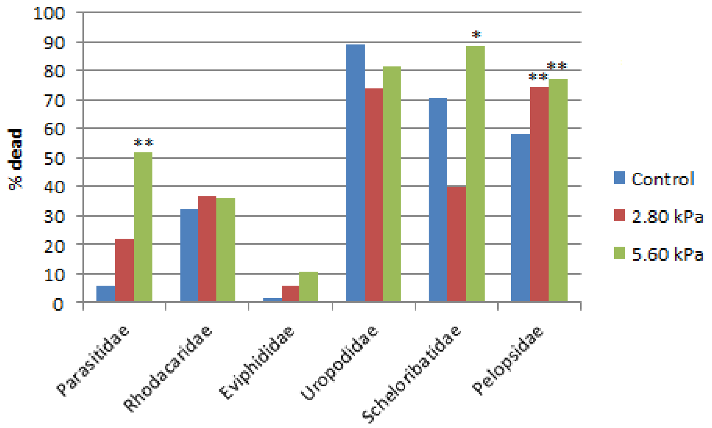

Figure 2.8. *Effects of laboratory compacted soil on soil fauna (*P = 0,05; **P = 0,01; others not significant). Data from (Whalley et al.,1995)*

Other fauna is also affected, of which an overview is provided in figure 2.8. *Enchytraeidae* is reported to have a reduced abundance after both conventional and conservation tillage after trafficking. *Collembola* (springtails) species abundance is also reported to decrease in response to an increased bulk density relevant to compactness values in the field. As these animals are unable to make their own burrows, the decrease in abundance is expected to be due to a decrease in pore space. Görres *et al.* (1997) reported that nematode activity remained constant even though the bulk density of the soil increased so much that it caused a decrease in root elongation in barley. Bouwman and Arts (2000) reported that the total number of nematodes did not change in response to different traffic treatments, but a shift in the type of nematode was observed. The number of beneficial nematodes (bacterivores and omnivores) decreased while the number of (plant-parasitic) herbivorous nematodes increased, which may be related to the poorer performance of the soil when compacted. However, poor root penetration was the main cause for the poor crop grass yield at high compaction levels.

2.4.3. Optimum in relative crop yields

The effect of soil compaction is often reported to be negative, but no effect and positive effects are also observed, depending on the level of soil compaction (see figure 2.9). An optimum in the degree of compactness is often observed, although the optimum of degree of compactness differs greatly between different crops (see figure 2.10a,b,c,d and figure 2.11a,b,c). Positive effects of slight soil compaction are often explained by an increase in contact between the roots and the soil particles which leads to a more rapid exchange of ions (Nawaz *et al.,* 2013). Arvidsson (1999) confirmed this, partly owing the increase in crop yield of barley due to increased nutrient

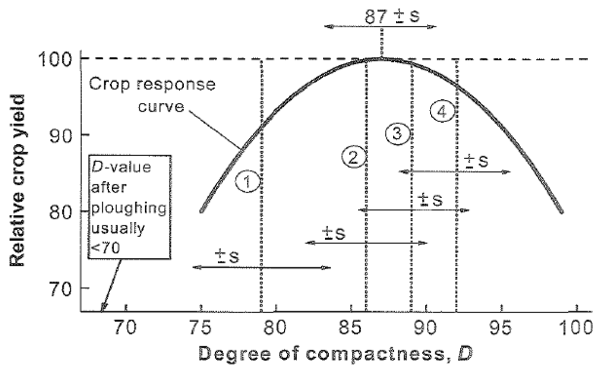

Figure 2.9. *General crop response curve to the degree of compactness in the topsoil. Values are given for spring barley (Håkansson, 2005).*

uptake in the recompaction of loose soil. Another explanation of a lower relative yield in uncompacted soils compared to moderately compacted soils is the variation in factors other than physical factors. Figure 2.9 shows that in this case a moderate degree of compactness provides the optimum relative crop yield, here indicated as 1 pass of a 2 to 3 tons vehicle with an inflation pressure ranging from 70 to 140 kPa.

Another method to assess the sensitivity of crops to soil compaction is by comparing yield responses of crops to reduced tillage. Reduced tillage (no tillage or shallow tillage) is generally assumed to increase compaction as ploughing is no longer used to loosen the topsoil (Arvidsson & Håkansson, 2014). A comparison like this was done by Arvidsson *et al.* (2014) in Sweden. They found that compaction in reduced tillage did not result in severe reduction of yield for cereals (wheat, barley, oats) whereas dicots (sugar beet, rape, peas) were more sensitive to compaction. These results coincide with results using the degree of compactness; sugar beet and rapes suffer more severe yield losses due to topsoil compaction than wheat and barley.

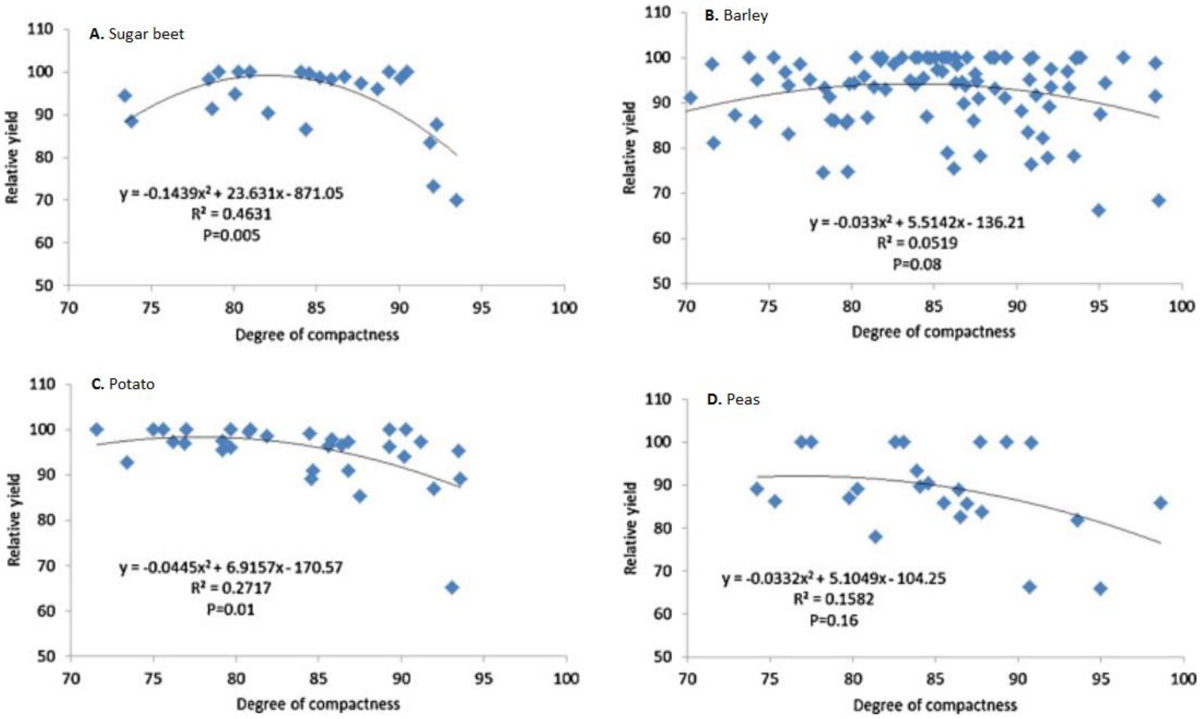

Figure 2.10. *The relative yield of sugar beet (A), barley (B), potato (C), and peas (D) as function of soil compactness. The treatment with the highest yield was set to the relative yield of 100% (Arvidsson & Håkansson, 2014).*

The differences in the response of crops to compaction are largely caused by the inherent root length density of the species. If the inherent root density of a species is already low, reduction to root system has more severe effects. This explains why for example sugar beet is more susceptible than barley due to higher potential transpiration rates (Brereton *et al.,* 1986). Other plant traits, like the root diameter and root respiration, also affect the species' sensitivity to soil compaction. Materechera *et al.,* (1992) found that the diameter of root tips in compacted soils were larger, mostly because thicker roots are better able to penetrate a soil with a high penetration resistance. Plant species that are able to respond to soil compaction by increasing root diameter are likely more resistant to soil compaction than species that respond less. Similarly, different plant species differ in the ability to respond to stress by oxygen deficiency (hypoxia) (Drew, (1997). Less is known of the effect of subsoil compaction on crop yield responses, except that the cumulative effects of subsoil compaction in can severely reduce crop yields (Gaultney *et al.,* 1982)

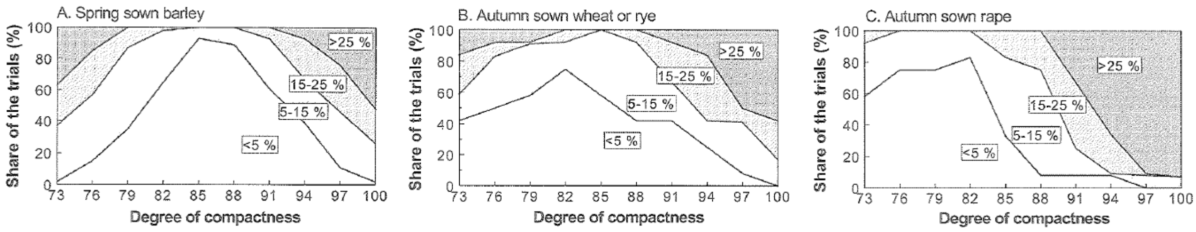

Figure 2.11. *Relative yield decrease of barley (A), wheat or rye (B) and rape (C) in response to the degree of compactness, expressed in percentage of trials. Results derived from Swedish one year experiments (Håkansson, 2005).*

2.5. Effect of Lasting Fields compared with conventional farming

2.5.1. Controlled traffic farming

To reduce soil compaction, Controlled Traffic Farming (CTF) was introduced in USA around 1950. It is a fixed path system in which the equipment of machines is adapted to reduce contact area of heavy machines with the soil (see figure 2.12). CFT results in paths that are more frequently used, resulting in more compacted paths, but leaves the soil in between uncompacted (Vermeulen *et al.,* 2010).

CTF is frequently found to have advantages over conventional farming by maintaining all aspects of good soil structure (Chamen, 2011). In the 1980s it was already realized that controlled traffic farming could increase yields (Perdok *et al.,* 1985), however at the time the lane system had poor economic potential for arable farming. A study in England showed that machinery investment could be decreased (up to 20%) and gross margin increased (up to 17%), because of reduced soil compaction (Chamen, 2011). Even after only 12 months improvements in soil structure can be observed (Chamen, 2006). As CTF is shown to restore soil structure (physical factors), it is expected that subsequently the chemical and biological factors are significantly reduced.

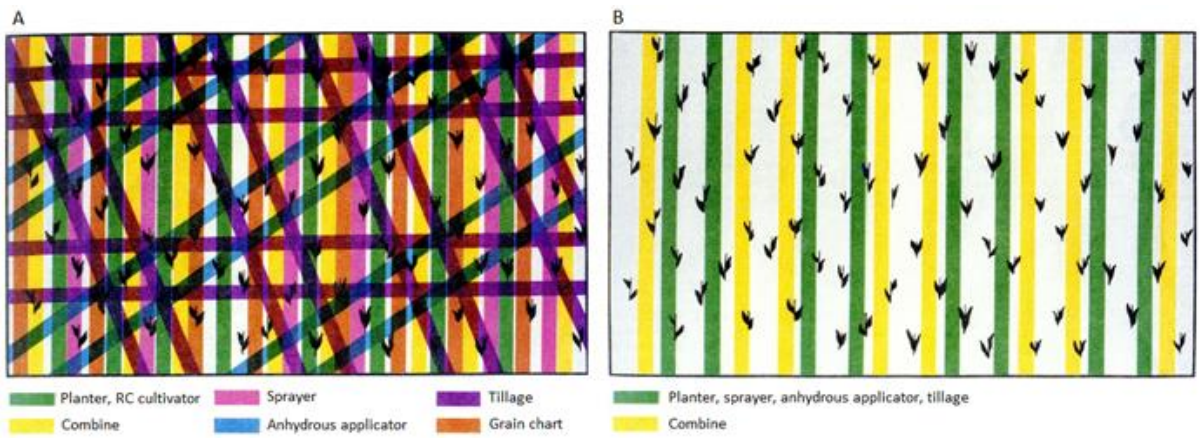

Figure 2.12. *Amount of area compacted by machines in A) a conventional system and B) Controlled Traffic Farming system (Jones et al., 1999).*

2.5.2. Lightweight machines

Based on figure 2.9, 2.10 and 2.11 it can be concluded that an optimum in soil compactness in relation to relative yield can be reached. From these figures the estimated potential yield increase due to soil compaction ranges from 0 to 20%, depending on the initial state of the soil and the type of crop. It is difficult to extrapolate this data to the situation in Lasting Fields as lightweight machines described in the literature are much heavier than the machines Lasting Fields will use. Lasting Fields will have smaller and lightweight machinery, which means that both the pressure on the soil and the depth of the pressure declines compared to conventional machines. Machines in conventional agriculture are likely to cause subsoil compaction, especially with high axle (or wheel) loads.

2.5.3. Increased wheeling frequency

We expect that the wheeling frequency increases for Lasting Fields compared to conventional farming. Based on figure 2.3a the wheeling frequency can increase soil compaction from 15% to 26%. These percentages were calculated by comparing the degree of compactness at a wheeling frequency of 0 to the degree of compactness at a wheeling frequency of 9. However, it is not known how lighter machinery might influence the impact of increased wheeling frequency.

2.5.4. Net effect of Lasting Fields compared to conventional farming

The machines of Lasting Fields are expected to especially decrease subsoil compaction, which is likely to increase yields. Note that the degree of compactness only takes the topsoil compaction into account. It is important that these machines will be light, as high axle loads are the main contributor in subsoil compaction and soil compaction also increases with the wheeling frequency. However, even if soil compaction occurs, controlled traffic farming will ensure that it is contained to the fixed paths. From figure 2.4 it can be seen that after 3 or 4 passes the soil compaction due to wheeling frequency stagnates.

2.6. Concluding summary

Soil compaction is a form of physical degradation in which particularly the soil structure is affected. Bulk density of the soil increases with compaction, while soil porosity, aeration, and hydraulic conductivity decreases. Reduced aeration leads to reductive conditions in the soil and affects aerobic microbes and plant roots in a negative way, while anaerobe microbes are stimulated, leading to denitrification. Nitrous oxide will diffuse to the atmosphere, increasing the need of fertilizer, while carbon dioxide emissions will decrease. Plant roots are negatively affected by severe soil compaction due to increased soil strength as roots will have difficulty penetrating the soil, reducing water and nutrient uptake. Furthermore, stress can make plants more vulnerable to soil-borne pathogens and hormonal signals from the roots of the plant to the shoot may decrease growth. Current conventional agricultural machines are often heavy enough to cause severe compaction. Tillage reduces the effect of compaction in the topsoil, but not in the subsoil. Particularly high axle loads and soil moisture cause compaction to penetrate deeper, causing subsoil compaction. Particularly the yields of root crops are negatively affected by soil compaction, like sugar beet and potato. Based on the degree of compactness (a relative measure of the bulk density) it is estimated that crop yield can be increased up to 20% due to the lightweight machines and controlled traffic farming in Lasting Fields.

3. Opportunities for intercropping and other cultivation systems

Lasting Fields offers the opportunity to deal with the mechanization difficulties of intercropping conventional machines are struggling with. Therefore, it was decided that the advantages of intercropping over sole cropping would be discussed more elaborately than other farming systems. The principles of intercropping (how the two or more crops interact with each other), the advantages, bottlenecks, and feasible crop combinations will be described. Finally, a calculation for the economic potential is explained to provide insights of the potential of intercropping in relation to Lasting Fields for future research.

3.1. Definition and description of intercropping

Intercropping is mainly practised by small scale self-sufficient farmers in Africa, India, and China (Knörzer *et al.,* 2009). Often these farmers have no access to markets for selling products and cannot buy inputs such as fertilizers, crop protection agents and farming machines. These farmers have to search for alternative cultivation systems such as intercropping to maintain a good yield and food quality with the use of fewer inputs (Lithourgidis *et al.,* 2011).

In Europe and North America intercropping has rarely been practised over the past 50 years due to the market oriented economy, increasing scale of farms, access to fertilizer and crop protection agents, and the mechanization of agriculture. Furthermore, agricultural research was mainly focused on sole cropping (mono-cropping) while the potential of intercropping was ignored (Lithourgidis *et al.,* 2011), as the technology at the time mechanization started was not equipped with dealing with intercropping. Mechanization is the biggest bottleneck for applying intercropping on large scale farming (Lithourgidis *et al.,* 2011). The development of agricultural machines allows farmers to increase productivity in sole cropped cultivated fields. With the current agricultural machines intercropping is not feasible, but with the small scale and autonomous machines of the Lasting Fields concept it could be made possible again. Intercropping has several advantages compared to sole cropping, which will be explained later on.

Intercropping refers to the situation where two or more crops are grown simultaneously on the same field (Li *et al.,* 2013). More efficient utilisation of resources and reduced pest (insect-pest, disease) pressure are advantages of intercropping that are generally reported. There are different methods of intercropping (see figure 3.1 3.2 and 3.3). Sequential intercropping refers to a situation in which the crops are grown on the same field in one year, but not together at the same time. In relay intercropping first one crop is grown and after a certain delay a second crop is grown, with partially overlapping growing periods. In full intercropping one or more crops are grown at the same time. Intercropping can also vary on a spatial scale. Mixed intercropping means that the crops are totally mixed (often randomly), so the crops are mixed between and within the rows as indicated in figure 3.1. In row intercropping two or more different crops are cultivated in separate rows which alternate (figure 3.3). Strip intercropping means that a stroke of several rows of a crop alternates with a stroke of several rows of another crop (figure 3.2). Strip intercropping would be most suited as it is easier to harvest for machines, but as it is not entirely mixed some of the advantages are lost.

A	B	A	B	A	B
B	A	B	A	B	A
A	B	A	B	A	B
B	A	B	A	B	A
A	B	A	B	A	B
B	A	B	A	B	A

***Figure 3.1.** Mixed intercropping*

A	B	A	B	A	B
A	B	A	B	A	B
A	B	A	B	A	B
A	B	A	B	A	B
A	B	A	B	A	B
A	B	A	B	A	B

***Figure 3.2.** Strip intercropping*

A	A	A	B	B	B
A	A	A	B	B	B
A	A	A	B	B	B
A	A	A	B	B	B
A	A	A	B	B	B
A	A	A	B	B	B

***Figure 3.3.** Row intercropping*

3.2. Advantages and disadvantages of intercropping

There are two mechanisms at work in intercropping that explain the difference in crop yields, facilitation and competition (Vandermeer, 1989). The mutual interaction between crop and environment is important for this concept. The first crop has an effect on the environment which has consequences for the second crop and vice versa.

3.2.1. Facilitation

When the crop influences the environment for the other crop in a positive way, the interaction is called facilitative. Facilitative interactions occur, for example, when a crop provides shelter for the natural enemies of the pest of the second crop, or repels the pest directly. For example, intercropping clover with another crop often reduces the amount of harmful insects (Trenbath, 1993). The mechanism behind it is not clear. However, it is proposed that the presence of clover might mask the odour of the crop or attracts predatory insects. Another explanation is that this intercropping combination simply alters the contrast of green (crop) and black (soil) to only green, so the insect has more difficulty finding its host plant (the crop). Sometimes the space between plants of the same crop can form a barrier for diseases. For example, the alternation of susceptible rice (indicated with S in figure 3.4) with resistant hybrid rice (R) in China reduces crop loss due to blast. The explanation given is that the leaves of the susceptible variant dries up more rapidly because it is more exposed to the wind compared to mono-cropping, as the

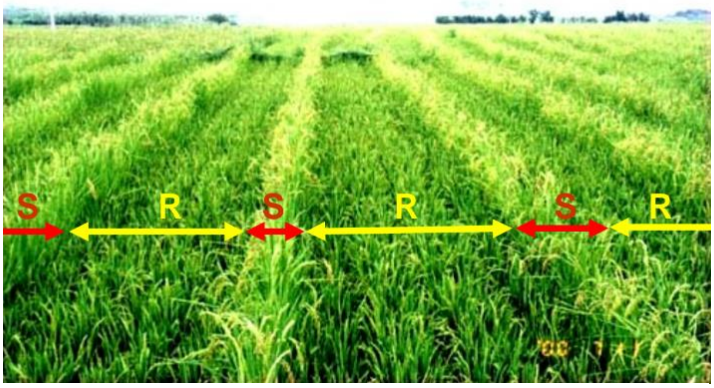

***Figure 3.4.** Alternation of susceptible rice (S) and resistant hybrid rice (R) in China (Bastiaans, 2014).*

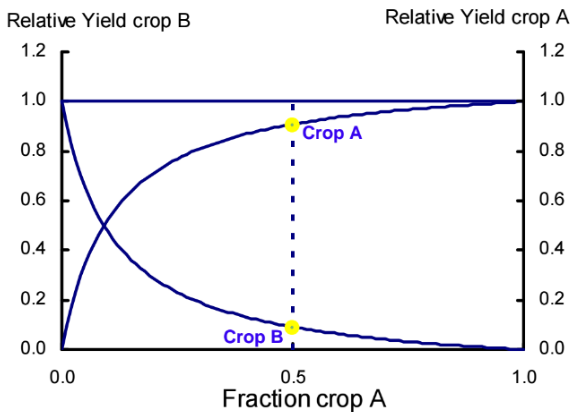

***Figure 3.5.** Replacement diagram illustrating the facilitative effect (crop B) on the yield of the main crop (crop A). The goal is to minimize competitive effect of the second crop on the main crop while maintaining the facilitation function (Bastiaans, 2014).*

resistant hybrid variant is shorter than the susceptible variant in the stage rice is susceptible to blast (Revilla-Molina *et al.,*2009). The success of this intercropping system is evident in the increase in farmers and area of land cultivating it (Revilla *et al.,* 2001).

Another example of facilitation is combining crops that are able to form a symbiosis with nitrogen fixating bacteria in root nodules with the main crop. The fixed nitrogen can be transferred to another plant from these root nodules or from decomposing crop residues, especially if the main crops have a deeper root system (Li *et al.,* 2013). Furthermore, most crops are able to interact with mycorrhiza yeast in the soil. Crops that are unable to, however, might benefit from being intercropped with a crop that can, which releases otherwise immobile nutrients and minerals like phosphorus. Citrate and malate excretions from faba bean could release phosphate that can be taken up by plants from calcium carbonate rich soils (Li *et al.,* 2013). Figure 3.5 shows the facilitative effect.

3.2.2. Competition

Competition between the crops in an intercropping system can decrease yields. Competition occurs when a crop has a negative environmental effect on the second crop. Generally a negative effect occurs due to similar utilization of resources (water, light, nutrients). However, some intercropping combinations result in an increase of damage due to pests and diseases. For example, increase of protein content within grains in a grain/bean intercropping makes the grain more favourable for pests and diseases such as rusts and aphids (Trenbath, 1993).

3.2.3. Resource use efficiency

Mechanisms behind yield increase/decrease are also based on the interspecific (between species) and intraspecific (within species) competition. In cases where the interspecific competition is lower than the intraspecific competition, intercropping will result into a yield advantage. In that case, the crops don’t experience a negative effect from the utilization of the same resources due to niche differentiation, leading to increased resource use efficiency (Lithourgidis *et al.,* 2011). This is explained further in the section below, in which aboveground and belowground components are distinguished (see figure 3.4.).

3.2.3.1. Above ground (light / heat and space)

Intercropping may have a better set up of crop canopies, more light will be absorbed by multiple crops than a sole crop. The component crops may also differ in peak growth periods, during these periods light is used most efficiently (Sharma & Banik, 2015). The period of soil cover may also be elongated, because the growing seasons of the component crops may partly overlap.

3.2.3.2. Belowground (water / nutrients)

Water could be better conserved into soil due to a better soil cover by crop canopy. During drought periods, the water will mainly leave the soil by transpiration by plants (photosynthesis) instead of evaporation (from bare soil).

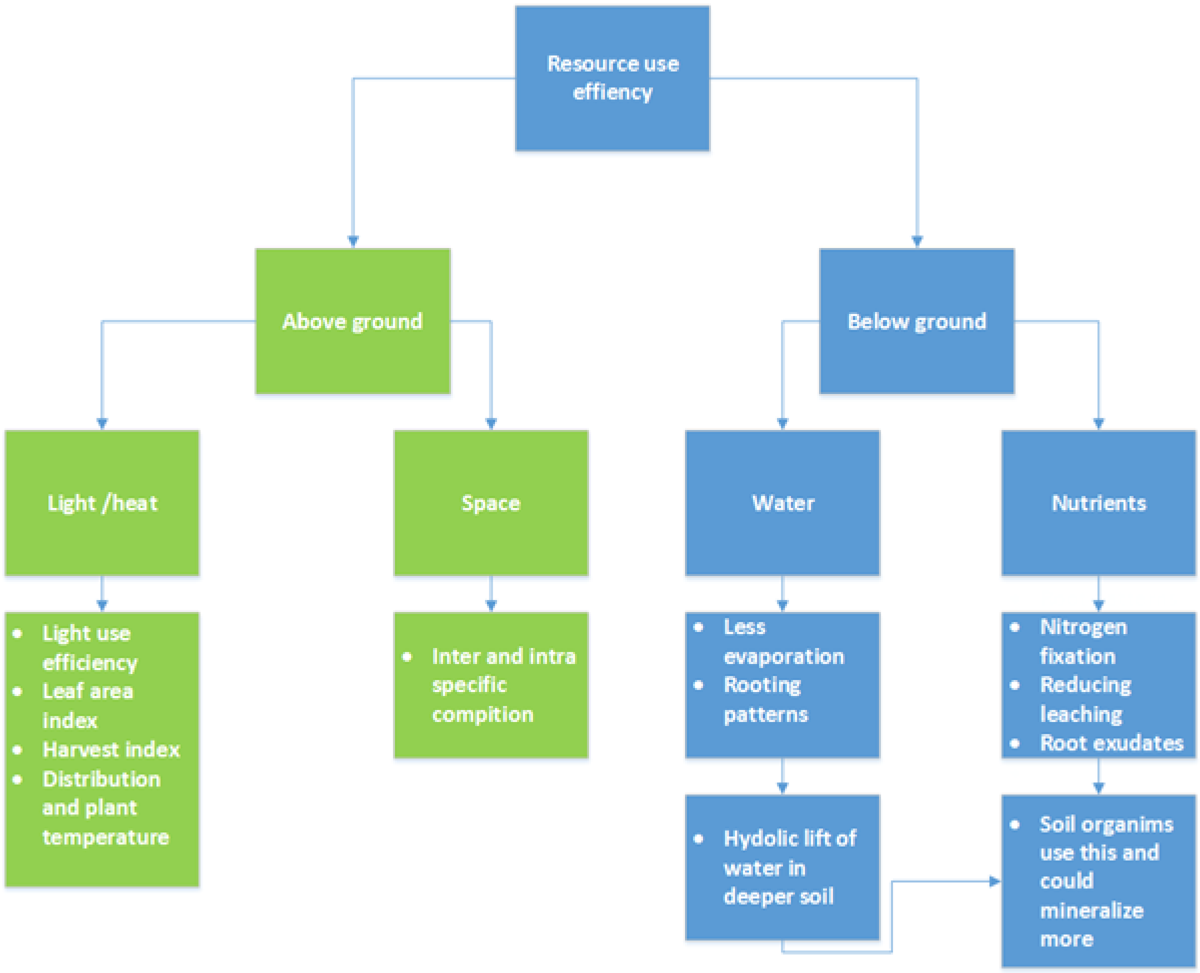

Figure 3.6. *Scheme of the beneficial effects of increased resource use efficiency on aboveground and below ground components*

Different crops may have different rooting patterns and different rooting depths. Water from deeper soil layers could also be utilized for photosynthesis. During drought periods soil organisms in higher soil layers could benefit with roots. The deep rooting plants could provide water to the soil organisms which contribute to mineralisation of soil organic matter. Nutrients could be caught better due to a better and deeper rooting pattern with intercropping. Nutrients in deeper soil layers could be caught and immobile nutrients better utilized. For example in a study of Li et al. (2013) it was considered that leaching decreases with an intercropping system with grains and leguminous crops. It was found that nitrogen leaching tends to be lower in a peas/barley system than by sole cropping of peas. It is considered that leaching from N fixing plants (peas) could be caught by deeper rooting non N fixing plants (barley).

3.2.4. Options to minimize competitive effect of the second crop

Cover crops or cash crops are often used as second crop. These crops modify the environment in such a way that the relative yield (see next section) is higher compared to mono-cropping, for example by covering the ground so that harmful weeds are unable to establish. A cash crop provides some of the facilitative function of cover crops, but has a financial yield as well. The choices include:

- *Time of introduction of the second crop.* When the cover crop is introduced before the main crop, the main crop benefits from weed suppression and allelochemical and/or physical impediment of germination and early growth of seeds/plants. When the cover or cash crop is introduced later than the main crop, the main crop is established better and has a better competitive position.
- *Measures to reduce the competitive ability.* When the cover crop is mown or roots are vertically cut, its competitive effect will decrease.
- *Species selection*. Ideal second crops are species that smothers weeds, develop a canopy quickly, but do not compete with the main crop too much. These species often have a shallow root system and remain low to the ground.

When competition is minimized (see figure 3.7B compared to 3.7A), intercropping can increase the relative yield total, or land equivalent ratio, explained in the next section.

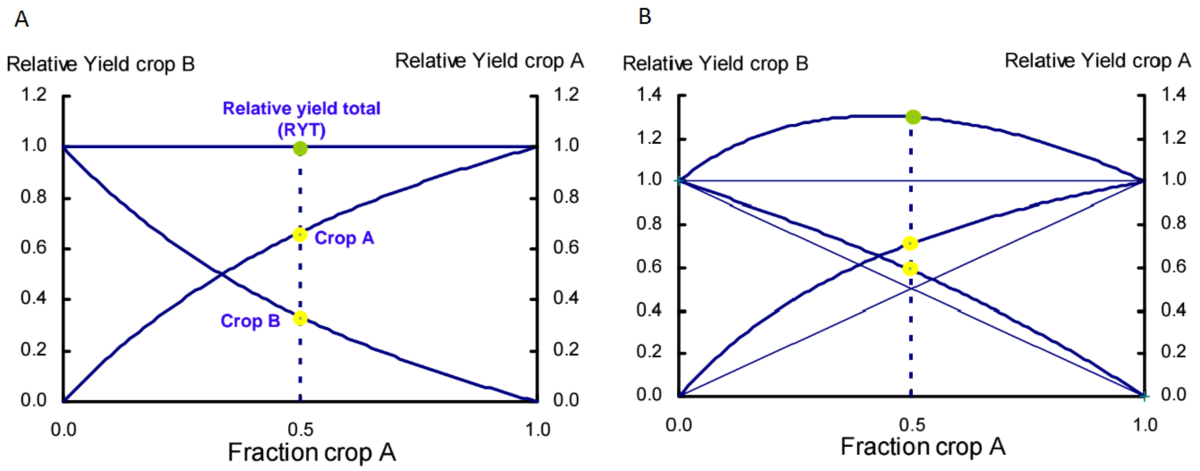

Figure 3.7. *Replacement diagrams illustrating the relative yield total (RYT) in two competition situations. A) intercropping situation with crops sharing the same niche, in which crop A is more competitive than crop B. B) intercropping situation with niche differentiation, leading to a higher yield compared with mono-cropping crop A and B (Bastiaans, 2014).*

3.2.5. Other advantages of intercropping

The environmental advantage intercropping offers over sole cropping often varies with the intercropping system and the crops used. However, intercropping is accompanied by an increase in biodiversity, because plants are the core of the food web and the amount of interactions in the food web will thus be increased.

Leaching can be decreased in intercropping systems, especially in a grains and a leguminous species combination. For example, nitrogen leaching tends to be lower in a peas/barley system than by sole mono-cropping of peas. It is considered that nutrients leaching from N fixing plants (e.g. peas) could be caught by deeper rooting of non N fixing plants (e.g. barley) (Li *et al.,* 2013). This will also lead to a decreased need of artificial fertilizer, leading to a decrease in eutrophication.

3.3. Calculating the change in crop yield and financial yield

A yield advantage is mainly expressed in land equivalent ratio (LER), which indicates the resource use, or the relative yield total (RYT), indicating biomass production. Li *et al.* (2013) define LER as follows: 'LER indicates the area needed under sole cropping to produce the same amount of crops as produced in 1 ha of intercropping or mixed cropping' (equation 3.1). The equation is the same for RYT but is expressed in area.

$$LER = \frac{intercropping\ yield\ crop\ a}{monocropping\ yield\ crop\ a} + \frac{intercropping\ yield\ crop\ b}{monocropping\ yield\ crop\ b} \qquad (3.1)$$

When LER or RYT is larger than 1, the net yield of intercropping is usually larger than the net yield of mono-cropping. However, it is important to note that LER does not calculate the economic potential. It is possible that a LER bigger than 1 will not result in a financial yield and vice versa. For example, the yield of crop A is increased by intercropping with crop B, but crop B is more valuable than crop A. The additional financial yield is calculated by multiplying the additional crop yields with the market prices.

Lithourgidis *et al.* (2011) and Vandermeer (1989) mentioned that crop combinations must meet the following criteria to obtain a yield advantage with intercropping, here divided in biological criteria which translate in financial criteria.

Biological criteria:

1. Interspecific competition < intraspecific competition.
2. The crops do not compete for the same ecological niche (same resources).

Financial criteria:

1. LER should be > 1.0 (Vandermeer, 1989)
2. Relative yield total > 1.0 for financial yield (Vandermeer, 1989)
3. Replacement value of intercropping > 1.0 (Vandermeer, 1989)

3.3.1. Relative Value Total RVT (also known as income equivalent ratio IER) Ma1>bM2

$$RVT = \frac{al1+bl2}{aM1} \qquad (3.2)$$

Ma1>bM2, with *a* being the price of crop 1 and *b* being the price of crop 2. *I1* is the yield of crop 1 under intercropping, *I2* is the yield of crop 2 under intercropping and *M1* is the yield of crop 1 under mono-cropping. Financial yield advantage for intercropping occurs when RVT>1. If RVT < 1 mono-cropping has a financial yield advantage (Vandermeer, 1989).

3.3.2. Replacement value of intercropping

$$RVI = \frac{aP1+bP2}{aM1-c} \qquad (3.3)$$

Here, the price of crop 1 and b is the price of crop 2. I1 is the yield of crop 1 under intercropping, *I2* is the yield of crop 2 under intercropping, and *M1* is the yield of crop 1 under mono-cropping. *c* is the cost which is saved by applying intercropping (such as fertilizer or herbicide cost). Financial yield advantage for intercropping occurs when RVI>1 (Vandermeer, 1989).

3.3.1. Feasible crop combinations for the Netherlands

Especially grains with leguminous crops could have a perspective for intercropping in Europe. Table 3.1 indicates which crop combinations tested in temperate climates such as Europe and parts of the USA. In table 3.2 the potential reduction of pest and diseases due to intercropping combinations are listed. Although these numbers cannot be translated in potential economic benefits directly, it gives an indication of the extent of benefits facilitative intercropping can have.

Table 3.1. *Crop combinations already tested in trial fields Europe.*

Crop combination	Country	Effect
peas + barley	Denmark, UK, France, Italy, Germany, USA	Improved the plant resource utilization to grain N yield with 25–30% using the LER, irrespective of site and intercrop design (Hauggaard-Nielsen *et al.,* 2009).
peas + wheat	Denmark	Maximum LER of 1.34, but with increased fertilizer nitrogen supply LER decreased to as low as 0.85 (Ghaley *et al.,* 2005).
clover + barley	Greece	No advantage of intercropping compared to sole cropping (<1 LER) but did result in highest total protein yield (Vasilakoglou & Dhima, 2008).
Vetch + wheat or barley	Greece	Intercrop resulted in higher dry matter than common vetch sole crop, but greatest dry matter yields were obtained with wheat and barley sole crops. Vetch with barley provided higher forage quality (Lithourgidis *et al.,* 2007).
leek + celery	Switzerland	LER>1 indicating an improved resource use by the crop mixture. RYT ~1 so no yield advantages were found with regard to biomass production. Due to competition a reduction of the quality of both crops was found (Baumann *et al.,* 2001).
bean + maize	Spain	LER averages 1.12 for intercropping bean with field maize and 0.93 for intercropping with sweet maize, but greatest net income was realized when bush beans were intercropped with sweet maize (Santalla *et al.,* 2001).
strawberry + bean	Turkey	Highest LER with intercropping, especially when 80 kg/ha nitrogen was applied (>2 LER) (Karlidag & Yildirim, 2007).
Cauliflower + lettuce, or onions, or radish, or snap bean	Turkey	LER>1 in all intercropping systems. Both yield and profitability likely highest with intercropping (Yildirim & Guvenc, 2005).

Intercropping could also decrease the requirement of agricultural inputs such as fertilizer and crop protection agents. Table 3.2 shows an overview of potential reductions of weeds, pest and diseases when intercropping is applied. Based on the results which are presented in table 3.2, it can be indicated that most of the reductions will be between 10% and 30%.

Table 3.2. *Potential reduction of pest and diseases by applying intercropping.*

Crop combination	Pest/disease	% reduction	Source
maize + beans	rust	25-52	Lithourgidis *et al.,*
leek + celery	soil cover by weeds	41	Lithourgidis et al.
peas + flax	soil cover by weeds	52-63	Lithourgidis et al.
bean + maize	bacterial blight in beans	5-23	Lithourgidis et al.
potato + maize	potato late blight (phytophthora)	32-39	Li *et al.,*2013
tobacco + maize potato + maize sugarcane + maize wheat + faba bean	maize leaf blight	17-19	Li *et al.,*2013
bean + maize	rust in beans bacterial blight in beans	16-25 20-29	Fenisha & Yuan, 2001

3.3.2. Stabilization of financial income

Lithourgidis *et al.* (2011) mentioned that the risk of crop failure is strongly reduced by intercropping. This can be ascribed to the partial restoration of diversity in intercropping compared to mono-cropping, which provides an insurance against crop failure due to extreme weather conditions such as frost, flood, hail, drought, and pest attack. With a single crop the entire field will be damaged or even the entire yield will fail. With intercropping part of the crops may be damaged while other component crops still could be harvested or are already harvested. This may contribute to a more stable farmers' income over years.

3.5 Other fields of application

Lasting Fields offers opportunities for arable farming due to reduced soil compaction and replacing labour by autonomous robots. In other fields of applications reducing soil compaction is not an important target. However, labour intensive practices in these other agricultural sectors are an important indicator of the total costs. In future visions of these sectors, automating these practices using robots is a common solution to solve labour intensity issues.

In orchards the tree rows offer good opportunities for navigation (Hamner *et al.,* 2011). Moorehead *et al.* (2012) used a laser scanner for navigation and row recognition, while Probotiq developed a teach and playback system for orchard tractors. By manually driving a path through the orchard, a route is saved. Afterwards the tractors are able to re-drive unmanned this planned path. The autonomous tractor is equipped with safety sensors and uses a precision spraying device. A LIDAR (Light Detection and Ranging) sensor is used to measure crop canopy and adjust the output of the sprayers. Up to 40% herbicide savings are reached with this teach and playback precision spraying solution. Other operations in orchards, like the pruning of fruit trees in autumn and winter, still require a lot of manual labour.

In field cultivation of vegetables, several production steps require a lot of manual labour. In asparagus production, for example, the growing beds have to be checked once every two days for asparagus spears that are ready for harvesting. However, these cultivation beds offer good opportunities for easy row navigation (Dong *et al.,* 2011). Vision detecting of harvestable asparagus spears is needed for complete autonomous harvesting.

In floriculture the operations needed for flower bulb cultivation are, to a certain extent, similar to arable farming operations. In current flower bulb cultivation a manual labour peak is needed for detecting virus infected flowers. Using a camera and spectral reflectance algorithms infected flowers can be detected (Polder *et al.,* 2010).

Forage (grass and maize) harvesting in dairy farming systems has similar disadvantages to crops like potatoes and sugar beets. High yield per hectare and a tight time schedule for harvesting are resulting in the use of high efficiency large machines. Other operations in dairy farming are already automated: milking, feeding and manure removing (Lely, 2014).

Labour costs in Dutch greenhouse horticulture constitute for 29% of the total production costs (Jukema & Van de Meer, 2009). In the past 30 years robots have been developed for greenhouse automation (Bac *et al.,* 2014). These robots are often just proof of principle machines and far from mature. Indoor food production, for example a plant factory growing lettuce, is increasingly investigated (BAC *et al.,* 2014). Lighting conditions can be controlled in an indoor environment, improving opportunities for vision and image processing systems. In indoor and greenhouse production systems plant development is more consistent, because climate conditions can be regulated. In greenhouses and indoor plant rail driving robots could be implemented without difficult navigation algorithms. Stationary robots could be used when crops grow on movable benches (Bac *et al.,* 2014).

In organic agriculture one of the main bottlenecks is the cost of labour**.** In this sustainable way of farming: synthetic pesticides, herbicides and fertilizers cannot be used, resulting in labour intensive weed control. In sugar beet, carrot and onion cultivation, weed control is still conducted manually, due to a lack of efficient machinery able to perform intra-row weeding (Thorpe & Durrant-Whyte, 2001). Lasting Fields could offer new opportunities for organic arable farming if Lasting Fields machinery were able to perform intra-row weed control.

3.6 Concluding summary

A facilitative interaction between crops means that one crop (often the second crop) modifies the environment in such a way that is beneficial for the other crop (often the main crop). Examples include repelling pests, fixating nitrogen in the soil, and decreasing the chance of diseases. However, the different crops compete with each other for resources (water, nutrients, light). The timing of the introduction of the second crop (sequential or relay intercropping), the mowing regime, and species selection can decrease the competitive effect of the second crop. Generally, when the intraspecific competition is stronger than the interspecific competition, the yield with intercropping is likely higher than when sole cropping. Reduced interspecific competition is due to increased resource use efficiency when species occupy different niches. Other environmental benefits may include reduced use of fertilizer, reduced leaching, and reduced use of herbicide and pesticide. Adjusting plant density and spatial arrangement to optimize crop yield, plant quality, and weed suppression harbours the most desirable outcome. The increase in yield of intercropping relative to sole cropping can be calculated with the land equivalent ratio (LER), which calculates the increase per unit area, or relative yield total (RYT), which uses dry biomass as measure. The relative value total (RVT), also called the income equivalent ratio (IER), is used to calculate the financial income gained from intercropping relative to sole cropping. Based on studies in Europe it is expected that a yield increase of 10-30% should be feasible in the Netherlands, depending on the crop combination. Another financial benefit is the stabilization of income because of intercropping, as the risk of crop failure by pests is reduced. In other fields of application Lasting Fields offers opportunities in decreasing the large demand of labour. Lasting Fields in combination with organic farming and intercropping results in an interesting vision on sustainable future proof arable farming.

4. Technology

Since the industrial revolution in the 19th century, mechanization and automation increased productivity. The agricultural sector benefits also for this growing availability of automation technologies. The introduction of precision agriculture technologies provided farmers the opportunity to deal with variability within the field. In other sectors, characterized by a controlled environment, automation is already common practice. The last decade different pilots for autonomously driven agricultural machines are developed (Table 4.1). These pilot studies have not yet resulted in a feasible alternative for current farming techniques. In contrast to these pilot machines the Lasting Fields concept is changing the whole concept of farming instead of evolving agricultural machines towards autonomous agricultural machines. This chapter focusses on the technology needed in the Lasting Fields concept. To that end characterizing technologies of Lasting Fields are compared with technologies that are used in autonomous driving pilot studies. Analysing the range of techniques used in these pilot studies provides an overview of the possible design alternatives to make the concept of the Lasting Fields more concrete. At the end of this chapter the techniques that can be used in Lasting Fields are described. These techniques are categorised considering the most important functions that need to be fulfilled by the Lasting Fields concept. A good design of the Lasting Fields concept fulfils these requirements. The set of technical principles that fulfil these functions are then evaluated using these requirements. To what extent these requirements are fulfilled by the technical principles determines the quality of the design.

4.1. Technical description of Lasting Fields

To be able to compare the concept of Steverink Techniek B.V. with other studies, regarding automation in arable farming, a technical description of Lasting Fields is needed. The current concept only exists on paper. Therefore a clear distinction between the current technical status and the future situation is made.

4.1.1. Current situation

To change the mind-set of farmers a proof of principle potato harvester is made by Steverink Techniek B.V. The capacity of this harvester is based on a standard potato crate (120 x 160 cm). This prototype potato harvester is neither using an operating system nor any sensing technologies.

4.1.2. Future situation

In the to-be situation a rail system is used for transport. Perpendicular to the growing beds this rail system transports machinery to the fields and transports harvested products towards the farm. In a future vision by Blackmore and Griepentrog (2002) autonomous agricultural vehicles in 2025 are characterised as: small, lightweight, exhibiting long-term behaviour, capable of receiving instructions and communication information, capable of being coordinated with other machines and behaving in a safe manner. The future situation of the on-field small robots of Lasting Fields is similar to this description. The autonomous robots of Lasting Fields are operating on a track width of 1.5 m. The robots are using a controlled traffic system, resulting in a crop area of 1.5 m between the wheels that is never compacted by the robot. In the first stage of development the on-field robots are using diesel as fuel. In a later stage rapeseed oil can be a solution, while electricity or hydrogen cells are also a possibility for the future.

4.2. Current state of autonomous technology in arable farming

The possibilities of autonomously driving agricultural machines are a main research topic in agricultural universities and research institutes. Since a couple of years, commercial agricultural mechanisation companies are starting with similar projects. In this paragraph six research and three commercially driven studies are discussed (Table 4.1).

Table 4.1. *Autonomous agricultural vehicle projects*

Project name	Organisation	Reference
Weeding robot	Wageningen University, Netherlands	Bakker *et al,*2010; Bakker *et al,*2011
Armadillo	University of Southern Denmark, Denmark	Nielsen *et al.,*2012
Hortibot	University of Aarhus, Denmark	Jørgensen *et al.,*2007; Sørensen *et al.,*2007
APU-Module	Aalto University, Finland	Oksanen, 2013
AgRover Gen.II	Iowa State University, USA	Xuyong Tu, 2013
SRFV	Queensland University of Technology, Australia	Bawden *et al.,*2014
BoniRob	Deepfield-robotics (Bosch start-up GmbH), Germany	Ruckelshausen *et al.,*2009
Robotti	Kongskilde, Denmark	Jakobsen, 2015, Technical University of Denmark
Oz	Naïo Technologies, France	Naio-technologies, n.d.

By dividing the technology needed for autonomous agricultural vehicles in several sub-functions, the different solutions for these sub-functions can be compared. The basic structure of the vehicle compares the main characteristics size and weight. The usage of different kind of wheels or tracks is influencing the impact on the soil. These technical possibilities are described in the motion paragraph. For vehicle motion energy is needed. This is discussed in the energy paragraph. In navigation & positioning, the range of sensors and navigation systems used in these studies is discussed. Besides these hardware aspects, software is also of great importance in developing an autonomous machine. In this paragraph the internal communication, the communication with the farmer, and communication between robots is discussed. For combining all the data obtained by the software, data management is needed. Therefore Farm management information systems are discussed. Without safety measures autonomous driving vehicles are not possible, and therefore these safety issues are also discussed. In Appendix A, the specifications of all nine prototype robots are given.

4.2.1. Basic structure

In general, the size and weight of autonomous field robots is reduced compared with conventional tractors. There is no need for a driver seat and the capacity can be lower due to a lack of working hour boundaries. Nielsen *et al.* (2012) specified the basic structure of the Armadillo robotic tool carrier: 425 kg 1.5 m width, 0.8 m length. The Robotti machine developed by Kongskilde has a similar weight: 400 kg. The BoniRob is a heavier: 1100 kg. A width of 2.8 m and a length of 2.4 m makes the BoniRob also larger. Due to a variable track width of 1 m up to 1.9 m and a ground clearance of 85 cm, the BoniRob is still capable of operating on small fixed paths.

Low weight is an important specification of most innovative robot systems. Chamen *et al.* (1994) stated that 70% of energy used in cultivation can be saved by using a non-trafficked gantry system. According to Blackmore and Griepentrog (2002), up to 90% of the energy of conventional cultivation is needed to repair soil damage, like soil compaction, done by the weight of tractors.

Blackmore and Griepentrog (2002) stated that 'small size' is an essential parameter for autonomous agricultural vehicles. Small size robots compared to conventional size autonomous machines are operating with higher precision, lower incremental investment and are relatively safe during system failure.

4.2.2. Motion

Individually driven and steered wheels are the most common in current agricultural robots. The WUR weeding robot, Hortibot, BoniRob and AgRover Gen II. are all equipped with four individually steered and driven wheels. The SRFV is built for dry Australian conditions and is driven by the two wheels, further supported by two castor wheels. The Armadillo and Robotti are both equipped with two tracks. These traction devices are resulting in a driving speed varying from 1.49 m/s (SRFV) to 2.7 m/s (Robotti).

4.2.3. Energy

All field robots are electrically driven except the diesel fuelled Wageningen University weeding robot and also diesel fuelled very basic Finnish APU-Module. All electrically driven prototypes are operating with batteries and a recharge station. On-board solar cells are not used in any of the projects. The operation time is an important issue concerning the battery packs of the electrically driven vehicles. Nielsen *et al.* (2012) obtained an average operation time of 10 hours, equal to the 60 V 200 Ah SRFV. The 24V 230 Ah BoniRob has the longest operation time, estimated 24 H. However the operation time has a large effect on the weight of the robot, for example: the 24H BoniRob weighs 1100 kg, while the 10 H Armadillo robot only weighs 425 kg.

4.2.4. Navigation & positioning

For navigation along a row of plants several sensors are used: machine vision (Weeding robot, Hortibot), video and LIDAR positioning (Light Detection and Ranging) (BoniRob) and an Xbox 360 Kinect (RGB and 3d imaging) (Jakobsen, 2015). Using machine vision results in a system that provides additional plant information, which is useful in crop scouting and monitoring. For navigation during seedbed preparation and seeding, there is no row of plants, and GPS is needed then.

GPS (WUR weeding robot, APU-module) or odometry methods like dead reckoning (Robotti) are common techniques for navigating and turning on the headland. Dead reckoning is a low cost and navigation solution that is easy to implement. Odometry positioning is very sensitive for slippery or calibrating deviations, resulting in a rapidly increasing positioning error (Adams, 2013). Odometry is often used as backup for more expensive techniques like vision or GPS. Bakker *et al.* (2010) stated that combining GPS with vision could lead to an improving the alignment for the next row. Headland vegetation makes using only machine vision, ultrasonic or optical sensors difficult applicable in practice.

3D LIDAR can be used to make a 3D map of the terrain in front of the sensor. However with this technique it is hard to properly detect transparent objects like electric cattle fences. RADAR (Radio Detection and Ranging) is less focused. However RADAR detects smaller objects than LIDAR, due to emitting radio signals instead of light pulses (Adams, 2013).

4.2.5. Data & software

Due to the complex biological variability in outdoor environments computational autonomy is a major challenge in agriculture. Route planning and other deterministic tasks can be computed before the actual tasks starts. However reactive tasks like obstacle avoidance have to be computed during the task (Blackmore *et al.,* 2007).

To interpret the data of the sensors described above, on-board software is needed. The collection of the data of the sensors and controlling the robot actuators can be categorised as internal communication software. External communication can be divided in communication with the farmer and other robots, and external data acquisition. In case of emergency or to update the task progress, communication with the farmer is needed. Weather and soil conditions are also influencing the robot operation.

An internal communication system like CAN bus is a commonly used principle for connecting sensors to the robot. Tool carrier designed field robots are often able to use a wide range of internal communication methods like, Ethernet, Wi-Fi, USB, RSxxx and Bluetooth (Armadillo, Bosch Deepfield-robotics). ROS (Robot Operating System) based operation systems like FroboMind and Linux are the most used operating systems (Oz, BoniRob, Armadillo). ROS programmed systems are characterised as open source systems. This means that functions and programs developed in the ROS programming language are not patented by the developers and are freely usable.

For communication with the farmer, Bakker *et al.* (2010) used a web page and board computer to change the robot settings. This web page and SMS were used to inform the farmer. The French Oz robot designed for mechanical weeding in vegetable fields also uses SMS as farmer warning mechanism.

Communication between robots is necessary when multiple robots are operating on a farm. Multiple machines result in three levels of interaction: coordination, cooperation and collaboration. Central coordination of robots, robots operating on separate plots, results in independently working vehicles. It is not necessary for these robots to be aware of each other. When multiple machines are working on the same time on the same field, cooperation is needed. Each robot should know which rows are already weeded by another robot for example. In the collaboration level multiple robots are carrying out tasks together and are complementing each other (Blackmore *et al.,* 2007).

External data needs to be collected to be able to react on changing environmental conditions. To some extent all tasks performed by mobile agricultural robots are weather dependent.

For example, an autonomous sprayer should stop when there is too much wind. Moisture content of the soil is another external condition influencing the performance of the mobile robots. Moisture content can be measured by static sensors placed on strategic positions in the field. Advanced and more expensive mobile sensors could be mounted on the mobile robot.

4.2.6. Farm management information systems

The data obtained by the autonomous vehicles could provide information for advanced farm management information systems (FMIS). Current farm management systems are not properly integrated and require large amounts of information handling (Sørensen *et al.,* 2010). The conceptual FMIS developed by Sørensen *et al.* (2010) contained the following components: Farm activity monitoring, data acquisition, data transfer, data processing, internal repository, search, internal information, documentation generation, extract to audit, automated validation, search external information, information filtration, operations plan generation, plan repository and plan execution. For this kind of systems, it is important for business support software to have the ability to represent different levels of personal preferences (Blackmore *et al.,* 2007). Attitudes towards risk, environmental impact and safety differ for individual farmers. These advanced decision support systems should also provide new management opportunities. Up-to-date weather, soil, crop and market data should result in detailed farmers specific decision support.

Trimble has developed Farm Works, an FMIS that focuses on combining yield maps and field/soil data resulting in a tasks map for seeding or fertilizing. AGCO's Variodoc management platform is able to synchronize the data obtained by Agronomic sensors in the machine with the Trimble Farm Works software. A Spin-off company of Claas called 365FarmNet is developing an FMIS that combines agricultural manufacturer specific software. Data collected by Claas harvesters can be used as input for Amazone seeding device for example. Currently about 20 manufactures are connected to this software. Functions like: field data, employee data, machine efficiency, machine locations and daily planning are included in this FMIS. However, data from other manufacturers still needs manual handling.

For a decision support system, models for processing and analysing the data into support for managerial decision making are needed. When building a custom database management system (DBMS) it is important to make a data model first. It is cheaper to make a data model before building a database in DBMSs like: Oracle MySQL, SQL Server or the simplified MS Access software. When designing a custom database management system, data processing decisions have to be made, like for example the kind of hardware, cloud or server based system (Hofstede, 2015).

4.2.7. Safety & legislation

In general there are two types of safety, internal safety and external safety; the former refers to safety of the robot by damaging itself and the latter refers to safety of the environment caused by the robot platform (Adams, 2013). Recognizing the limits of the robot's capabilities and evaluating parameters like fuel level are needed for operating without damaging itself. The navigation and positioning techniques like machine vision, GPS, RADAR, LIDAR, ultrasonic sensors, microwave sensors and tactile sensor can also be used to detect unsafe situations in the environment. These sensors can operate in a super or sub canopy way; detecting obstacles above the crop or between the crops (Bakker *et al.,* 2010). Ultrasonic, tactile and microwave sensors are typically used to detect obstacles close to the robot. The versatility and the low costs are advantages of this kind of sensors. The high rate of false positive detections, resulting in unnecessary stops, is the main disadvantage.

The Dutch ministry of infrastructure changed public road legislation to encourage the development of autonomous cars. For pilot studies it is possible to obtain dispensation (Ministry of Infrastructure and Environment, 2015). However, automated vehicles in agriculture are not using public roads. For robots in arable farming no specific legislation exists. This legislation gab is similar to the former lack of legislation about UAVs (unmanned aerial vehicles). Nowadays, a 'remotely piloted aircraft system operator' certificate, airworthiness of the drone certificate and an approved operations manual, is needed for the commercial use of drones (Staatssecretaris van Infrastructuur en Milieu, 2015). Regarding accidents, the manufacturer of the autonomous vehicle is accountable. However, unauthorised changes made in the system's software result in an expired manufacturer's accountability.

4.2.8. Applicability (operation devices)

The Armadillo, Hortibot, AgRover, BoniRob and SRFV are developed as a multipurpose platform. The Oz, Weeding Robot and Robotti are primarily developed as weeding machine, however in case of the last two projects the multipurpose possibilities are taken into account. The APU-module is tested using a conventional seeding. Blackmore *et al.* (2007) divided the applicability options of autonomous agricultural vehicles in three categories: crop establishment, crop care and harvesting.

In crop establishment agricultural robots are providing opportunities for seedbed preparation, seed mapping, seed placement and re-seeding. In seedbed preparation water-jetting or a vertical punch can be used as seeding method. When mapping the seeds during seeding, a seed map can prevent crop losses, due to the exact coordinates of the individual crop. This seed map can also be used for reseeding. When a plant has not emerged at a certain coordinate, a small robot, not disturbing the surrounding plants, could transplant a seedling. Robots could also change the way of placing the seeds: instead of row cultivation the seeds could also be planted in a grid. The crop density could also be variable within the field, taking variances in resources into account, like light and soil moisture. These precise and autonomous seeding methods could result in phased cropping (see sequential intercropping, in chapter intercropping), resulting in a reduced peak of machinery workloads, more efficient machine usage and a reduced possibility of crop failure.

In crop care agricultural robots are providing opportunities for crop scouting, weed mapping, mechanical weeding and micro spraying. Several sensors can be used in collecting information about the growing crop. Therefore, cheap sensors can be placed at strategic positions within the crop or by placing more expensive sensors on a robot. Recording the position, density and species of different weeds using machine vision, and weed mapping provides essential information for the physical or sprayer based weeding methods. In row crops the pattern of plant spacing can be used to detect inter-row weeds (Bakker *et al.,* 2010). By applying highly targeted chemicals and threatening only the weeds the amount of herbicide used can be reduced. Graglia (2004) stated that when herbicides are targeted in the right way and at the right time reduction from 720 grams of glyphosate down to 1 gram per hectare can be reached.

Agricultural robots provide also new opportunities for selective harvesting. Up to 60% of the harvested vegetable crop is not of best saleable quality (Blackmore, 2015). Harvesting only the vegetables that meet a certain size criteria or grains that are below a fixed protein content could be possible due to small autonomous harvesting machines. Therefore it is necessary to sense the quality of the product before harvesting the product without harming surrounding plants. In acre crops, selective harvesting concepts are more difficult to design (Blackmore *et al.,* 2007). Current autonomous harvesting crops are mainly developed for high value, high labour demand crops like asparagus, strawberry and greenhouse crops (Bac *et al.,* 2014). In these crops selective harvesting methods are used, due to a large variability within the crop. Currently autonomous harvesting robots are not developed for conventional arable farming crops.

4.2.8.1. Crop specific tasks

Blackmore (2014) stated that harvesting large crops like potatoes (40 t/ha) and sugar beet (70 t/ha) will also need large manned machines in the future. The relative low labour needed for harvesting these crops results in a difficult scope for improving these harvesting methods using small autonomous vehicles. Due to the high yields of these crops, high storage capacities on the harvesters are needed, which is difficult to achieve with small autonomous robots. Crop sensing techniques like machine vision could be used to improve crop handling and partly autotomize the harvesting process. Human input will be needed for safe and fast harvesting.

4.2.8.2. Transportation

Autonomous transporters (with or without a rail system) have to be able to connect with the harvester and the unloading device at the storage area. If the overall load per vehicle is low, multiple vehicles could be ferrying products around the farm without compacting the soil (Blackmore *et al.,* 2007).

4.3. Future vision on autonomous technology in arable farming

This future vision is based on a concept solution obtained using systematic design methods (Cross, 2008). The objective of designing the Lasting Fields concept can be described as 'replacing conventional arable farming principles by autonomous, low soil impact vehicles'. Based on the pilot studies on autonomous vehicles in agriculture described in chapter 4.2 the requirements for reaching this objective are obtained. These requirements can be split up in fixed and variable requirements. A final design or vision that does not satisfy all the fixed requirements is not feasible, while the variable requirements have to be fulfilled to a certain extent. The quality of the design is determined by the extent of fulfilment of these variable requirements.

4.3.1. Requirements

Fixed requirements:

- Good driving in cultivated land
- Robot platform supports intelligent implements for data acquisition
- Robot platform width equal to fixed paths width (1.5 m according to Steverink).
- Applicable in combination with conventional arable farming techniques
- All robot platform tasks are performed autonomously
- Robot platform must not cross the field boundaries
- Robot platform has a sufficient clearance height
- Robot platform informs the farmer when the tasks are finished or if an important safety issue occurs.

Variable requirements:

- Lasting Fields robot platform supports intelligent implements/devices for common arable farming tasks
- Simple and modular design and construction of the Lasting Fields robot platform
- Crop damage due to Lasting Fields robot platform is at least as low as conventional arable farming techniques
- Soil compaction of the Lasting Fields robot platform is lower than conventional arable farming techniques.

When evaluating possible concept solutions these requirements are used as criteria.

4.3.2. Key functions

For defining possible concept solutions key functions of Lasting Fields are defined. The key functions are categorised as; on field operation, transport, logistics, and farm management. For each key function several principles are possible as solution for a function. The Morphologic chart containing these key functions and the according principles is shown in Appendix B.

Key functions of on-field robots within the Lasting Fields concept:

1. Moving (and steering)
2. Energy supply
3. Determine if in field
4. Navigation in the field
5. Navigation along the crop row
6. Determine if on headland
7. Navigation on the headland
8. Internal communication
9. Communication with other on field robots
10. Detect unsafe situations
11. Changing application of robot
12. Seeding
    1. Seed conditioning
    2. seeding
    3. Seed placement
    4. Positioning of seeding device
13. Crop protection
    1. Weed scouting
    2. Mechanical weeding or spraying
    3. Positioning of weeding/spraying device
14. Crop care
    1. Crop scouting/monitoring
    2. Crop care (fertilizing)
    3. Positioning of crop care (fertilizer) device
15. Harvesting
    1. Crop scouting
    2. (selective) harvesting
    3. Positioning of harvesting device

Key functions of the transportation system:

16. Moving
17. Transport of products (harvested products and seeds)
18. Transport of robots
19. Communication with on-field robots

Key functions of the farm management system:

20. Input of robot settings
21. Updating robot status
22. Decision support

4.3.3. Concept solution

From the Morphologic chart in Appendix B, possible design concept considering the defined key functions is constructed. The concept solution provides a view on how several technical aspects could be combined within Lasting Fields. In the concept solution below one possible design concept is described. This design concept is based on the current view on autonomous robotics in agriculture and the future vision of Lasting Fields. This concept design is based on common just principles in automation. This specific combination of principles makes the design a suitable Lasting Fields design. Technological development, another point of view, and investment budget could change this design concept.

For the on-field robots within the Lasting Fields concept, four individually steered wheels are the interesting way of moving and steering. The energy needed for accomplishing all robot tasks is provided by electric wheel engines and actuators. Therefore the weight/operation time ratio of the batteries is an important issue to solve (SRFV: 10 hours, total robot weight 600 kg; BoniRob: 24 hours, total robot weight 1100 kg). In practice 24-hour operation time is not needed, while for applications like harvesting weather conditions like dew make day round operation impossible.

GPS is the easiest way for the robot to define the field boundaries. For standard navigation in the field GPS is also used. For navigation along a row of plants vision is used, which also provides information about the crop health useful in the function crop care. Due cropland vegetation GPS is the most reliable method to determine if the robot is on the headland. A combination of GPS and odometry is the most reliable way of turning on the headland. Vision can be used for a better aligning for the next row. When multiple robots are operating in the same field the position of the robot needs to be updated regularly to the FMIS. The vision methods on the robot could also be used to detect obstacles and other unsafe situations. Tactile sensors are needed to detect super canopy unsafe situations near the robot. For each application (seeding, weeding, crop care and harvesting) other devices and actuators are needed. The changing method of these devices depends on the size and application of the devices.

In Lasting Fields the use of conventional machines like tractors can be used as an ultimate backup. Therefore conventional row seeding is necessary. The row density could be variable to respond optimal to variable soil conditions. In the future grid seed placement, re-seeding, nutrient placement near the seed and variable seed depth placement could be possible. Seed mapping is essential for weeding and harvesting applications, therefore precise positioning of the seeding device is necessary. GPS, vision or dead reckoning methods can be used in precise seeding.

Before the actual weeding, weed scouting is needed. In rows, pattern recognition of crops is a useful method of determining where to weed. Accurate seed mapping could be another way of determining where 'not' to weed. Mechanical, inter and intra row' weeding offers opportunities for organic farming and low environmental impact farming (as no resources like herbicides are used). For the positioning of the weeding device similar methods to the seeding device can be used.

For determining crop health, shape and colour recognition or spectral reflectance algorithms are the most common methods. Precise crop health is about plant specific treatment resulting in optimal crop yield. In the future plant specific (organic) fertilizer doses could be injected near a plant. For the positioning of the crop care device similar methods to the seeding device can be used.

In a future utopia selective harvesting is used in Lasting Fields. In full field arable farming this is difficult, whereas in vegetable (cabbage for example) farming selective harvesting results in better crop quality and higher yields (Bac *et al*, 2010). For selective harvesting crop scouting algorithms similar to crop health algorithms are needed. Accurate positioning of the harvesting device is also necessary in selective harvesting. The possible methods are similar to the seeding device positioning methods.

The transportation system is an essential part of the Lasting Fields concept. Using rails results in a low energy demand transportation solution. The rails can also be considered as X-axis in the on-field robot dimension. When connecting with the rails position of the on-field robot could be recalibrated. In the future on-field pre-sorting of the harvested products (by the harvesting robot or another device) should reduce the needed transport capacity. However this increases on-field complexity and is therefore not feasible in an early stage of Lasting Fields development. The rail system is the easiest way of transporting the robots, due to the high energy efficiency of the rail system. The rail system could also provide a recharge possibility for the on-field robots. These on-field robots are equipped with a range of 'smart' techniques. Therefore, these 'smart 'robots should connect to the rail system for communication between the on-field robots and the rail system. Using a rail transportation system results in an optimal field size. All plots of the farms should be connected to the transportation system. A group of plots at a certain distance of the farm needs a certain combined size allowing a rail transport system to be feasible.

The overall system is operated and monitored by a farm management information system. An optimal farm management system combines up-to-date weather, soil, market and crop data in supporting the farmer in making decisions.

4.4. Concluding summary

This chapter provided a comprehensive overview of the technical solutions that can be used in the Lasting Fields concept. Lasting Fields is in an early stage of development, therefore a large range of functions of the concept are not designed up to now. The current technical state of Lasting Fields focusses on low weight and low energy input. In literature these aspects are considered essential in future farming concepts. However, alongside these practical aspects automation in farm (data) management is also considered crucial.

The current state of knowledge regarding autonomous driving is comprehensive. A wide range of autonomously driven pilot vehicles is developed in the previous years. The knowledge obtained during these research studies is useful in detailed designing Lasting Fields machinery. In the

Morphologic chart and in paragraph 4.3.3, the concept solution, technical solutions of detailed Lasting Fields functions are described. However, the focus in these research projects is mainly on driving autonomously in the field, conducting tasks like seeding and harvesting is hardly researched. In developing Lasting Fields the technical principles considering autonomous driving can be used from other studies, while performing autonomous agricultural tasks needs more elaborate research.

Energy usage and robot weight are interrelated. When using electrical energy, the operation time of the machine is related to the weight of the battery pack.

In future farming systems decision support is necessary to help the farmer manage the farm without getting lost in the large amount of data. Advanced farm management information systems should combine data and provide farmer specific advice. Large agricultural manufacturers are currently developing comprehensive FMISs. However due to proprietary and conventional machine based systems, direct use within the Lasting Fields concept is not possible.

For robots on private (arable) fields there is no legislation. However, safety is an important issue. Failing safety measures resulting in an accident is accountable for the manufacturer. An excellent internal and external safety system is needed to provide safety. In the future safety certificates and regular MoT (Dutch: APK) tests could be introduced to guarantee safety.

Concluding, the wide range of research studies regarding autonomous driving in arable farming provides technical design solutions for the Lasting Fields concept. Crucial for the Lasting Fields concept is; maintaining safety during all circumstances, managing data using an advanced farm management information system and using energy efficient solutions. Further developing Lasting Fields could result in an interesting and completely different alternative for conventional arable farming techniques.

5. Life cycle assessment

This chapter investigates the environmental impact of the Lasting Fields concept in comparison to a conventional farming system. In order to provide a clear overview and a comparable analysis of the concept a Life Cycle Assessment (LCA) is conducted. The LCA analysis is performed for the production of 1 kg of potatoes. The main factors that contribute in reducing the impact are the lower fuel consumption, caused by extremely lightweight machinery with few horsepower, the lower amount of materials used to build the machines and finally the lower environmental impact caused by the transportation system from the fields to the barn. The transportation of biomass from the fields to the barn will be carried out with a rail system. That is light, efficient and propelled with photovoltaic energy.

Note that in this life cycle a few assumptions were made when conducting the analysis.

1. It was assumed that the same inputs of fertilizer and crop protection agents are required in the original (conventional arable farming) and the in Lasting Fields concept.
2. Same levels of crop yield were assumed for both systems.

5.1. Introduction to Life Cycle Assessment (LCA)

LCA is a structured, internationally standardized method and management tool for quantifying the emissions, resources consumed, environmental and health impacts that are associated with goods and services. The LCA takes into account the product's full life cycle: from the extraction of resources, through production, use and recycling up to the disposal of the remaining waste. All these phases together are usually called from 'cradle' to 'grave'. Impacts considered in a LCA include several categories depending on the methodology used; the emissions and resources are assigned to each of these impact categories. In this study we used the 'CML_2002' impact assessment methodology that was developed in the Netherlands in 1999 and later updated in 2002. Table 5.1 shows the category in 'CML_2002' adopted in this analysis (European Commission, 2010).

Table 5.1. *Impact Assessment method used is CML_2002*

Impact Category	Reference Unit
Climate Change – GWP100	kg CO_2 eq.
Acidification Potential	kg SO_2 eq.
Eutrophication	kg PO_4 eq.
Human Toxicity	kg 1.4-dichlorobenzene eq.
Photochemical Oxidation (NO_x)	kg ethylene eq.
Terrestrial Ecotoxicity	kg 1.4-dichlorobenzene eq.
Marine Aquatic Ecotoxicity	kg 1.4-dichlorobenzene eq.
Freshwater Aquatic Ecotoxicity	kg 1.4-dichlorobenzene eq.

In order to conduct a complete and reliable LCA, a huge amount of data is needed. For this reason, data collection and database building are needed. These databases are usually setup by national environmental agencies, the European Commission, or by specialized private companies. The Lasting Fields concept is a new concept and of course not included in those databases. Therefore, in order to conduct the LCA, many assumptions were made. The used assumptions are discussed in the paragraphs below.

The LCA on Lasting Fields is based on the production of 1 kg of potatoes from 'cradle' to 'grave' at farm level. That means from the seed production till the end product at the farm. This chapter focuses on fuel consumption reduction, reduction in machinery weight and substituting the trailer system to move the biomass from the field to the barn by an efficient rail system propelled with photovoltaic energy. This chapter discusses every change made in the system elaborately.

5.2. Fuel consumption and Machinery weight

The Lasting Fields concept is also focused on reducing environmental impact of arable farming. Emissions caused by the diesel consumption of tractors and machinery are the main factor influencing environmental impact. Besides the emissions, fuel consumption is also an important economic parameter. For these reasons reduction in diesel consumption is really important.

Before describing the calculations made in the LCA, some considerations are relevant. Initially implementing vegetable oil, for example rapeseed oil, as diesel substitute was considered. After literature research was decided to not include a diesel substitute. There are currently two possibilities of using vegetable oils in diesel engine; 'raw'/'straight', in other words: not refined, or blended with diesel. The blend with diesel has the advantage that it can be used with existing engines, however these blends have the disadvantage to not reduce the polluting emissions. In fact, the emissions of diesel and vegetable oil are very similar. The amount of CO is slightly higher for vegetable oils, NO_2 emissions are lower, HC emissions are lower or higher (depending on the engine type) and CO_2 emissions are equal or higher. Furthermore, at present, vegetable oils are generally more expensive than diesel fuel, a small amount of power loss happens when using vegetable oil and tractors have higher specific fuel consumption values due to lower energy content of vegetable oils (Altın *et al.,* 2001; Hansson *et al.,* 2007). From the other side 'raw' or 'straight' vegetable oils have the disadvantage that they cannot be used in normal diesel engines due to their higher flash point, resulting in tar deposits (Sidibè *et al.,* 2010). From the studies discussed above it can be concluded that the most important advantages of vegetable oils are the renewable characteristic, and the easy way of producing. The renewable characteristics refer to their renewable energy sources compared to the limited resources of petroleum, while the easy way of producing is referring to the fact that vegetable oils show promise of providing all the liquid fuel needed on a typical farm by allocating 10% or less of the total acreage to fuel production. Furthermore, the extraction and processing of vegetable oils are simple low energy processes that make use of equipment simple for most of the farmers (Altın *et al.,* 2001; Sidibè *et al.,* 2010). Having said that, the big difference from a LCA point of view is the lower diesel consumption due to reduced horsepower and weight of the tractor. For these reasons we implemented in the software only a reduction of diesel consumption and not a simulation with vegetable oil propelled machinery.

Machinery that is similar to Lasting Fields is currently not used in practice. However, Steverink built a proof of principle potato harvester. This harvester is about 600 kg and it is self-propelled. An average potato harvester could be self-propelled or pulled by a tractor. Since the prototype built by Steverink is self-propelled, a self-propelled machine is used in LCA analysis. Generally, a self-propelled potato harvester is able to harvest 2 rows at once and weighs minimally 15,000 kg. This means that the weight difference between a conventional and Lasting Fields harvester is 96%. When assuming that a harrowing machine from Lasting Fields is about 600 kg and a normal one is about 200 kg plus 3000 kg of a compact tractor, it means that the Lasting Fields machine is 80% lighter. Assuming again that the Lasting Fields fertilizer spreader is done with the same machinery and similar weight of 600 kg, and that a compact tractor of 2000 kg with spreader is normally used, then we have a difference in weight of 77%. With these assumptions, in the LCA software the average weight of machinery is reduced by 85%. As a consequence of lighter machinery, the fuel consumption was reduced by 45%. In fact, many studies proved that on average it is possible to save 20% of fuel every 35% to 40% of weight saving. **[**35% weight reduction can lead to 12% to 20% reduction in fuel consumption (Government of Canada, 2016); a weight reduction of 20% results in a fuel saving of 10% (simulation for 6000 kg trucks) (Casadei & Broda, 2008); 40% reduction in weight leads to 23% reduction in fuel consumption (simulation with SUV) (Pagerit, Sharer, & Rousseau, 2006; U.S. Department Of Energy, 2011)**].** Assuming a linear relation between weight and fuel consumption means that Lasting Fields machinery can save around 45% of fuel.

It is also relevant to consider that the potato harvester prototype by Steverink does not have an autonomous steering wheel and for this reason the final product might be heavier, but it is difficult to estimate to what extent. In the LCA the weight for the machinery was set as 600 kg, which is the same as potato harvesting prototype. Another consideration is about the speed of the Lasting Fields machinery. In LCA this was assumed to be the same for every agricultural operation.

5.3. Transportation

The rail system is well-known to be one of the most efficient transport system, and much more efficient than trucks. From the literature is known that on average a rail system consumes 0.034 kWh/ton-km (Jong & Chang, 2005). We can assume that the Lasting Fields rail system has a lower energy consumption due to the lack of additional services, such as conditioning, which has a relevant impact. For these reasons we can assume a 15% energy reduction due to the Lasting Fields railed transport system. Therefore, a value 0.0289 kWh/ton-km is used (Ice & Shinkansen, 2003). Using the data provided by Steverink about the weight of the rail trailer (100 kg = 0.1 ton) the energy needed for moving is calculated: 1 km of the Lasting Fields rail system requires 0.0028 kWh. Assuming the trailer works at low speed, and that the air drag of the system can be ignored.

Assuming an average farm size of 50 ha, 2328.25 tons of biomass is produced per year (see Economic Chapter, Table 9.2.). Assuming a transport capacity of the rail trailer of 10 tons per trip, 233 trips are needed. Assuming a 1 km distance from field to barn, the total distance per trip will be 2 km. Finally this results in a total distance per year of 465 km.

The yearly amount of energy needed by the rail system can be calculated:

$$0.028 * 2328.25\ tons * 465\ km\ =\ 30{,}310\ kWh.$$

In case the transport capacity of the rail system would shift to 15 tons, the early energy needed will be 20,150 kWh.

5.4. Solar Panels

In the Netherlands the average solar irradiation per year is 1000 kWh/m² (figure 5.2).

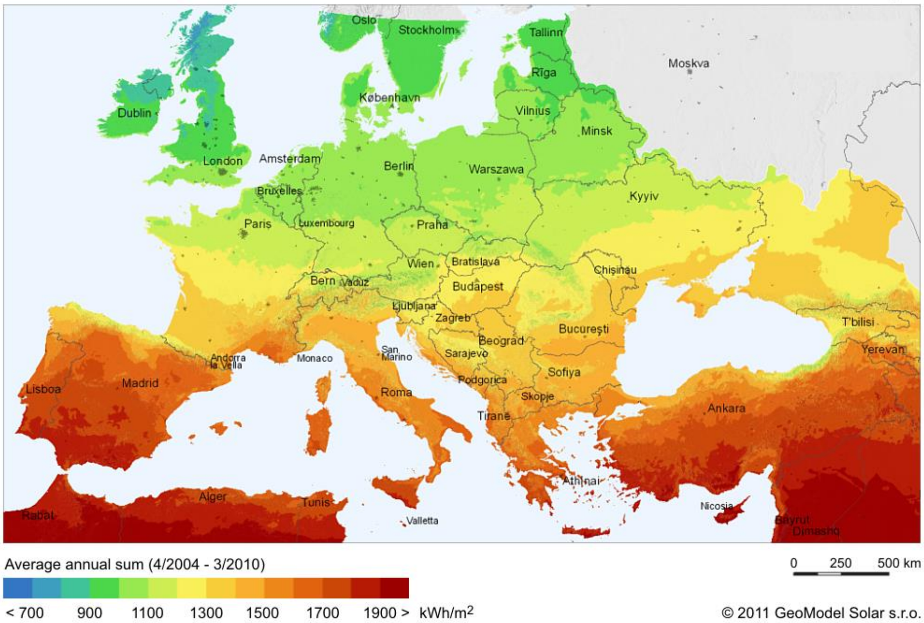

Figure 5.1. *Average solar irradiation in Europe (http://geomodelsolar.eu)*

Figure 5.2. *Average solar irradiation in the Netherlands (http://geomodelsolar.eu)*

Assuming the average surface available on barn roofs for solar panel installations is 200 m^2, the total radiation is 200,000 kWh. The average efficiency of solar panels is 15%, while a performance ratio (due to losses such as shadow, dust, snow and resistance caused by the cable) of 0.85 can be assumed. According to these assumptions, the yearly amount of energy available for the farmer is:

$$200{,}000\ \text{kWh} * 15\% * 0.85 = 25{,}500\ \text{kWh}$$

The amount of energy would be partly or fully sufficient to reach the self-sufficiency for the rail system that transport biomass from fields to barn. The assumptions and calculations regarding energy obtained by solar panels were not included in the LCA analysis due to lack of data in the database used.

5.5. Energy self-sufficiency

From the calculations and assumptions above, it is evident that the rail transport system from field to barn can be energetic self-sufficient. For the economic sustainability the depreciation value should be taken into account.

For a farm level analysis of energy self-sufficiency all other operations in the field, such as ploughing, weeding, and harvesting have to be taken into account. The results could vary significantly depending on the type and the amount of energy used in these operations. The latter is in fact not known and also difficult to estimate since the Lasting Fields machinery for those operations does not exist yet. Furthermore, as stated previously, several studies (chapter 5.2) demonstrated the possibility to be fuel self-sufficient with 10% of the farm allocated to vegetable for oil production. Financially vegetable oil production for fuelling farm equipment is not feasible. The costs producing and refining rapeseed are too high for financially feasible fuel. On the other hand, the lower costs of producing bioethanol from winter wheat are compensated due to engine modifications that are needed (Hansson *et al.,*2007). For these reasons it is impossible to make assumptions on the energy consumption of the whole Lasting Fields concept.

5.6. Concluding summary

The LCA results are shown below in table 5.2. A normalized comparison is made in the figure 5.3.The graph (figure 5.3) shows clearly that the Lasting Fields concept has some advantages in terms of pollution. However, the advantages in this model are not so large. In fact differences do not exceed 9%, except for photochemical oxidation. The latter represents the emission of nitrogen oxides (NO_x) that are dropped in the new model due to the lower diesel consumption. This model can be taken as a first stage of analysis of the Lasting Fields projects. In fact, it focuses only on the production of 1 kg of conventional potatoes and do not take into account intercropping or an eventually fuel alternative. Concluding, the Last Fields concept has the potential to reduce the environmental impact and the extent can be higher than this simulation if all the aspects of Lasting Fields are implemented.

Table 5.2. *LCA impact category values for 1 kg of potatoes.*

Impact category	Lasting Fields	Original	Reduction with Lasting Fields
Acidification potential ($kg\ SO_2$ eq.)	6.53407 E-04	7.17481 E-04	8.93%
Climate change - GWP100 ($kg\ CO_2$ eq.)	-3.33968 E-01	-3.24797 E-01	2.75%
Eutrophication ($kg\ PO_4$ eq.)	5.24366 E-04	5.40203 E-04	2.93%
Freshwater aquatic ecotoxicity (kg 1.4-dichlorobenzene eq.)	2.90764 E-03	2.90892 E-03	0.04%
Human toxicity (kg 1.4-dichlorobenzene eq.)	-4.96881 E-03	-4.75044 E-03	4.39%
Marine aquatic ecotoxicity (kg 1.4-dichlorobenzene eq.)	9.44693 E-01	9.50077 E-01	0.57%
Photochemical oxidation (NO_x) (kg ethylene eq.)	3.37180 E-07	9.08519 E-07	62.89%
Terrestrial ecotoxicity (kg 1.4-dichlorobenzene eq.)	-7.10473 E-03	-7.10420 E-03	0.01%

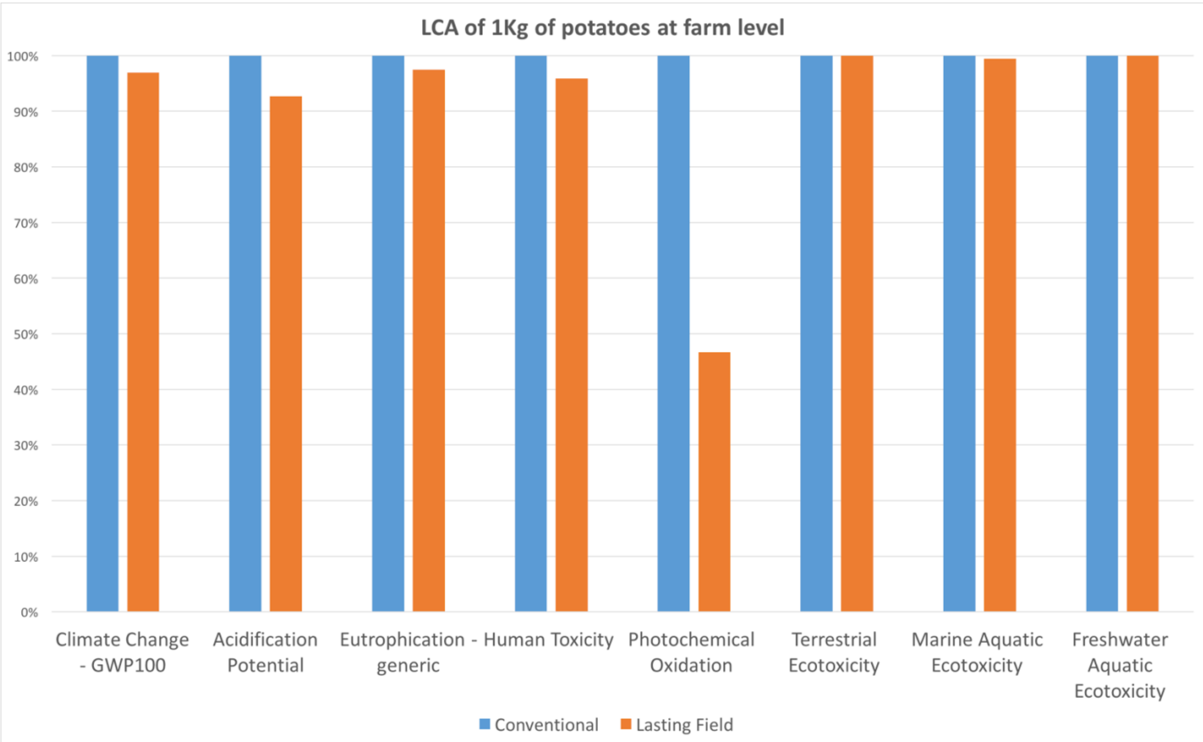

Figure 5.3. *Comparison of the LCA of* Lasting Fields *with the original arable farming*

6. Economy

In the previous chapters it is made clear that the Lasting Fields concept comes with a lot of benefits. The environment benefits by means of decreased soil compaction and the farmer benefits by means of increased yields and decreased use of inputs. In the previous chapters the effects of Lasting Fields are not monetized. Monetizing the effects of Lasting Fields will be the first topic of this chapter. Also other applications of Lasting Fields will be discussed. This chapter finishes with ideas about the business model that may be suitable for Lasting Fields.

6.1. Hypothetical Farm

The Lasting Fields concept is still in an early stage. To estimate the potential monetary benefits of Lasting Fields, a starting situation is needed. Therefore, a hypothetical farm was created. Because the development of this concept is done in collaboration with the Flevoland Development Agency, it is likely that the first implementation of the concept will be done in Flevoland. The hypothetical farm is therefore based on a standard farm cultivation plan of the Flevopolder: Central Sea Clay 2 (Van der Voort *et al.,* 2008). This hypothetical farm's cultivation plan is the following:

Table 6.1. *Hypothetical farm at the Dutch Flevopolder (Van der Voort et al.,2008).*

Standard Cultivation Plan Flevopolder	
Crop	Percentage
Winter Wheat	25%
Sugar Beet	25%
Cons. Potato	25%
Seed Onion	12,5%
Peas	12,5%

The average consumption of inputs can be calculated using the cultivation plan of this hypothetical farm and KWIN-AGV (2015). In KWIN-AGV (2015) all inputs and outputs of the cultivated crops are summarized and differentiated by soil type. Because the hypothetical farm is said to be located in the Dutch province of Flevoland, the numbers of 'Clay, IJsselmeerpolder' are used when this information was available. Otherwise the data on average clay soils were used. The data is summarized in table 6.2. The use of fertilizer, crop protection, diesel, labour, and contract labour, as well as the profits has been rounded.

The farm size chosen for this hypothetical model farm is 50 hectares, because that is the average farm size in the province of Flevoland (Centraal Bureau voor de Statistiek, 2015). The data summarized below is therefore a summary for a farm with 50 hectares of arable land.

Table 6.2. *Revenues and costs for the hypothetical farm (KWIN-AGV, 2015).*

crop	percentage	yield (kg)	byproduct (kg)	fertilizer (€)	crop protect (€)	diesel (ltr.)	labour (hr.)	Contr Labour (€)	Revenue (€)	profit
winter wheat	25%	115000	56250	2800	2300	1500	110		26200	17600
sugar beet	25%	1152500	0	3100	3100	1500	160	5050	64500	48200
cons. potato	25%	669500	0	6100	8000	3300	370		104200	72700
seed onion	12,5%	348125	0	2400	5000	1100	220	720	47400	28800
peas	12,5%	43125	0	1100	2200	400	40		14700	10400
sum	100%	2328250	56250	15500	20600	7800	900	5770	257000	177700

*without costs of labour demand, investments, and land rent / opportunity costs of land

6.2. Economic benefits Lasting Fields

When the Lasting Fields concept is implemented, the use of inputs and the harvested amount can change.

6.2.1. Intercropping

First of all, it becomes easier for farmers to cultivate a wider variety of crops with intercropping with Lasting Fields. Currently mono-cropping is common, because of economies of scale and because current machinery is built for large plots on which mono-cropping is applied. Current machinery is not designed to deal with smaller strips with differing crops. Cultivating a wider variety of crops could not only reduce the peak demand of machinery for harvesting, but it can also reduce the use of crop protection agents. As mentioned in the intercropping chapter, pest and diseases are reduced with 5% to 63 % depending on the crop combination and on the pest / disease. These are the more extreme values. When giving a more general indication on the reduction of pests and diseases we would say that there will be a reduction of 10% to 25%. That does not mean there will be a reduction of 10% to 25% in the use of crop protection agents. Some pests and diseases are combated pre-emptively. Against other pests and diseases only curative protection is available. It is difficult to estimate how much the use of crop protection agents can be decreased with intercropping. The frequency can be lowered, but the dose can also be decreased. However, we estimate that the use of crop protection agents can be lowered with 10% when intercropping is applied. Please note that the decrease in pest and disease control only applies when intercropping is applied. It is assumed that Lasting Fields itself does not reduce the need for crop protection. Another benefit that comes with intercropping is that the yield increases. As mentioned in chapter 6, intercropping can increase total yield by 10% to 30%.

As stated in chapter 6, intercropping increases income security for farmers, assuming that a wider variety of crops is cultivated. The farmer would be less dependent on the success of one crop, and spreads his risk over more crops. This may however be a logistical challenge, which needs to be further researched. The machinery should also be able to handle a wider variety of crops without increasing the costs of machinery too much. One machine should be able to deal with more than one crop, for example.

6.2.2. Soil compaction

Another effect of implementing the Lasting Fields concept is that the amount of soil compaction decreases. The heavy machinery of today causes a lot of soil compaction. The soil can be divided in topsoil and subsoil. Compaction of the topsoil can be undone by ploughing, but a high energy input is needed. Compaction of the subsoil, however, is very difficult and expensive to undo, and the effects of subsoil compaction may be larger. With lighter machinery like Lasting Fields machinery subsoil compaction is expected to decrease, but it may take years for the subsoil to recover. It is difficult to estimate how long it will take the subsoil to recover. Subsoil compaction is namely depending on many different factors. However, it is estimated that yields may increase between 0% and 20% when the soil is less compacted in the topsoil. Besides, energy (diesel) consumption will go down. When lighter machinery is used there is a decreased need for ploughing, which requires a lot of energy. The founding father of the Lasting Fields concept, Wim Steverink, therefore estimates that energy consumption will be reduced with approximately 50%.

6.2.3. Financial benefits

When Lasting Fields is implemented, intercropping can be used as a cultivation system. As mentioned in the intercropping chapter, the increase in yield could be around 10% to 30%. The current revenue of the model farm, which can be found in table 6.2, equals €257,000. For the sake of simplicity, it is assumed that the increase of yield is equal to the increase in revenue. Therefore, the revenue could increase by around €25,000 to €75,000. Of course, this is depending on crop combinations and it is likely that the costs will also increase.

As a result of reduced soil compaction, the yield may increase by 0% to 20%. The additional revenue ranges between €0 and €50,000. In the Netherlands soil compaction is widespread, so it is likely that the yield per hectare will not remain constant, but increase. Next to an increase in output, a decrease in inputs is also expected. If intercropping is applied, crop protection agents can decrease with around 10%, which equals a cost reduction of around €2100 annually. Diesel consumption is expected to be cut in half, which equals a cost reduction of €3900 annually. Both reductions are calculated on the basis of the model farm. The total increase in revenue equals the increase in yield combined with the reduction of inputs, which ranges from €31,000 to €131,000. However, it is not logical to add up the increases in yield, because the effects of lower soil compaction and intercropping probably influence with each other. The maximum increase in revenue of €31,000 is therefore expected to be different. The Lasting Fields concept is nevertheless a very promising concept. However, if intercropping is not applied, the increase in revenue will be lower. The decrease in diesel consumption and the increase in yield as a result of reduced soil compaction will still hold, but the decrease in crop protection inputs will not hold.

6.2.4. Notes

The increase in yield and the decrease in crop protection are now calculated for the five standard crops of the model farm, while in the used literature these numbers are calculated for different crop combinations. The possible increase of revenue and decrease in the use of crop protection agents is therefore hard to estimate for the model farm. The other crops have a different profit per hectare, which makes the calculations not rock-solid. However, it does show that intercropping can be a huge potential for farmers.

6.3. Other applications of Lasting Fields

Implementing Lasting Fields provides an increase in revenue for the farmer. However, with Lasting Fields labour intensive vegetable crops with high profits per hectare could become very interesting for farmers to cultivate. For cultivating green asparagus, for example, harvesting requires approximately 208 hours per hectare when the harvesting is done without mechanized devices (KWIN-AGV, 2015). If a special Lasting Fields module is programmed in such a way that manual labour can be replaced with a machine, it will have major advantages. For example, average total labour costs per hour in agriculture were around €21 in 2014 (Centraal Bureau voor de Statistiek, 2014). This is including employers' costs. If only 100 hours could be saved with Lasting Fields, it will already save €2100,- per hectare annually. This should, of course, be investigated more elaborately, but it can be a very interesting application of the Lasting Fields concept, even without intercropping cultivation systems. For other labour intensive crops Lasting Fields can be promising as well, but it naturally depends on the costs of the Lasting Fields machinery.

6.4. Business model

During the interview with Joris IJsselmuiden, he mentioned that open source hardware and software development can be very interesting for concepts like Lasting Fields. Instead of applying for a patent for every part of the development, everybody can use the acquired knowledge and build on that knowledge to improve the whole concept. This will reduce the price of the Lasting Fields machinery, because the Research and Development does not need to be done by each manufacturer individually, but is made publicly (open source). This leads to a reduction of costs for each potential manufacturer, and hence a lower selling price is possible. However, that also implies that the profit margin on the machinery is not likely to be very high. If the profits would be very high, it is relatively easy for another firm to enter the market, because open source would be applied. In that case, manufacturers have to make their profits on providing services to farmers.

Another way to put the Lasting Fields concept on the market is by not using open source development. The most important change is that the machinery will become more expensive, because research and development costs are expected to be higher. That is not negative per definition. When the manufacturer is able to protect their developments through patenting, money can be earned through patent licensing as well. Other than the higher selling price, which is needed to recover the research and development investments, little has to change for the business model. The Lasting Fields machinery will use advanced technology, and the maintenance of it cannot be done by the farmer in the same way as the farmer can repair his own tractor. External mechanics may be needed for maintenance and Lasting Fields can also make profit by acting as an intermediary.

6.4.1. Leasing

Another way of marketing Lasting Fields machinery is leasing. In the beginning a lot of capital is needed, because the machinery already needs to be manufactured, while the manufacturer does not receive the payment at once, but in instalments. Even though capital may be a problem in the beginning, leasing certainly has many benefits. Leasing generates a steady cash flow of instalments paid by the farmer, so the manufacturer will have an income that is fixed for a certain amount of time. Also for farmers leasing can be very interesting. The farmers do not need to buy all Lasting Fields machines at once, which can be very costly. Instead the farmer leases the machines, so that he or she does not require a huge amount of capital at the beginning.

Manufacturers of agricultural machinery themselves offer their products in combination with several financial services, like leasing and purchasing on credit (Case IH, n.d.; New Holland, n.d.). Also banks offer services to farmers to buy on credit or lease machinery (ABN AMRO, n.d.; Rabobank, n.d.). Both the manufacturers and the banks offer the leasing including insurance and service. For sceptical farmers who question the reliability of Lasting Fields machinery, but are intrigued by the concept, this could be the guarantee they need to implement Lasting Fields.

6.5. Concluding summary

Lasting Fields is a very interesting concept which will both reduce costs (without taking the costs of machinery into account) and increase yields, especially when intercropping is applied. Even though the benefits of Lasting Fields are highest when intercropping is applied, the concept is still very interesting for farmers when intercropping is not applied, because the reduction in soil compaction is also expected to increase yield. Unfortunately, it is impossible to calculate the costs of implementing autonomous driving systems. Information about which sensors are installed on the machine (e.g. the potato harvester), and a cost estimation of writing the software needed. The economic study focuses on the financial gains of reduced soil compaction and intercropping, which are realistic effects of the Lasting Fields concept. However, the feasibility of Lasting Fields cannot be given, because the costs of implementing Lasting Fields are unclear. Lasting Fields is not only interesting for arable farming of the common crops. If Lasting Fields machinery can replace manual labour in labour intensive crops it may have a large potential, especially on root crops. The most difficult aspect of Lasting Fields may not be the technological part, but the social part. Just as the introduction of the milking robot, it may take a while before farmers accept the new reality of autonomously driving machinery.

7. Roadmap

The Lasting Fields concept is in an early stage of development. The concept is still open for new ideas and suggestions, however a proper planning is needed for reaching the future vision. Implementing Lasting Fields can be considered as developing a completely new product. In product development conducting a roadmap is essential in showing the product vision to stakeholders. In figure 7.1 a roadmap for the Lasting Fields project is shown. Some steps of the roadmap are already conducted by the current Lasting Fields cluster. This roadmap indicates a logical order of steps to be taken in order to reach the goal of this roadmap: Commercially implementing Lasting Fields. Investment budgets and available knowledge is not known at the moment, therefore the timescale of the roadmap is missing.

Forming a development cluster is essential in succeeding a large project like Lasting Fields. The Lasting Fields cluster should meet the complete range of requirements needed for developing and implementing the product. Lasting Fields partners could consists of: research institutes, innovative farmers (early adopters), an environmental NGO, a software developer, manufacturers and a marketing company. Research partners like, PPO Lelystad and CAH Dronten are in this stage already part of the project, while the Farm Technology Group of Wageningen University (interview with Joris IJsselmuiden) is also interested. Steverink Techniek BV is the manufacturing partner within this project. The start of a development cluster is already made, however software developing and marketing companies are not included at this stage.

During the whole project it is useful to get awareness for the product. Steverink built a proof of principle potato harvester, directly resulting in an increased interest in the project. Conferences also increase the awareness for the concept. Each stage of the development process provides interesting results and ideas for discussion. Attending conferences could also result in potential additional partners for the project.

Before developing Lasting Fields machinery, the effects of Lasting Fields have to be researched. More information is needed on the quantitative effects of Lasting Fields on the soil, like the environmental impact of Lasting Fields. Furthermore decisions on the development focus are needed. For example, the crop that is most suitable for the first prototype of Lasting Fields and the robot task that needs to be developed.

Besides developing a pilot tool carrier and rail system, multiple years of trails on a demonstration farm is needed to quantify the effects of Lasting Fields machinery. During the development and field trials the design needs to be reflected and improved continuously. Furthermore research should be done on the effects of these Lasting Fields on the demonstration farm. Effects on the soil and crop yield, the possibilities of implementing intercropping and the economic feasibility of the farm should be taken into account.

Finally the Lasting Fields concept could be implemented on the field of the innovative farming partners. Furthermore a business plan is needed before selling and market Lasting Fields products.

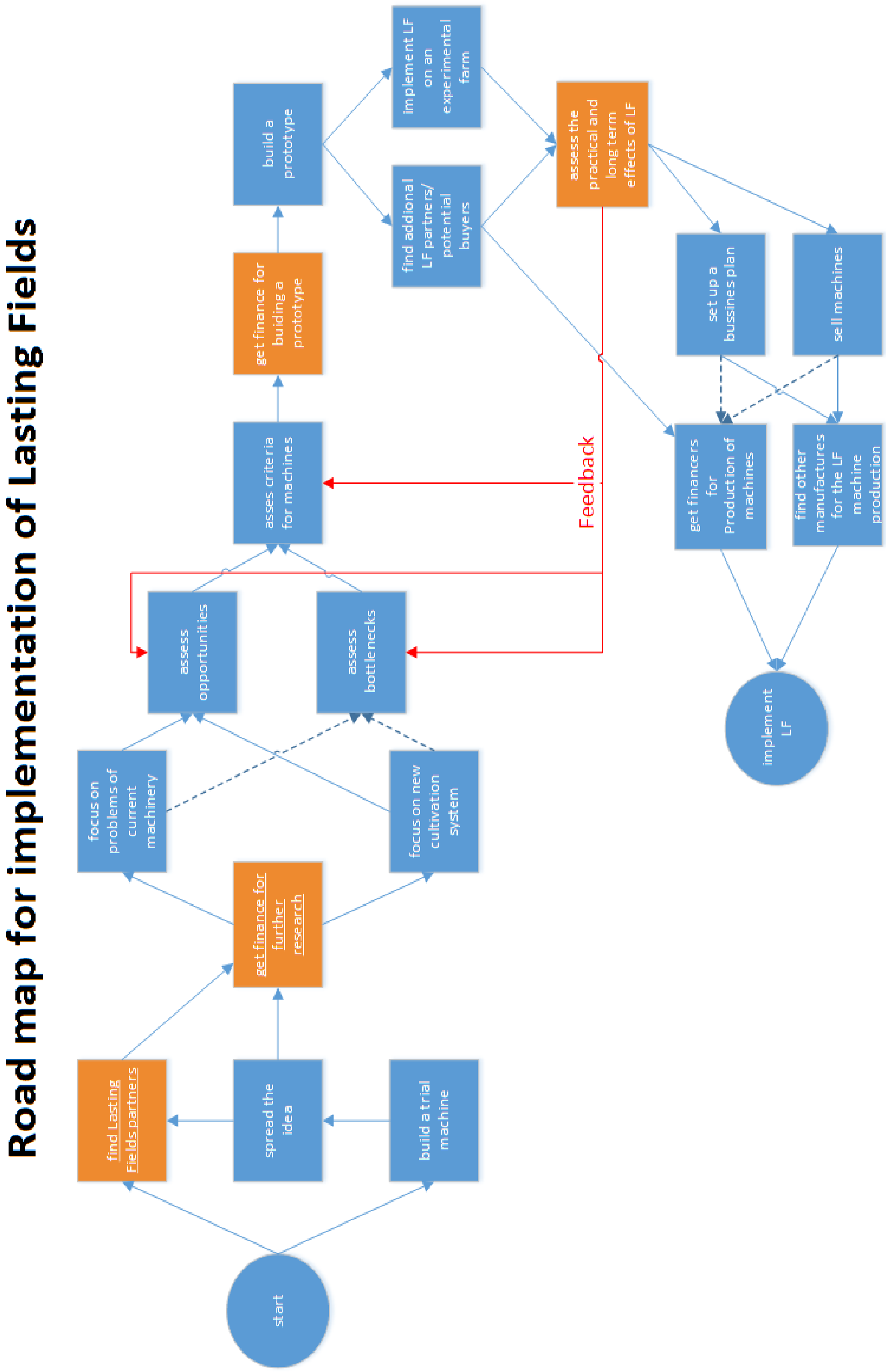

Figure 7.1. *Road map for implementation* Lasting Fields *The orange colour indicated the key steps which are required to make progress in the implementation. The underlined aspects indicate for which steps our report is useful. The red lines indicate the steps where feedback is provided from the assessment of practical and long term effects. The dotted lines are just to clarify the directions of the arrows when several arrows cross each other.*

7.1. Roadmap related to the report

The aim of this report was to provide our commissioner more information about the potentials of Lasting Fields. The relevance of the report with respect to further developing Lasting Fields is shown in the Roadmap. Furthermore the relevance of this report related to steps of the roadmap is explained below.

The report describes the consequences of soil compaction on physical, chemical and biological soil properties. Also a Life cycle assessment is created to estimate the energy consumption by the current way of potato cultivation in the Netherlands. Further research is needed to quantify the problems caused by conventional machinery. Furthermore, cultivation systems which are not applied in the Netherlands need further research. In intercropping machinery forms an important bottleneck. The machinery of Lasting Fields could be a key solution for implementing cultivation systems such as intercropping. The focus in this report was mainly on intercropping because there was a time constraint and the commissioner was mainly interested in intercropping.

In this report the potentials of reducing soil compaction and applying intercropping are estimated. For soil compaction an estimation of yield increase is estimated while for intercropping the increase range of yield and reduction range of weeds, pest and diseases**.** In this report some bottlenecks related to the problems of current mechanisation and new cultivation systems are indicated. The bottlenecks are about; capacity during labour peaks, knowledge gaps about energy saving potential, crop yield increase, costs of implementing Lasting Fields, long term effects, intercropping in practice in the Netherlands.

Every machine within Lasting Fields has to perform several functions. The best solution for a certain function can change over time due to technological development, changing view of the developer and investment potential for example. This set of design solutions is subjected to change, in every reflective iterative loop of machine development, the solutions to the concepts key functions have to be analysed. Important requirements like: low crop damage and low weight, should not be disrupted by changes made in the design concept.

8. Discussion & conclusion

The previous chapters provided an overview of the effects of soil compaction and intercropping. Furthermore, opportunities provided by Lasting Fields to reduce soil compaction and implement intercropping are discussed. Thereafter; the technology needed to develop Lasting Fields, environmental impact of Lasting Fields machinery and the economic potential are discussed. However, the Lasting Fields project is still in an early stage of development, therefore assumptions are made in these chapters. In this discussion chapter, the assumptions made to be able to conduct the chapters are discussed.

8.1. Soil compaction

Soil compaction can be caused by a wide range of factors, while a wide range of soil properties is affected by soil compaction. These changes in soil properties finally result in lower crop yields. Due to the wide range of causes and effects quantitative effects of a single cause is hard to determine. Therefore, the specific effect soil compaction has on a soil, especially the subsoil, is difficult to determine, because the vulnerability of the soil to compaction as well as the quantification of compaction is not straightforward. Compaction is a dynamic process in which for example aggregate strength (which determines soil porosity) is not static. Furthermore the quality of the structure of clay soils is more important than the bulk density or soil porosity, while for sandy and sandy loam soils this is not the case (Van den Akker, 2006). Additionally, other soil physical characters are not taken into account while particularly the initial state of the soil determines both the degree of (physical) change as well as the effect the change has on the chemical and biological consequences in response to compaction.

It is important to realize that beside the bulk density of the soil, the effect of soil compaction on plants also depends on soil structure, parent material, climatic conditions, organic matter content, presence and position of a root restricting layer, and the crop itself. Moreover, it is reported that the bulk density is not a very good indicator of soil compaction (Logsdon & Karlen, 2004). Although not a perfect measure for soil compaction, the degree of compactness still provides a reasonable indication of the effect of topsoil compaction on crop yields. Furthermore, it should be noted that the degree of compactness is not always measured by determining the uniaxial test with 200 kPa. In other studies higher pressure is sometimes used, although this was not the case in studies researched in this report.

It is important to realize that the effects of controlled traffic farming and light machines are not cumulative as they both involve decreased soil compaction. Effects of soil compaction and intercropping may partially overlap, because some of the negative effects of soil compaction may be mitigated by some of the positive effects of intercropping. Although no evidence of this was found in the literature of this effect it is possible that simply adding the yield increase by alleviating soil compaction with the yield increase by intercropping is likely to give an overestimation of the overall yield increase.

We focused on the physical and biological effects, while the chemical effects are not discussed very elaborate. The fertilizer requirements of the crop are probably affected by the rate of compactness of the soil.

8.2. Intercropping

Mechanisation is the major bottleneck for the application of intercropping in conventional European farms (Lithourgidis *et al.,* 2011). Machinery development is focussed on large uniform plots; therefore intercropping is mainly applied in developing, low labour costs, countries. Practical management and implementation of intercropping is also difficult when the two crops have different requirements for fertilizer and crop protection. Due to the reasons described above there is still no machinery designed to apply intercropping.

Lasting Fields machinery could handle this bottleneck. The small scale of the machines creates the possibility to cross the fields multiple times without creating severe damage to the soil (see 'Soil compaction' chapter). The small scale machinery could also handle with the strips of different crops or rows within the crops. The automation of the machinery could also solve the bottleneck of the intensive and expensive labour requirements in several labour intensive agricultural practices.

The reason why intercropping is not applied in the Netherlands is that agriculture is a market related economy. As intercropping is mainly interesting for farmers, support of farmers for such a system needs to be created first. Intercropping may be interesting to consumers that value organic products because part of the biological diversity is restored and other overall environmental benefits. Organic agriculture is also feasible in the Netherlands because consumers are willing to pay more for products that benefit animals and environment. This indicates that, with a proper market strategy that informs consumers of these benefits, intercropped products may increase in value compared to sole cropped products.

Currently farmers are not willing to adopt intercropping, due to the bottlenecks described above. Lasting Fields may be able to offer solutions in solving these bottlenecks; however the mind-set of farmers towards intercropping still needs to be changed.

8.3. Technology

All autonomous agricultural autonomous farming machines discussed in the technology chapter are in an early stage of development. The vehicles are developed in pilot studies. Therefore, currently no commercially arable farming mobile platforms are sold. The technological principles described by these studies are not proven to last considering all possible agricultural conditions. The focus is on studies about vehicles that navigate on cultivated land (row navigation or open field) for analysing mobile robots. Non-agricultural rough terrain robots are not taken into account, however these vehicles could also be applicable in arable farming. The set of solutions for every key function is based on the range of technical principles found in the literature about mobile robots. However, other field of research could provide additional technical principles.

The design concept described in the technology chapter is based on a personal point of view after analysing the currently developed agricultural mobile robots. The technological principles chosen as solution for every key function could differ over time, considering: technological development, changing point of view of the developer, stakeholder interference and investment potential for example.

Lasting Fields characteristics like small size, light weight and autonomously driven, match future visions of technological research studies. The wide range of research studies regarding autonomous driving in arable farming provides technical design solutions for the Lasting Fields concept. Autonomously conducting all farming tasks (tillage, seeding, weeding, fertilizing and harvesting) is not realized in research at the moment. Crucial for the Lasting Fields concept is; maintaining safety during all circumstances, managing data using an advanced farm management information system and using energy efficient solutions.

8.4. Life cycle assessment

The LCA shows that the Lasting Fields concept can be beneficial for the environment. It is important to take into account that intercropping was not included in the calculations, as well as the solar energy. In case these things will be implemented there are some marginal improvements in the results

It is likely that for next year's main fuel will remain diesel. Vegetable raw oils needs engine modification while mixed ones are not less polluting and still expensive. Others energetic source could be taken into account with further development of technology. For example when good batteries will be developed that can be implemented in the tractors. Batteries can be charged with solar panel that in coming years will also increase their efficiency.

8.5. Economy

Lasting Fields is a very interesting concept which will both reduce costs (without taking the costs of machinery into account) and increase yields, especially when intercropping is applied. Even though the benefits of Lasting Fields are highest when intercropping is applied, the concept is still very interesting for farmers when intercropping is not applied, because the reduction in soil compaction is also expected to increase yield.

Unfortunately, it is impossible to calculate the costs of implementing autonomous driving systems. Information about which sensors are installed on the machine (e.g. the potato harvester), and a cost estimation of writing the software needed. The economic study focuses on the financial gains of reduced soil compaction and intercropping, which are realistic effects of the Lasting Fields concept. However, the feasibility of Lasting Fields cannot be given, because the costs of implementing Lasting Fields are unclear. Lasting Fields is not only interesting for arable farming of the common crops. If Lasting Fields machinery can replace manual labour in labour intensive crops it may have a large potential, especially on root crops.

The most difficult aspect of Lasting Fields may not be the technological part or determining the effects on soil, crop and environment, but the social part. Acceptation of autonomous arable farming by farmers and society may take a while, similar to the introduction of the milking robot. Nevertheless, further developing Lasting Fields could result in an interesting and completely different alternative for conventional arable farming techniques.

9. Recommendations

This report focussed on the opportunities of Lasting Fields in solving arable farming problems, like soil compaction, applicability of new farming methods, increasing labour costs and energy efficiency. However, analysing the weaknesses of current arable farming practices and the new possibilities offered by the Lasting Fields project did not result in exact outcomes. Further research is needed to determine the quantitative impact of implementing Lasting Fields on arable farming. Therefore the following recommendations can be taken into account.

It is assumed that the increased wheeling frequency will compact the soil up to a maximum point like in figure 2.4, and that the decreased axle loads sufficiently decrease soil compaction. However, data of machine mass equal to the range of weight Lasting Fields will use and the relation with the wheeling frequency is missing. Therefore, it is not clear if Lasting Fields is better off without controlled traffic farming. Additionally, we found that some soil compaction is beneficial for the plant growth of at least some crops. This should be further researched.

The chemical effects are not very elaborate due to time limits, so we decided to focus more on the physical and biological aspects, because that is most useful with regard to soil compaction. The exact effect of soil compaction and denitrification and subsequently the need to increase fertilization is not analysed here. Relevant literature (mostly reviews) include:

- Hansen, S., Maehlum, J. E., & Bakken, L. R. (1993). N 2 O and CH 4 fluxes in soil influenced by fertilization and tractor traffic. *Soil Biology and Biochemistry*, *25*(5), 621-630.
- Ruser, R., Flessa, H., Russow, R., Schmidt, G., Buegger, F., & Munch, J. C. (2006). Emission of N 2 O, N 2 and CO 2 from soil fertilized with nitrate: effect of compaction, soil moisture and rewetting. *Soil Biology and Biochemistry*, *38*(2), 263-274.
- Sitaula, B. K., Hansen, S., Sitaula, J. I. B., & Bakken, L. R. (2000). Effects of soil compaction on N 2 O emission in agricultural soil. *Chemosphere-Global Change Science*, *2*(3), 367-371.

Reducing soil compaction affects the environmental impact of the system. Compaction of the soil reduces the carbon dioxide emission of the soil, whereas nitrous oxide emission increases. Nitrous oxide is a more potent greenhouse gas than carbon dioxide, so agriculture with compacted soils likely contributes to global warming. Further research on the environmental impact of reducing soil compaction is needed to be able to quantify the total impact of Lasting Fields.

For applying intercropping within the Lasting Fields project additional knowledge regarding the possibilities of intercropping in Dutch agriculture is needed. Furthermore research on the crop combinations with the highest potential is needed. Beneficial crop combinations should be investigated for determining the quantitative yield increase of the crops and the effect on fertilizer and crop protection agents use. The implementation of practical intercropping practices within the Lasting Fields project needs further research. Furthermore the relationship between yield advantages due to intercropping and yield advantages caused by reduction of soil compaction is not known.

A possible design concept is described in the chapter technology. The best solution of a certain function can change over time due to technological development, changing view of the developer and investment potential for example. The set of design solutions is subjected to change, in every reflective iterative loop of machine development, the solutions to the concepts key functions have to be analysed. Requirements like: low crop damage and low weight, should not be disrupted by changes made in the design concept.

The studies discussed in the chapter technology mainly focused on autonomous driving. Sensing techniques and software for row recognition and path planning are already developed by several research institutes. A high labour demand for manual weeding in organic farming resulted in a focus in research on autonomous weeding. Currently high capacity autonomous seeding and harvesting robots are not developed. On-board storage of seeds and harvested products often results in heavy machines. Intelligent logistics are needed to solve this storage problem and maintain seeding or harvesting capacity. Research on autonomous harvesting or seeding in combination with an intelligent logistics system (Rail system and on-field transportation robots) could improve the Lasting Fields feasibility. A farm/data management system needs to be developed. Completely automating arable farming results in an overdose of data, this farm management information system should provide farmer specific advice and create a safe and reliable way of farming.

The economic chapter discusses the monetary yield of reduced soil compaction and intercropping. However, the costs of machinery are not dealt with. Besides that, the economic chapter uses only one model farm with 50 hectares of adjacent fields. In further research, other model farms should be investigated. Also, when the costs of Lasting Fields machinery are clearer, these should be included in future studies. The economic potential of Lasting Fields is likely to decrease significantly when the fields of the farm are not adjacent. In further research it has to be studied from which plot size on Lasting Fields has economic potential.

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Appendix A: Autonomous vehicles specifications

Table 1. *Weeding Robot by Wageningen University*

Project name:		**Weeding robot**
Wageningen University, Bakker et al, 2010		
		
Dimensions:		
Weight	[kg]	1250
Traction:		4 steered wheels
Driving speed (field)	[m/s]	0.1 -1.8
Travel speed	[m/s]	3.6
Max steering speed	[deg/s]	180
Max steering angle	[deg]	360
Wheel sensors		cogwheel (100 pulses per revolution),analog angle sensor
Ground clearance	[cm]	50
Transmision:		hydrostatic
Energy:		
Supply		diesel
Engine		31.3 kW
Software:		
Connectivity		CANbus
Communication with farmer		webpage, SMS and board computer
Kind of operation:		weeding
Navigation & positioning:		
Weed recognistion		pattern recognition of plant spacing
Navigation along the row		machine vision
Determine if within field		GPS
Determine if on headland		GPS
Navigation on headland		GPS

__Table 2.__ Armadillo and Armadillo Scout by University of Southern Denmark

Project name:		**Armadillo**	**Armadillo Scout**
University of Southern Denmark , Nielsen et al 2012			
			
Price:	[$]	50000	50000
Weight	[kg]	425	425
Width	[m]	1.5	1.5
Length	[m]	80	80
Traction:		2 tracks	2 tracks
Driving speed (field)	[m/s]	2	2
Food print	[cm]	18x80 per track	
Energy:			
Supply		electric engine	electric engine
Engine		3 kW per track	
Battery type		AGM	LiFePO4
Battery pack		48 V 100 Ah	160 Ah
Battery weight	[kg]	150	100
Operation time	[h]	2.6	10
Recharge time	[h]	4.5	
Software:			
Connectivity		CAN, USB, RSS and Ethernet	CAN, USB, RSS and Ethernet
Operation system		FroboMind (ROS)	FroboMind (ROS) & MobotWare
Kind of operation:		tool carrier	

Table 3. Hortibot by University of Aarhus

Project name:		**Hortibot**
University of Aarhus, Jørgensen et al, 2007		
		
Price:	[$]	63363
Traction:		4 steered wheels
Wheel sensors		speed sensor, wheel angle sensor
Transmission:		hydrologic wheel motor
Energy:		
Supply		electric motor for steering
Software:		
Control module		16 bit Atmel AVR microprocessor
Connectivity		CANbus
Operation system		iComLinux
Communication with farmer		internet database
Kind of operation:		tool carrier
Navigation & positioning:		
Navigation along the row		machine vision (Eco-Dan A/S)

Table 4 APU-Module by Aalto University

Project name:		**APU-Module**
Aalto University, Oksanen, 2013		
Dimensions:		
Weight	[kg]	5900
Traction:		4 steered wheels (Ackermann)
Driving speed (field)	[m/s]	1.8
Max steering speed	[deg/s]	8-dec
Max steering angle	[deg]	22
Wheelbase	[m]	2.7
Transmission:		hydrostatic
Energy:		
Supply		diesel
Engine		123 kW
Kind of operation:		seeding
Navigation & positioning:		GPS

Table 5. *AgRover Gen.II by Iowa State University*

Project name:		**AgRover Gen.II**
Iowa State University, Xuyong Tu, 2013		

Dimensions:		
Width	[m]	1.85
Traction:		4 steered wheels
Energy:		
Supply		electric
Engine		150 W
Battery pack		24 V
Software:		
Connectivity		CAN-USB
Kind of operation:		Tool carrier
Navigation & positioning:		RTK-GPS

Table 6. *SRFV by Queensland University of Technology*

Project name:		**SRFV**
Queensland University of Technology, Bawden et al, 2014		

Dimensions:		
Weight	[kg]	600
Width	[m]	3
Length	[m]	2
Traction:		2 wheel drive + 2 castor wheels
Driving speed (field)	[m/s]	1.39
Transmission:		50:1 two stage gearbox
Energy:		
Supply		electric
Engine		10 Kw
Battery pack		60V 200 Ah
Operation time	[h]	10

Table 7. BoniRob by Deepfield-robotics

Project name:		BoniRob
Deepfield-robotics, Ruckelshausen et al, 2009		
		
Capacity:	[h/ha]	3 @ 40 weeds/m2
Dimensions:		
Weight	[kg]	1100
Width	[m]	2.8
Length	[m]	2.4
Traction:		4 steered wheels
Driving speed (field)	[m/s]	1.5
Track width	[m]	1.0 - 1.9
Max steering angle	[deg]	90
Ground clearance	[cm]	85
Energy:		
Supply		electric
Engine		2.6 kW
Battery pack		24V 230 Ah
Operation time	[h]	24
Software:		
Connectivity		CANbus, Ethernet, Wi-Fi, USB, Bluetooth
Operation system		Ubuntu Linux (ROS + Gazebo)
Kind of operation:		Tool carrier
Navigation & positioning:		GPS
Navigation along the row		video and LIDAR positioning

__Table 8.__ Robotti by Kongskilde

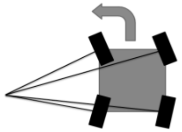
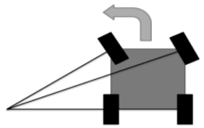
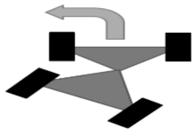
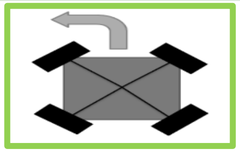
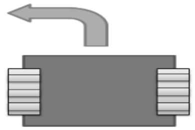
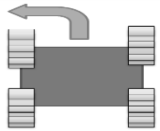
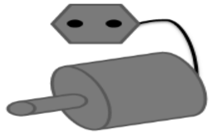
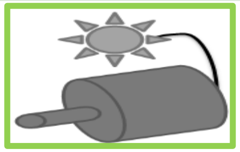
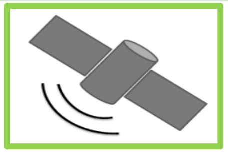
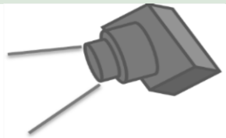
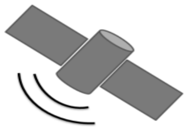
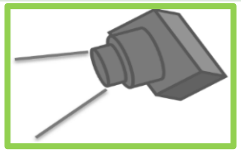
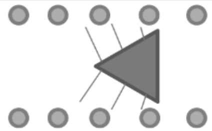
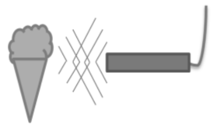
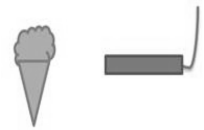
Project name:		**Robotti**
Kongskilde, Jakobsen, 2015		
		
Dimensions:		
Weight	[kg]	400
Traction:		2 tracks
Driving speed (field)	[m/s]	2.7
Transmission:		
Energy:		
Supply		electric
Engine		5 Kw per track
Kind of operation:		weeding
Navigation & positioning:		
Weed recognition		RTK-GPS
Navigation along the row		Xbox 360 Kinect (RGB and 3d)
Determine if within field		
Determine if on headland		Xbox 360 Kinect
Navigation on headland		odometry

__Table 9.__ Oz by Naio Technologies

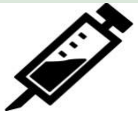
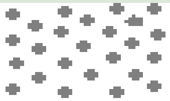
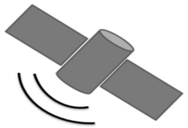
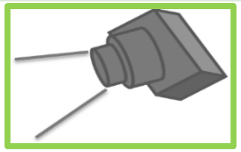
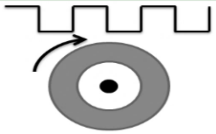
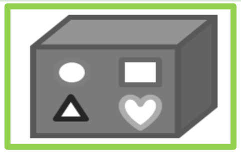
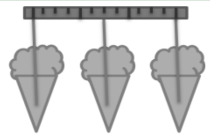
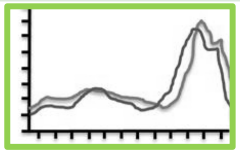
Project name:		**Oz**
Naïo Technologies		
		
Capacity:	[h/ha]	48 rows of 100m /4h
Dimensions:		
Width	[m]	0.4
Length	[m]	0.7
Traction:		4wd, differential steered
Energy:		
Supply		electric
Software:		
Operation system		FroboMind
Communication with farmer		SMS
Kind of operation:		weeding

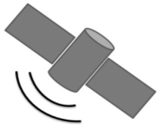
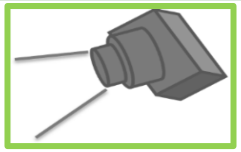
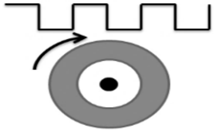
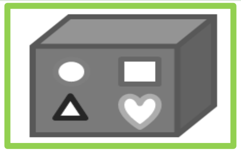
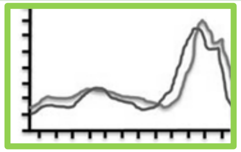
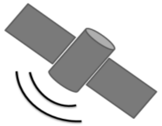
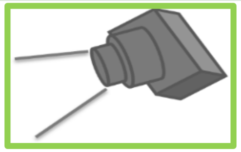
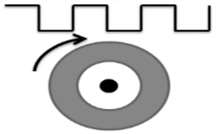
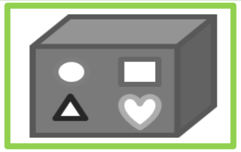
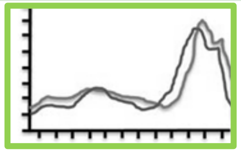
Appendix B: Morphologic chart

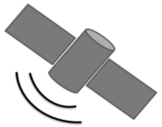
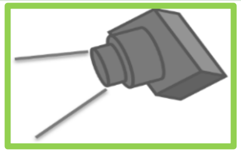
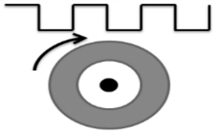
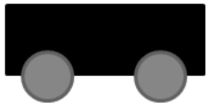
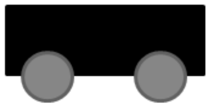
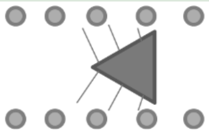
Part of the concept solution

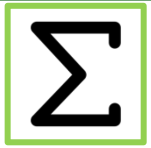
Operation:	Function:	design solutions: 1	2	3	4	5	6
On field operations: General	Moving (&steering)	 4 wheels (4*Ackermann)	 4 wheels (2*Ackermann)	 4 wheels (articulated steering)	 4 wheels (4 360^{o} steered wheels)	 2 tracks	 4 tracks
	Energy supply	 gas engine	 diesel engine	 electric engine + recharge point	 electric engine + solar panels	 Hydrogen cells	
	determine if in field	 GPS	 Vision				
	navigation in the field (row crop)	 GPS	 Vision	 Tactile	 Ultrasonic	 Optical	

navigation in the field (full field)	GPS	Dead reckoning				
determine if on headland	GPS	Vision	Tactile	Ultrasonic	Optical	Dead reckoning
navigation on headland	GPS	Dead reckoning	Vision			
communication within the vehicle	CAN	Ethernet	USB	Wi-Fi	Bluetooth	RSS
communication with other on field robots	preplanned paths	continues updating robot position				
detect unsafe situations	super canopy	sub canopy				

seedbed preparation	changing operation device	 device dropped by the robot	 Device placed in robot by other system		
	Seed conditioning	 adding nutrients while seeding	 variable seed placement depth		
Seeding	seeding	 reseeding	 vertical punch mechanism	 water-jetting	 conventional mechanical
	seed placement	 row	 grid	 variable density	 full field
	positioning of seeding device	 GPS	 Camera	 Dead reckoning	
Weeding	determine where weeding has to be	 Seed mapping	 shape & colour	 pattern	 spectral reflectance

	weeding	 mechanical weeding	 precision spraying	
	positioning of weeding device	 GPS	 Camera	 Dead reckoning
	crop scouting	 shape & colour	 spectral reflectance	
Fertilizing	fertilizing	 precision spraying	 Injecting near plant	
	positioning of fertilizing device	 GPS	 Camera	 Dead reckoning
Harvesting	crop scouting	 shape & colour	 spectral reflectance	

		harvesting	 selective harvesting	 Conventional harvesting	
		positioning of harvesting device	 GPS	 Camera	 Dead reckoning
Transport and logistics:	General	Moving (&steering)	 rails	 by on field robots	
	Transport of robots	communication with robots	Robot digitally connects to transportation device	Robot and rail system up-date to FMIS	
		transporting the robot	 Lifting/carrying robot	 Robots drive itself	
	Transport of - .	Detecting harvested crop	 tactile	 Weight sensors	 Data from harvest robot

		transporting the products	 pre-sorting on the field	 transporting all harvested products	
Farmer:	communication with robots	input of robot settings	 board computer	FMIS FMIS	
		updating robot status	 SMS	FMIS FMIS	
	farm management	decision support	 Weather data	 Soil data	 Market data