Swedish University of Agricultural Sciences

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How Local Ecosystem Service Management may Reduce Climate Change Impact of Weed Control

- Case studies in organic vegetable production

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Abstract

This study was performed in cooperation with a participatory research group called 'Climate-Smart Agriculture – Sustainable Solutions for the Future'[1]. It investigated how the use of local ecosystem services in organic weed management could decrease the impact on climate change of fossil fuel-intensive mechanical and thermal weeding methods. The study was designed to examine global challenges that have been internationally emphasised during recent years, such as climate change, peak oil and ecosystem degradation. A premise of the study was that it is necessary not only to increase efficiency or replace the energy source but also to perform large reductions in the total amount of energy used.

Participatory research methodology and a systemic approach were used. Weed management strategies that reduce the use of fossil fuels with the help of ecosystem services were developed for three farms in consultation with their owners. An on-farm experiment with mechanically spread green mulch from fresh ley was performed on one of the farms. Other weed control methods discussed within the study included green mulch from leftover silage, intercropping vegetables with a permanent red clover ley, consumer participation in weeding, weed-competitive ley species mixes, annual ley species mixes grazed by horses in late autumn, increasing the amount of autumn-sown crops and/or ley, increasing the amount of annual crops, which are less labour-intensive than vegetables, and inter-row cultivation, i.e. vegetables transplanted into a dead cover crop. Some of the methods could be adopted immediately, while others need to be developed and tested for different local specific conditions.

A sustainability evaluation tool was developed based on the system conditions of the Natural Step and spider diagrams. The tool needs further development but proved suitable for the purpose of evaluating agricultural practices from a wide perspective of sustainability and for identifying knowledge gaps concerning the sustainability of the agricultural practices.

Suggestions are given on how to use participatory methods to increase the development and adoption of climate smart weed management strategies.

[1] See www.scwartzstiftelse.se (in swedish).

English-Swedish Dictionary, Abbreviations and Terms

Allelopathy	En negativ effekt på växter orsakat av biokemikalier som produceras av en levande organisk eller mikrobiell nedbrytning av en växt.	An adverse effect on plants caused by biochemicals that are produced by a living plant or by the microbial degradation of a plant.
Annex 1 countries	Annex I till Climate Convention (UNFCCC) listar alla länder OECD plus länder i transition; Central- och Östeuropa (utom ex. Jugoslavien och Albaninen). Övriga länder kallas därmed icke-Annex I länder.	Annex I to the Climate Convention (UNFCCC) lists all the countries in the Organization of Economic Cooperation and Development (OECD), plus countries with economies in transition, Central, and Eastern Europe (excluding the former Yugoslavia and Albania). By default the other countries are referred to as Non-Annex I countries.
Annual Ryegrass (*Lolium westervodium*)	Westervoldiskt rajgräs	
Antropogenic	Orsakat av människan	Human induced
Barn hay drier	Skulltork	
Barren brome (*Bromus sterilis*)	Sandlosta	
Basic fertilizing	Grundgödsling	
Biodigested material	Rötslam från t.ex. biogasproduktion	
Black grass (*Alopecurus myosuroides*)	Renkavle	
Black Nightshade (*Solanum nigrum*)	Nattskatta	
Broom (*Cytisus scoparius*)	Harris	
Brush	Oönskad buske eller litet träd.	Undesirable bush or small tree.
Carrot fly (*Psila rosae*)	Morotsfluga	
Chisel plow	Kiselplog eller alvkultivator	
Cock's-foot (*Dactylis glomerata*)	Hundäxing	
Cockspur (*Echinochloa crus-galli*)	Renkavle	
CO_2 eq.	Koldioxid ekvivalenter. Varje växthusgas multipliceras med dess värmande potential jämfört med koldioxid.	Carbondioxide equivalents. Each greenhouse gas multiplied by their warming potential compared to CO_2
Common bird´s-foot-trefoil (*Lotus corniculatus*)	Käringtand	
Quackgrass or Common couch (*Elytrigia/Elymus repens*)	Kvickrot	

Common vetch (*Vicia sativa*)	Fodervicker	
Corn spurrey (*Spergula arvensis*)	Åkerspärgel	
Cover Crop	Marktäckningsgröda som sås in i eller efter huvudgrödan och dödas (mekaniskt) innan nästa gröda planteras. Resterna lämnas på marken som död marktäckning.	Any living ground cover that is planted into or after a main crop and then commonly killed before the next crop is planted
Creeping thistle (*Circium arvense*)	Åkertistel	
Crop-rotation	Växtföljd	
Cucumber (*Cucumis sativus*)	Gurka	
Cultivator	Djupharv	
Dandelion (*Taraxacum*)	Maskrosor	
Disc harrow	Tallriksharv	
Dock (*Rumex longifolius, Rumex crispus*)	Skräppa	
Fat-hen (*Chenopodium album*)	Svinmålla	
Field bean (*Vicia faba*)	Åkerböna	
Flail forage harvester	Slaghack	
Floating row cover	Fiberduk	
Forb	Blommande örter som inte tillhör gräsen eller gräslika botaniska familjer.	Herbaceus flowering plants that are not graminoids (grasses, sedges and rushes).
GHG	Växthusgas	Greenhous gas
Gorse (*Ulex europeus*)	Ärttörne	
Graze	Beta	
Green manure	Gröngödsling	
Green mulch	Marktäckning med dött organiskt material	
Green nightshade (*Solunm physalifolium* Rusby)	Bägarnattskatta	
Hide	Skinn	
Inter-row cultivator	Radhacka	
Harrow	Harv eller harva	
Lactic acid fermentation	Mjölksyrning	
Late blight (*Phytophthora infestans*)	Potatisbladmögel	
Leaf sucker (*Trioza apicalis*)	Morotsbladloppa	

Ley	Vall	
Littleseed canarygrass (*Phalaris minor*)	Småflen	
Living mulch	Samodling eller marktäckande samodling.	Cover crops planted either before or with a main crop and maintained as a living ground over throughout the growing season
Lucerne (*Medicago sativa*)	Lusern	
Mitigation	Mitigation is defined here as an anthropogenic intervention to reduce the sources of greenhouse gases or enhance their sinks.	
Moldboard plow	Vändskiveplog	
Mower	Gräsklippare. slåttermaskin	
Oat (*Avena sativa*)	Havre	
Pasture	Bete	
Pea (*Pisum sativum*)	Ärta	
Pineapple Weed (*Matricaria matricarioides*)	Gatkamomill	
Plough	Plog eller plöja	
Pale Persicaria (*Persicaria lapathifolia*)	Pilört	
Persian clover (*Trifolium resupinatum*)	Perserklöver	
Precision chopper	Exakthack	
Rangeland	Expansiva landskap som till större delen är outvecklade där majoriteten av växtligheten består av inhemska gräs, gräsliknanade växter, örter och buskar. Kan i vissa fall inkludera sådda arter men dessa hanteras som den inhemska vegetationen	
Red clover (*Trifolium retense*)	Rödklöver	
Resilience	Resiliens är förmågan hos sociala och ekologiska system att motstå och återhämta sig från t.ex. klimat och ekonomiska shocker/katastrofer/attacker. (www.stockholmresilience.org)	Resilience refers to the capacity of a social-ecological system both to withstand perturbations from for instance climate or economic shocks and to rebuild and renew itself afterwards. (www.stockholmresilience.org)
Root-pruning	Rotbeskärning	
Rye (*Secale cereale*)	Råg	
Schredder	Betesputs	
Semi-naturall pasture	Naturbete	
Sea-buckthorn (*Hippophaë rhamnoides*)	Havtorn	
Slurry	Rötslam från t.ex. biogas produktion	

Smooth Meadow-grass (*Poa pratensis*)	Ängsgröe
Spring-tooth harrow or spring-tine harrow	Fjäderharv, halvstyvpinneharv
Tillage	Jordbearbetning eller brukad jord (Wikipedia 06.10.2008)
Timothy (*Phleum pretense*)	Timotej
Top dressing	Övergödsling
Triticale (*x triticale*)	Rågvete
white clover (*Trifolium repens*)	Vitklöver

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1. Introduction

1.1. Background

This study was performed in cooperation with a participatory research group called 'Climate-Smart Agriculture – Sustainable Solutions for the Future'[2]. It investigated how the use of local ecosystem services in organic weed management could decrease the impact on climate change of fossil fuel-intensive mechanical and thermal weeding methods. The study was designed to examine global challenges that have been internationally emphasised during recent years, such as climate change, peak oil and ecosystem degradation. These challenges are described in more detail in appendix A-C. Here the premises will be made explicit to explain why the focus of the study is on decreasing the use of fossil fuel with the help of ecosystem services.

Since the 1950s food production has been able to grow at a high speed with the help of fossil fuels and through large ecosystem changes (MA, 2005). Now the Millennium Ecosystem Assessment (MA, 2005)[3] has shown that the basis for food production – functioning ecosystem services – have been severely degraded over the same short time period. It has also been shown that climate change and the degradation of the ecosystem services have disproportionally affected the poor (MA, 2005; IPCC 2007b; UNDP, 2007/2008). It can thereby be assumed that food production will not be able to continue increasing at the same pace or by the same methods as before. The Intergovernmental Panel on Climate Change (IPCC)[4] reports from 2007 showed the dangers of climate change and the urgency of action. The Stern Review on the Economics of Climate Change[5] explained that solutions to climate change today are more affordable than the costs of inaction or future measures. There is an international agreement of not exceeding 2°C temperature increase compared to pre-industrial times in order to avoid dangerous climate change (EU Commission, 2007). This implies that the emission peak should occur no later than 2015 and there should be a global reduction of greenhouse gas (GHG) emissions with at least 85 % by 2050 (IPCC, 2007c). The countries in the South have historically contributed much less to climate change. They are also less capable of financing climate change mitigation. These facts have motivated an international scientific group including the Stockholm Environmental Institute (SEI) to develop an emission reduction model called Green Development Rights (GDR). The model admits the right of the countries in the south to release larger amounts of GHGs than the countries in the North (Kartha *et al.*, 2008). This means that the countries in the north should take a larger part of the responsibility to reach the global emission reductions needed to avoid dangerous climate change above 2°C. According to the GDR model the European Union suggestion of reducing its emission by 20% in 2020 and 50% by 2050 is far too limited (EU, 2008a; Kartha *et al.*, 2008). A SEI report based on GDR suggests that Sweden needs to reduce the emissions

[2] See www.scwartzstiftelse.se (in swedish).
[3] The objective of the MA was to assess the consequences of ecosystem change for human well-being and the scientific basis for action needed to enhance the conservation and sustainable use of those systems and their contribution to human well-being. The MA has involved the work of more than 1,360 experts, governments, NGOs and the private sectore worldwide. [http://www.millenniumassessment.org/en/index.aspx]
[4] IPCC is a comprehensive, objective assess of the the latest scientific, technical and socio-economic literature produced worldwide relevant to the understanding of the risk of human-induced climate change, its observed and projected impacts and options for adaptation and mitigation. The panel is made up of the UN, governments and scientists. [http://www.ipcc.ch]
[5] The Stern review was ordered by the government of the United Kingdom and excecuted by Sir Nicholas Stern, Head of the Government Economic Service and Adviser to the Government on the economics of climate change and development. [http://www.hm-treasury.gov.uk/sternreview_index.htm]

with 122%[6] by 2020 (Kartha *et al.,* 2008). This information is chocking and therefore difficult to believe. Nevertheless it is difficult to argue against a fair and safe path of climate change mitigation. Furthermore it must be emphasized that positive feedbacks and non-linear relationships are the rule in the Earth system. Since our knowledge about theses relationships is very limited there is no way of knowing if a certain level of GHG emissions will result in only 2°C (Steffen, 2006; IPCC, 2007a).

It is expected that already with moderate temperature increases within a short term drought will increase and yields decrease from the south of Europe down the whole southern hemisphere (IPCC, 2007b:66-67). At the same time northern latitudes are expected to experience increased yields (IPCC, 2007b:66-67). It is therefore reasonable to assume that there will be large movements of refugees from the south to the north. At the same time the world population is increasing. Efforts to reduce population growth are highly important but it can be assumed that the efforts will not succeed in maintaining the population on its current level. Hence food production in the north will need to increase both to replace imported food from the south and to feed an increased population in the north. If further climate change is to be avoided the increased production should rely on methods which decrease the emission of greenhouse gases. The single most dominant source of greenhouse gases is the burning of fossil fuels (IPCC, 2007c:4). Reducing the dependency on declining resources of fossil fuels would make food production less vulnerable. It would also help mitigate climate change.

The International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD, 2008)[7] emphasized the need to move from industrial agriculture to a locally adapted and resilient agriculture in order to advance in rural development and food sovereignty. Added to this there are strong indications that oil has reached its peak production and will eventually start to decline (Bentley *et al.,* 2007; Aleklett and Campbell, 2003;). The Hirsch report (2005) ordered by the US government was an eye-opener for the impacts, mitigation and risk management of the oil peak. Oil is providing 40% of traded energy and 90% of transport fuel, hence a peak will imply a historic turn point affecting most aspects of human life on Earth including agriculture, which means food (Aleklett and Campbell, 2003). Food production is today heavily dependent on oil both as a fuel during the production of agricultural inputs, driving tractors, food processing, storage and distribution, and oil as a raw material in packaging, fertilizers, pesticides and herbicides (Johansson 2005, Pimentel *et al.,* 2008). When we are forced to reduce our oil consumption there is a great risk of famine, military actions and social insecurity (Leder and Shapiro, 2008). To avoid part of these impacts mitigation must be initiated at least a decade before peaking according to the Hirsch report (2005). Therefore it is assumed that research and action should focus on immediate and substantial reduction of fossil fuel dependency in all aspects of society.

A continued use of the remaining fossil fuels will highly increase the risk of dangerous climate change for three reasons 1) the technology for cleaner and safer use of fossil fuels

[6] The percentage is higher than 100 since it includes both national emission reductions and reductions to which Sweden contriubtes to in countries in the south.

[7] The IAASTD was launched as an intergovernmental process, with a multi-stakeholder Bureau, under the co-sponsorship of the FAO, GEF, UNDP, UNEP, UNESCO, the World Bank and WHO. The objective was to evaluate the impacts of agricultural knowledge, science and technology on hunger, poverty, nutrition, human health, and environmental and social sustainability in relation to both the past and the future. The process brought together governments; Non-governmental Organizations (NGOs); the private sector; producers; consumers; the scientific community; Multilateral Environment Agreements (MEAs) as well as multiple international agencies involved in the agricultural and rural development sectors to share views and gain common understanding and vision for the future [www.agassessment.org].

will not be widely spread yet for a long time 2) there are no guarantees that the new technology will be adequate 3) there is no guarantee that even the most stringent CO_2 emission scenario of the IPCC will prevent the world from entering dangerous climate change. Alternatives to oil as large scale biofuel production will not be enough and will further increase the competition for arable land and water for food production as well as the functioning of ecosystem services (Azar, 2007; Giampietro *et al.*, 1997; Helmfrid and Haden 2006; Pimentel and Patzek, 2007). This increase in competition comes in a time when 1) world population is growing, 2) climate change is diminishing the arable area and fresh water availability of the world as well as increasing pest problems (IPCC, 2007b) and 3) several ecosystems are in danger of collapse (MA, 2005). The ones most prone to suffer the consequences are, again, the poor. Several studies have shown that most other oil substitutes will only (perhaps) be available in more distant future and/or they are associated with high risk, cost and environmental pollution (e.g. IPCC, 2007c; EWG, 2006; Odum, 1996; Azar *et al.,* 2003)

According to Eksvärd (2007) when using a systemic approach the first question to be asked should not be, are we doing this thing right, but, are we doing the right thing? Due to the risks and limitations of the oil substitutes and the urgency and amplitude of avoiding dangerous climate change this study assumes that there is a need for a greater focus on reducing our dependency on high amounts of energy. Only relying on more efficient technology out of which some are expected to perhaps be available and adequate by 2030 or later does not seem to be a viable option. Hence, the right thing to do would be to develop and implement methods, habits and practices which require low input of commercial energy and other resources.

Weed management is a part of organic food production which is dependent on important amounts of fossil fuels (Dalgaard *et al.,* 2002; Ahlgren, 2003). Hence in this study the aim is to investigate how this dependency can be decreased to avoid further ecosystem degradation. It will be investigated if the agricultural systems on the farms can be managed in such a way that it strengthens ecosystem services which in turn can help reduce the need for external resources in weed control.

The following reflection about the challenges the global community is facing can be found in the Human Development Report (UNDP, 2007/2008) *"The battle against dangerous climate change is part of the fight for humanity. Winning that battle will require far-reaching changes at many levels - in consumption, in how we produce and price energy, and in international cooperation. Above all, though, it will require far-reaching changes in how we think about our ecological interdependence, about social justice for the world's poor, and about the human rights and entitlements of future generations."*

1.2. Objectives

The overall aim of this study was for all participants to learn how a practical issue, sustainable weed control, can be managed in a local setting in the light of the above mentioned challenges; climate change, peak oil, ecosystem degradation and their social consequences. The main sustainability issue addressed in weed control was decreased impact on climate change. The study investigated the possibility to achieve this by e.g. reducing the amount of fossil fuel consumption and by managing local renewable ecosystem services. In order to develop new weed management practices which take into account the various challenges and benefits that farmers encounter it was decided that the study should be based on case studies. Hence the weed management strategies were developed for three organic vegetable farms together with their owners.

The appendixes on Climate Change, Ecosystem Services and Peak Oil and Oil Alternatives are literature reviews which can serve as background material in communication with other actors (farmers, students, family, media, consumers, politicians etc). In the same way the farm case studies can be used to give indications on how to work with weed management with less impact on climate change.

Defining global challenges is not an exact science. There are different perspectives or premises in the form of assumptions, interpretations and priorities. Nevertheless the assumptions, interpretations and priorities are always part of the equation when decisions are made about which research questions and development issues it is relevant to focus on. One of the aims of this study was to make the premises explicit (*1.1. Background*) based on a more thorough literature review for each challenge (*appendix A. Climate Change, appendix B. Ecosystem Services and appendix C. Peak Oil and Oil Alternatives*). The premises are made explicit in order to explain why it is relevant to reduce not only the use of fossil fuels but overall energy consumption with the help of ecosystem services.

Within the aim of the study both global theoretical issues and local practical issues are included. The aim and the method of the study lead to three different kinds of outcomes:

a) Chapter 3.1. A presentation of weed management measures developed together with the farmers while taking into account the premises of the study, expected climate change and its impact on weed management as well as the properties of the farms and the social situation of the farmers. Also some weed management strategies which were not directly applicable on the participating farms but could be viable options on similar farms were discussed amongst the participants and presented in the thesis to increase its usefulness in communication with other actors.
b) Chapter 3.2. Presentation of the sustainability evaluation of weed management strategies with the help of a sustainability evaluation tool developed within the study. The purpose was to include the complexity of the real-life situation and to see what impact the strategies may have on overall sustainability where the global challenges mentioned earlier are included.
c) Chapter 3.3.-3.6. A presentation of what was learnt about the strengths (what has been achieved) and weaknesses (what limited the process) of the participatory research process as well as suggestions of how to improve the process in the future.

1.3. Literature Review of Weed Management Practices, Greenhouse gases and Energy Consumption in Today's Organic Agriculture.

This chapter will show the relative importance of agriculture and weed management to total national GHG emissions. It also points out the dependency of organic weed management on fossil fuels and compares the fossil fuel consumption and GHG emissions during weed management to other agricultural practices. Thereafter follows an introduction to an array of weed management strategies. Finally it will be discussed which weed management practices could be regarded as based on local ecosystem services.

The total amount of greenhouse gas emissions in Sweden is about 70 million ton CO_2 eq to which agricultural production contributes with 15%[8] (SJV/SCB, 2008). Only direct emissions are included in the 15%, hence e.g. the highly energy consuming production of N fertilizer is not included. Organic soils which are the most dominating source of GHG emission are not included. Production of biofuels is also excluded. A study by Edström (2005) showed that out of the total direct and indirect energy[9] used in Swedish primary agriculture production 26% originated from fossil fuels consumed during crop production (including ley). The study also showed that mixing and spreading animal manure represented 6% while fertilizer production consumed 31%. According to a review by Dalgaard *et al.* (2002) Danish agriculture contributes with 20% of the total GHG emission in Denmark. Out of that 25% of the agriculture emissions originate from the burning of fossil fuels.

There is no national summarizing statistical data on energy consumption during mechanical weeding and soil operations associated with weeding. Hence information from farm case studies and models based on general values must be used. Very few studies on energy balances on ecological farms have been found. Those found are of different quality some comparing the same crop rotation in ecological and conventional agriculture (which is rare in practice) others compare typical crop rotations for the two production system but may choose to allocate the GHG emission differently to different crops. No studies including vegetables have been found but it can be assumed that the energy consumptions associated to weeding will be higher in vegetable production due to more inter-row weeding. Those found will only give a partial picture since the important factors as crop rotation, soil type, machinery and weather differ from farm to farm.

Organic agriculture often has a lower energy consumption per ha than conventional agriculture, in some cases even up to 50% lower (e.g. Daalgard *et al.,* 2002; Mäder *et al.,* 2002; Pimentel *et al.,* 2005). Most energy benefits in organic agriculture were gained by not using synthetic fertilizers and less imported fodder (Törner, 1999; Pimentel *et al.,* 2005; Mäder *et al.,* 2002). Counted per kg produce the energy consumption is sometimes inceases for organic production often due to lower yields, however normally the energy consumption is still lower or equal to conventional production (Törner, 1999; Dalgaard *et al.* 2002; Mäder *et al.,* 2002). In some cases the energy consumption used in production with mechanical weeding has been shown to be higher than in production with chemical weed management (Ahlgren, 2003) showing that mechanical weeding does contribute with GHG emissions which cannot be disregarded. Ahlgrens study did however only compare the option of mechanical or chemical weeding within conventional production. In organic production a large part of the total emission caused by the production of synthetic fertilizers would have been excluded.

According to Danish agricultural extension office at Landscentret (2008) the far largest amount of energy associated with soil tillage is caused by plowing (excluding sugarbeet harvesting).

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[8] Only direct emissions are included, hence emissions created during e.g. production of machinery is not included.

[9] Energy originating form; diesel, coal, oil, gas, electricity and biofuels.

In Wicks *et al.* (1995) it is stated that much energy can be saved in mechanical weed management by;

- Using no-till planting where possible.
- Using chisel plowing or disking instead of moldboard plowing.
- Avoiding *primary tillage*[10] deeper than 20 cm.
- Reducing the number of *secondary tillage*[11] operations.
- Avoiding secondary tillage deeper than 10 cm.
- Combining various operations, e.g. pulling a spring-tooth harrow behind a disk.
- Traveling in the highest gear practical and ease on the accelerator.
- Maintaining proper driver-wheel slippage.
- Ensuring that tillage equipment is properly adjusted.
- Matching implement size to tractor size.

Apart from increasing erosion and contributing to soil water loss (Wicks *et al.,* 1995:78-79) tillage also increases the GHG emission of CO_2 and sometimes N_2O from the soil (Smith *et al.,* 2008). However it should be mentioned that there is more water loss through weeds in the field than through tillage (Wicks *et al*., 1995:58).

Even though organic agriculture seems to have a lower or similar total energy consumption compared to conventional agriculture there is still a need to decrease dependency on fossil fuels where possible. Although there is limited data on diesel consumption and GHG emissions from weed management it can be concluded that reduced soil tillage, especially reduced plowing, and increased yields/ha in organic agriculture have the potential to reduce GHG emissions in organic weed management. Both options are associated with different challenges. If efforts to increase yields are made, care should be taken not to; compromise with biodiversity, increase eutrophication by adding more N to the terrestrial and aquatic systems, reduce long term soil fertility and thereby crop quality in form of human nutrition and resistance or tolerance of pest and disease attacks. Reduced soil tillage must not increase weed problems, especially perennial weeds, to an unacceptable level. However possible synergies could also be found. For example; a closer row spacing can decrease the need for weeding per kg crop, decrease nitrogen leakage as well as increase yield (Brewster, 1994:66-68; Båth and Kling, 2001), cover cropping may increase soil fertility and hence yield while at the same time control weeds (Altieri, 1995:219-220), grubbing pigs can control pest and weeds, decrease need for mechanical tillage (hence diesel) and fertilize the field (Fogelfors and Lundkvist 1999:139), intercropping two or more crops may not only help compete against weeds (Baumann, 2001) but also increase the yield per ha by decreasing the area needed per crop (Bentley *et al*. 2004). In well combined intercropping systems crops complement each other by using resources as light, water and nutrients at different times or locations (e.g. different root systems and canopies) which leaves less resources to weeds and requires less land than a monoculture (Bentley *et al*. 2004).

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[10] Primary tillage equipment is used initially to break and loosen the soil to depths of up to 75 cm (Wicks *et al.,* 1995).

[11] Secondary tillage is used for weed management, erosion management and seedbed preparation (Wicks *et al*., 1995).

1.3.1. Organic weed management practices

This chapter presents a brief introduction to organic weed management practices. Since herbicides are not allowed in organic agriculture they will not be brought up in this thesis. There are some natural herbicides which would sort under biological weed management (e.g. mustard flour, acetic acid) but they are uncommon, not allowed in Sweden and will not be described here.

Before introducing different kinds of weeding practices it should be stated that no matter which weed management strategy is used, to achieve an efficient weeding it is important to know the critical period of the crop. This is the time when weeds do the most damage to crop yield (Ascard, 2003). The critical period usually starts a few weeks after emergence and for crops as carrots and onions which are sensitive to weed competition it can continue up until half the cultivation period (Ascard, 2003).

1.3.1.1. Hand and mechanical weed management

Hand and mechanical weeding is probably the most common strategy against weeds in organic agriculture. In crops with a lot of weeds it is not uncommon that hand weeding may take 100-300 hours/ha (Ascard, 2003). In some cases it could take only 50 hours/ha however there are also cases of 500 hours/ha (Ascard, 2003). In Sweden it is often difficult to find people to employ for weeding even with a salary of 120 SEK (app. 12€) (Ascard, 2003). The work is often seen as monotonous and hard (Ascard, 2003). Smaller and more diversified farms as the ones participating in this study often employ people for a range of different chores which makes the work more attractive. However the cost is still a problem and often limits the production (Ascard, 2003). A wide array of tools and techniques have been developed to lower the labor requirement as; blind harrowing, delayed sowing, various inter-row cultivation tools, plowing and stubble cultivation (Fogelfors and Lundkvist, 1999; Smith, 1995). Thermal weed control is performed using flaming before emergence in for example carrots and onions and after emergence in onions (Ascard, 2001; Ögren *et al.,* 2003). Another form of thermal weeding is soil steaming in narrow bands (Fogelfors and Lundkvist 1999; Hansson and Svensson, 2006).

To efficiently control perennial weeds with vegetative multiplication from roots it is important to know the compensation point of the weed. By tilling roots of these weeds are partitioned into smaller pieces. Each piece can produce a new shoot (Fogelfors and Lundkvist, 1999:155). The compensation point is the point in time of the plant when the emerged weed has used up its nutrient reserve in the root and before it has started to store new carbohydrates through photosynthesis (Ascard, 2003). If a mechanical weeding at this time is performed the weed has no way of storing more nutrients in its roots (Ascard, 2003). If this is repeated several times the roots will be starved and unable to produce new shoots (Ascard, 2003). For quackgrass (*Elymus repens*) this time occurs when the weed has developed between 3-4 leaves while for creeping thistle (*Circium arvense*) the time occurs at 5-8 leaves (Dock-Gustavsson, 2004). The mechanical disturbance should be performed after a period with enough soil moisture to make the weeds emerge. After the weeding the weather should preferably be dry to dry out the roots of the weeds on the soil surface (Fogelfors and Lundqvist, 1999:159-160).

1.3.1.2. Biological weed management

In this study biological weed management will be defined according to Cardina (1995:280) who states that there is a difference between biological *control* and biological *management.* According to the author *"biological control involves the deliberate use of organisms such as insects or fungi to control weeds; biological management also involves the use of crop competition, allellopathy*[12]*, resistant varieties, natural chemical agents and other approaches."* Cardina also explains that *"the difference in biological control is often to obtain the same dramatic reduction in weed populations as may be obtained by chemical weed control. Biological weed management objectives are broader and include more subtle restrictions and constraints on weed populations resulting from the manipulation of organisms or the environment."*

Forms of biological weed management can be; weed free seeds, competition, intercropping, allellopathy, green mulching, cover cropping, grazing and weed control using insects, fungi, viruses or bacteria (Cardina, 1995; Foglefors and Lundkvist, 1999).

1.3.1.2.1. Competition

Competition can be used by choosing cultivars which compete well with weeds by their speed of germination, early growth potential, canopy shape, crop height, production of allellochemicals, shade tolerance, nutrient and water uptake efficiency and tolerance and resistance against stress (Fogelfors and Lundkvist 1999:108-132; Cardina, 1995:283, 286). For example a ley which includes species that establish a close crop stand in early spring are very competitive against both annual and perennial weeds (Fogelfors and Lundkvist 1999:111). During optimal growth conditions the following order in weed competitiveness is set up for spring and autumn sown annual crops according to Fogelfors and Lundkvist (1999):

Autumn sown: autumn *rye (Secale cereale)* > triticale (*x triticale*) > autumn barley > autumn wheat > autumn turnip > autumn rape

Spring sown: barley *(Hordeum vulgare)* ≥ *oat (Avena sativa)* > spring wheat *(Triticum aestivum)* ≥ spring turnip *(Brassica rapa var. rapa)* ≥ spring rape *(Brassica napus)* > peas *(Pisum sativum)* > potatoes *(Solanum tuberosum)*, root vegetables, vegetables.

The authors explain that if growth conditions are not optimal the relation may change. For example spring wheat performs as well as barley in lower soil nutrient conditions. It is also stated that autumn sown crops generally are more competitive against weeds than spring sown.

Crops can also be managed to compete better with weeds by being planted as seedlings and by choosing planting distances and patterns which increases soil coverage (shading out weeds) (Cardina, 1995:285-286).

1.3.1.2.2. Intercropping, cover crops, and green mulch

Examples of intercroppings used for weed management are undersowing *ley* or peas in cereals (Olrog, 2004) or the traditional intercropping of squash, beans and corn *(Zea mays)*

[12] Allellopathy is an adverse effect on plants caused by biochemicals that are produced by a living plant or by the microbial degradation of a plant.

(Gliessman 2000:223). Ammon and Hartwig (2002) defined *cover crop* as: *"any living ground cover that is planted into or after a main crop and then commonly killed before the next crop is planted"*. Cover crops die off naturally (winter annuals) or are mowed before the main crop is planted or sown. The *dead* cover crop can prevent weeds from growing and competing with the main crop by mechanical obstacle, decreased light interception and sometimes by having an allellopathic effect (e.g. Mennan *et al.* 2006; Teasdale, 1993). *Living mulch* is a form of intercropping and is defined by Ammon and Hartwig (2002) as: *"cover crops planted either before or with a main crop and maintained as a living ground cover throughout the growing season"*. Here the mulch is *alive* throughout the growing season. *Green mulch* is sometimes used as a general term also including the two terms explained above. Most commonly however, it refers to above ground remains of cut/harvested organic material which are *moved* from the field where they grew to be applied on the surface of the soil in another field (e.g: fresh ley or green manure cuttings, bark, pine needles, hay, straw, silage). This is how the term will be used in this thesis. The weed suppressing ability of green mulch, living mulch and cover crops is further discussed in the chapter on results and discussion and in a separate paper in *appendix D*.

1.3.1.2.3. Allellopathy

Allellopathy is defined by Cardina, (1995:291) as "an adverse effect on plants caused by biochemicals that are produced by a living plant or by the microbial degradation of a plant." The author states that allellopathy is used against weeds by choosing allellopathic crops, rotational or companion crops. Some examples are: barley, beet, hairy vetch, field bean, lupine, corn, oat, rye, wheat and sunflower (Cardina, 1995:291-293). When using allellopathic crop residues care must be taken not to damage the vegetable crop. It seems that small seeded crops as lettuce, radish and sometimes tomatoes can be adversely affected while larger seeds as beans, cucumber and peas are more tolerant to these allellopathic compounds (Cardina, 1995:295).

1.3.1.2.4. Grubbing and Grazing

Pigs are used to remove quackgrass when they grub (Fogelfors and Lundkvist, 1999:139; Mandelmann, pers. commun., 2008). Experiments with pigs and strip grazing where the pigs were moved along with the development of the quackgrass showed that only 20-25 pigs/ha were needed (Fogelfors and Lundkvist, 1999:139). Studies have been performed in Sweden where pigs are part of the crop rotation. The pigs are moved between different fields where they eat weeds, terminate leys, "plough" and eat up harvest residues (Fogelfors and Lundkvist, 1999:139). In a survey performed for the purpose of the present study one of the participants, Bergström, mentioned that his farm Gammelbo Gård AB, used pigs for weeding quackgrass and creeping thistle. The pigs were found to be thorough and the farm owner, Bergström (pers. commun., 2008), recommends the method if someone has time and interest in pigs. Horses, cows, goats, rabbits, hens, geese and sheep can keep weeds down by grazing (Cardina, 1995:301; Fogelfors and Lundkvist, 1999:138). According to Palmpers (pers. commun., 2008) hens are very efficient at removing pests and all perennial weeds except for creeping thistle on the farm. The hens are rotated with the vegetable production and an area of 5-10 m^2/hen has been found to be suitable. Palmpers estimates that about half the weeding labor is saved this way. Geese have been shown to control weeds in strawberries *Fragaria x ananassa*), *Salix* spp, cotton (*Gossypium sp*), peppermint (*Menta x piperita*) and orchards while sheep have been used in seedling Lucerne (*Medicago sativa*) and in corn (*Hordeum vulgare*) late in the season (Cardina 1995:301; Radosevich, 1997:386; Fogelfors and

Lundkvist, 1999:139). In Norwegian and Swedish trials it has been shown that geese between 3-12 weeks are the most suitable and 1-2 adults per $1000m^2$ is sufficient (Fogelfors and Lundkvist, 1999:139). Cattle grazing during a few weeks on cereal stubble have been shown to efficiently reduce quackgrass (Fogelfors and Lundkvist, 1999:139). Most commonly however grazing animals have been used on pastures and rangelands (Cardina, 1995:301). Each animal has different way of grazing and to some extent favors different weed species. Cattle prefers grasses, sheep prefer *forbs*[13] while goats are very suitable for *brush*[14] control (Cardina, 1995:301). Examples of weeds common in Sweden which have been controlled by grazing animals are Dandelion (*Taraxacum*) by sheep and Thistles (*Circium*) by goats (Cardina, 1995:302).

Strip grazing is a form of managed intensive grazing when the animals are only allowed to graze a smaller area which is continuously moved (Wickipedia, 2008; Pollan, 2006:192-219). After a certain time the ley in the first area has grown back and the animals start grazing a second time. Since the area is limited the animals graze the whole ley to the ground instead of selecting the species they prefer. Hence the ley is well kept and no species have time to flower and set seed. As mentioned above perennial weeds as quackgrass can be exhausted of their energy reserves if a well managed strip grazing is used.

1.3.1.2.5. Biological control

Eilenberg *et al.,* (2001) define biological control as: “The use of living organisms to suppress the population density or impact of a specific pest organism, making it less abundant or less damaging than it would otherwise be”. Living organisms are insects, fungi, bacteria and viruses (Fogelfors and Lundqvist, 1999:140-143). Eilenberg *et al.,*2001 and Cardina, 1995 suggest the following unifying terminology and definitions in biological control:

Classical biological control: “the intentional introduction of an exotic, usually co-evolved, biological control agent for permanent establishment and long-term pest control” (Eilenberg *et al.,*2001).

Inoculation biological control: “the intentional release of a living organism as a biological control agent with the expectation that it will multiply and control the pest for an extended period, but not permanently” (Eilenberg *et al.,*2001).

Inundation biological control: “the use of living organisms to control pests when control is achieved exclusively by the released organism themselves” (Eilenberg *et al.,*2001). This means that only the released individuals will achieve the control. The organism is not assumed to multiply and stay within the system where it is meant to perform the control.

Conservation biological control: “modification of the environment or existing practices to protect and enhance specific natural enemies or other organisms to reduce the effect of pests.” This can be achieved by for example providing alternative overwintering sites for beneficial insects or by reducing the activity of parasites and predators responsible for mortality of these beneficial insects (Cardina, 1995:306).

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[13] Forb = Herbaceus flowering plants that are not graminoids (grasses, sedges and rushes).
[14] Brush = Undesirable bushes or small trees.

When using biological control to control weeds care must be taken not to damage non target plants (e.g. crops or wild species) (Fogelfors and Lundqvist, 1995). On the other hand if the biocontrol agent is too specialized additional methods may be needed to control weeds which are not affected by the biocontrol agent. However, most other methods normally would eliminate the targeted weed as well hence making the biocontrol unnecessary. The review of Hatcher and Melander (2003) shows that often the biocontrol agent, on its own, is not efficient enough to control weeds. Cardina (1995:316) mentions that fungi often require specific environmental conditions as humidity and a narrow range of temperature also exposure to some wavelengths may be detrimental.

Several scientists have described possibilities of combining different methods to improve the efficiency of biological control (e.g. Cardina 1995, Norris and Kogan, 2000, Hatcher and Melander, 2003). Cardina (1995:305) mentions a case where insects feeding on weed seeds have been coated with a plant pathogenic fungi. The combined effect of insect and fungi reduced seed viability of velvetleaf (*Abutilon theophrasti*) with 98%. Hatcher and Melander argue that biocontrol development should focus on methods where it could be combined with other weed management methods. The authors have identified the following possible combinations:

- Mechanical weeding can improve the infection of plant pathogenic fungi or bacteria.
- Biocontrol agents could be used to suppress weeds which are difficult to manage as *Rumex* and *Cirsium* species.
- Biocontrol agents could be used to control weeds within the rows of vegetables after emergence where weeding is costly and time consuming.
- Biocontrol agents which decrease the reproductive ability of weeds or the viability of their seeds could be used to manage weeds at the end of the season. At this time weeds normally no longer pose a problem to the yield of the crop but need to be controlled not to increase the weed seed bank in the soil.
- Infection with biocontrol agents can be improved by cover cropping or intercropping due to improved environmental conditions as humidity and temperature.

1.3.1.2.6. Crop rotation is biological and mechanical weed management combined.

Weeds can be suppressed with the help of crop rotation which usually is a combination of biological and mechanical weed management. The weed flora adapts to the cultivation system. If a lot of annual crops are grown the annual weeds will dominate and if perennial crops are grown then perennial weeds will dominate (Dock-Gustavsson, 2004). Quackgrass and creeping thistle are creeping perennials with rhizomes and rapid plant regeneration after mechanical disturbance (Håkansson, 2003:22). Hence these species are promoted by extensively managed leys. Even intensively managed leys with good establishment and 2-3 well timed cuttings may need to be complemented with intense mechanical disturbance before or after a crop to manage these weeds (Dock Gustavsson, 2004). Frequent mechanical weeding in vegetables decreases these weeds (Dock Gustavsson, 2004). Spring germinating annual weeds are favored by spring sown/planted crops and decreased by leys or autumn sown crops (Fogelfors and Lundkvist, 1999:104-107). The above mentioned relationship between the crop rotation and weed species was seen at two of the participating farms as well as farms participating in the survey (Johansson, pers. commun., 2008b). Hence by mixing between perennial, annual, winter sown and spring sown species the development of the weeds is interrupted (Dock-Gustavsson 2004). Well established cover crops sown after the main crop in autumn can compete well against weeds in autumn and spring if the cover crop is winter annual or perennial (Fogelfors and Lundkvist, 1999). However tillage against perennial weeds after harvest is limited by this method (Fogelfors and Lundkvist, 1999).

1.4. Weed management with local ecosystem services

This chapter attempts to answer the question of when a weed management activity can be called an ecosystem service and when not. It will be argued that not all biological weed management activities can be called ecosystem services. Decreased use of fossil fuels through decreased mechanical tillage often implies increased workload (cost) with hand weeding. The purpose of managing local ecosystem services is to decrease this workload (cost) and at the same time achieve other positive effects which strengthen the ecosystem as a whole.

Ecosystem services are defined as the conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfill human life (Daily, 1997:3-4). In other words the ecosystem services are the benefits people obtain from ecosystems (MA, 2005). A rich biodiversity can be seen as the basis of the existence of ecosystem services. Ecosystem services can be divided into four groups (Daily, 1997; MA, 2005):

- **Provisioning services** such as food, forage, water, timber, biomass fuel, pharmaceuticals, fiber, industrial products and their precursors.
- **Regulating services** that affect climate, floods, disease and pest control, wastes, and water quality.
- **Cultural services** that support diverse human cultures and provide recreational, aesthetic, and spiritual benefits.
- **Supporting services** such as soil formation and fertility, photosynthesis, dispersal of seeds, pollination, and nutrient cycling.

The concept of ecosystem services is complex and not well defined from a strictly scientific point of view. Therefore it deserves some reflection. It is for example based on an anthropocentric world-view where humans stand outside of nature which provides us with services. This thesis is based on a view that humans are part of nature but that they are in *some aspects* unique beings in this world. This uniqueness has given humans a large power of impact in nature. For example all other beings only use renewable resources while humans are able to use fossil fuels. This access to large amounts of concentrated, high quality energy has allowed humans to occupy, control and impact a disproportionate large amount of ecosystems and ecosystem functions. Some of these functions are benefitting humans and can therefore be called services. With an eco-centric view on the other hand, humans are not distinguished from the rest of nature and hence one could not identify any special ecosystem functions devoted to support humans. The ecosystem functions were not created for us and are not dependent on our well-being. We however are dependent on the well-being of the ecosystem functions. The concept of ecosystem services was therefore developed to make the ecosystem functions which we depend upon visible.

This thesis focuses on how ecosystem services instead of being degraded could be incorporated into weed management to create a more sustainable farming system. For the purpose of this study a weed management activity will be an ecosystem service if:

- It is, or could easily be, mainly based on local renewable resources. The need for commercial energy provided by humans should be low.
- The ecosystem service is produced locally within the agroecosystem. For example fossil fuels are excluded since this ecosystem service is historical and performed in the earth crust and mantle.

The definition is not water proof but it serves the purpose of being a "reminder tool" or with other words a tool to manage sustainability.

Below examples will be given to show which of the weeding practices mentioned in *chapter 1.3* also could be regarded as ecosystem services. The use of cultivars which are competitive against weeds can be sorted under local ecosystem services if they are bred through selection in the local area. Some genetic combinations will show better weed competition within the local agroecosystem compared to others. Intercrops and living mulch can compete by capturing resources more efficiently than the weeds (Gliessman, 2000:152). Deep root system, long root hairs, nitrogen fixation and canopy shape which intercepts light well are some ways of competing against weeds (Fogelfors and Lundkvist, 1999:108-110*;* Cardina, 1995:283, 286). Crops can also directly prevent the development of weeds by for example excreting allellopathic substances (Cardina, 1995:291) or by the shape of their canopy prevent neighboring weeds from intercepting light (Baumann, 2001; Bentley *et al.*, 2004). Today most farmers in Sweden buy their seeds and do not breed or save their own seeds. However since this could easily be changed it could still be seen as an ecosystem service.

Classical biological control can not be called a local ecosystem service since it uses non local "exotic" biological agents. Inoculative and inundative biological control relies on multiplying and maintaining the biological control agent to be able to release it when needed. This is performed by laboratories with considerable use of commercial energy and not easily done within the agroecosystem. However conservation biological control is a very good example of a local ecosystem service. With very little input of commercial energy natural enemies can be enhanced by improving their habitat.

Finally when grazing, grubbing and draught animals on the farm are fed from the local agroecosystem and remove weeds they also perform a local ecosystem service.

1.5. Climate change in the regions of the participating farms

The Swedish Meteorological and Hydrological Institute (SMHI) have performed climate scenarios for different regions in Sweden based on two of the four IPCC scenarios namely A2 and B2[15] (SMHI, 2008a). A2 and B2 show a medium impact on the climate while e.g. scenario A1F1 leads to large climate change and B1 to more moderate climate change. For more information on IPCC scenarios please read box A.1. The limitations of climate scenarios, models and our knowledge about the sensitivity of the planet to climate change are mentioned in *appendix A*. Since A2 and B2 are only medium impact scenarios one must keep in mind that these are only possible indications which may help us to start preparing and that a large safety marginal should be assumed. For this study a summary of expected climate change will be presented for the two regions in which the participating farms are found; Vänern, Vättern and Östra Svealand. SMHI relates all climate changes to the average values

[15] At the time of this thesis only A2 and B2 scenarios were described however more IPCC scenarios will be adapted to Swedish regional models.

of the years 1961-1990. The IPCC often use comparisons to pre-industrial times or to 1980-1999. According to IPCC (2007b:67) the global mean temperature had increased with 0.5°C between pre-industrial times to the years 1980-1999. In Sweden which is closer to the North Pole the temperature change may have been even larger. Hence it is assumed in this thesis that *at least* 0.5°C could be added to the temperatures presented by SMHI to compare to pre-industrial levels. However the data presented here will not include the additional 0.5°C. For the purpose of this study the climate scenarios between the years 2020-2030 will be presented. The reason for this is that it is easier to relate to 2030 than 2100 and all scenarios in a distant future are related to higher uncertainty. When no information on 2020-2030 is given by SMHI the closest time interval available have been used. In general it can be said that changes which are already visible in 2020-2030 will increase considerably until 2100.

1.5.1. SMHI climate scenarios

Two of the participating farms, Senneby Trädgård and Sundvik Trädgård, are localized in the climatic region Östra Svealand. Since both are proximate to the sea their weather is somewhat different from the region average. According to the farmers the largest difference is less than average rainfall. The third farm, Stora Fårvallsslätten, is located in the climatic region between the two great lakes Vänern and Vättern. All the information on climate change in these regions (SMHI region 7 and 19 resp.) has been taken from the SMHI web page (SMHI, 2008c). Table 1.1. shows a summary of how some climate parameters are expected to change during the years 2020-2030 compared to they years 1961-1990.

Table 1.1. *Expected climate change in the two regions by the years 2020-2030. Since there are only small differences between the A2 and B2 scenarios the range of both scenarios is summed and presented as one.*

	Spring Temp. increase (°C)	**Summer Temp. increase (°C)**	**Autumn Temp. increase (°C)**	**Winter Temp. increase (°C)**	**Precipitation**	**Growth period increase**	**Last day of spring frost**
Östra Svealand	2-3	1-2	1.5-2½	2-3½	Great variation. Increase in winter, small decrease in summer.	~40 days	10-15 days earlier
Vänern Vättern	2-3½	1½-2	1½-2	3-4	Great variation. Increase in winter.	~60 days	10-20 days earlier

1.5.2. Climate change by the end of the century

In both regions the largest differences in temperature will occur after 2030-2050. Most noticeably the growth period will be prolonged with about 100 days by the end of the century. The temperatures will rise with several degrees by the end of the century and mostly in winter. Precipitation will also increase during winter with up to 60% and 20-30% during spring and autumn by 2100. Summer precipitation may decrease with up to 40%. Summertime the days with small amounts of precipitation will increase while days with larger amounts of precipitation will decrease. The periods of very hot temperature will be prolonged with a few days. At the end of the century the amount of days below 0 ^{o}C will decrease from 50% to about 15%.

1.5.3. Implications for vegetable production

Summarizing the main implications of climate change on vegetable production in 2020-2030 will probably be (SOU, 2007:60);

- Earlier sowing and planting date since the last frost day will come earlier each year.
- Increased fertilization and weeding need due to longer growing season.
- Cultivation of new crops due to longer growing season.
- Lower yields due to drought or increased needs for irrigation (and then possibly higher yields) since temperature will increase during summer and spring while precipitation stays the same or decreases at least during summer. At temperature over 30^{o}C many plants increase their respiration (CO_2) which could actually lower the biomass production.
- Increase problems with weeds (see box 1.1.), pest and diseases.

In the already drought prone areas of Senneby Trädgård and Sundvik Trädgård this may cause difficulties especially for crops which normally are not irrigated as cereals and leys. Stora Fårvallsslätten is located in a less drought exposed area. Still, summer droughts and autumn rains are already causing problems according to the farmers. In vegetable production summer drought could create a benefit against weeds if drip irrigation for the crops would be used. This way the crop is irrigated while the weeds are not. Drip irrigation is labor intensive but may become necessary where water is scarce.

Box 1.1. Weed Development due to Climate Change

When climate changes it has an impact on the weed flora (SOU, 2007:187-188). The fastest way of introducing new weed species is by human transportation. The new weed must adapt not only to temperature, precipitation and length of growth season but also to the prevailing photoperiod and crop rotation and management (SOU, 2007:187-188). The Swedish Climate and Vulnerability Investigation (SOU, 2007:186-193) assessed the potential weed development due to climate change. It was concluded that;

- Increased CO_2 concentration in the atmosphere would favor C3 plants over C4 since the C4 plants are less dependent on the CO_2 concentration in the atmosphere. However C4 plants grow more efficiently in dry and warm climate due to a mechanism of CO_2 accumulation which allows them to decrease stomata opening and thereby transpiration. Hence weeds of limited importance today as: cockspur (*Echinochloa crus-galli*) and common amaranth (*Amaranthus retroflexus*) may increase. Possibly their short daylength requirement will impede spreading to northern parts of Sweden.
- Increased temperatures especially winter time will allow the over wintering of weed species as green nightshade (*Solanum physalifolum* Rusby) and black grass (*Alopecururs myosuroides*) further north in Sweden.
- Increased growth season and higher temperatures may allow for new noxious weed species as littleseed canarygrass (*Phalaris minor*) to fulfill their life cycle and hence spread in the Swedish agricultural fields.
- Longer growth season and higher temperatures will favor the cultivation of late maturing species as maize and soya beans as well as late maturing weeds. The wide row spacing of maize and soya beans favors weeds with normally low competitive ability as; cockspur and common amaranth.
- Drier springs will disfavor spring cereals and oilseed plants leading to a higher amount of autumn sown crops. This will favor winter annual weeds as black grass and barren brome (*Bromus sterilis*).

2. Material, Methods and Research Process Used

2.1. Participatory Research and Systemic Approach

Here the participatory research (PR) and systemic approach of the study will be explained and the reasons for choosing this approach will be given. The study was performed in cooperation with a participatory research group called 'Climate Smart Agriculture – Sustainable Solutions for the Future'[16]. More information about the group and the participatory process and methods used is presented in *chapter 2.2. The Research Process.*

When a farmer decides to adopt an agricultural practice or not she/he not only considers the biophysical properties of the farm but also socioeconomic, cultural and political characteristics of the household (Reijntjes, 1992:26-27). To make sure that the developed weed management strategies within this study would be implemented by farmers and sustainable they needed to be both viable and desirable from the growers' perspectives (McAllister, 1999:3-4). To achieve this, a methodology was needed which went beyond the investigation of the technical and biological aspects directly associated with the specific weed problem (Chekland and Poulter, 2006:3). Hence a systemic approach was used meaning that both the biophysical and social settings of the farms were investigated and described when deciding which weed management strategies to develop (Chekland and Poulter, 2006:4). To include this knowledge the participation of the farmers was necessary. Therefore a participatory methodology was chosen (McAllister, 1999:3-4).

The objective of the study was also to empower all participants by learning how to develop new weed management practices with less negative impact on climate change. Participatory methodology is suitable also for this purpose (McAllister, 1999:3-4). The joint learning was achieved by including both farmers and author in defining the current weed management situation, the weed management situation when it is improved and how to reach the improved situation. A close interaction between the participants allowed for a sharing of knowledge and joint development of improved weed management strategies.

Social and natural environments are constantly evolving. Therefore the sustainability of a weed management strategy will also change. To manage sustainability in changing environment stakeholders should be encouraged to identify indicators of change and sustainability which can be easily measured and which have a sufficient degree of accuracy (McAllister, 1999:11). Efforts were made within this study to develop a sustainability evaluation tool which could be easily used to evaluate the developed weed management strategies but also other future management choices.

When using quantitative data one tries to reduce the uncontrollable variables (Holliday, 2002:30). Since the aim of this study is rather to discover which the variables are and include them when developing new weed management strategies quantitative social methods were not found suitable for the purpose. Instead qualitative methods were chosen for the study since qualitative research investigates social variables directly rather than tries to, eliminate them (Holliday, 2002:30). According to Holliday (2002:8, table 1.2) validity in qualitative research is achieved by explaining to the reader the appropriateness of the choice of social setting, choice of research activities and the choice of themes and focuses (presented in *chapter 2.2. Research Process* as well as *chapters 3.3.-3.6.*). Kvale (1996:59 *ff*) explains that within the positivistic, quantitative tradition, this way of validitizing is often difficult to understand since validity, according to a

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[16] See www.scwartzstiftelse.se in swedish.

positivist, is obtained if the findings can be generalizable. Kvale (1996:60) means that the positivist tradition is still so dominant in our western society that many people define science as generalizable knowledge, however, a different and broader definition of science exist: "the methodological production of new, systematic knowledge." It is important to remember that even a positivistic hypothesis is based on the researcher's preconceptions (Thurén, 1991). One of the aims of this study was to use participatory methodology in order to increase the extent to which the developed weed management practices would be adopted by the farmers. Hence the extent to which the farmers believe they will experiment with the practices was presented

2.2. Research Process

The research process will be presented according to Hollidays (2002:8, table 1.2) method of validitizing qualitative research (see the *chapter 2.1.* above).

2.2.1. Choice of social setting

The cooperation with the participatory research group Climate Smart Agriculture was initiated by the author. The idea was for the author and group to choose a study subject for a master thesis within horticultural sciences which would be of relevance to the work of the group. The group is composed of eight farm households, a researcher from the Center for Sustainable Agriculture at the Swedish University of Agricultural Sciences (SLU) and a facilitator in sustainable development issues. The aim of the group is to contribute to the development of farming practices with low resource use and environmental impact while maintaining high food and energy production. Their work is based upon the use of local ecosystem services on the farms and on spreading the knowledge about this issue by communicating with policy makers and the general public. The group communicates through amongst other things farm visits, contact with consumers, books, their homepage, participation in other forums, articles, news reports and conferences. Cooperation with the group was found interesting since it actively works with many of the global challenges society is facing. Three vegetable producing farms within the group chose to participate in the study.

2.2.2. Choice of themes and focuses

When the initiative of the study came up the group was recently formed. It was difficult for the group to suggest a common proposal for the subject of the study. Instead the author was presented with the aims and interests of the group and asked to suggest a subject. Since the group focused on mitigation of climate change and the use of ecosystem services these were the basic criteria. Vegetable production was chosen to correspond to the interest and education of the author. Weed management was chosen since an important part of the total commercial energy used in organic production is consumed during weed control practices and especially soil tillage operations.

2.2.3. Research activities.

Participatory tools and methods were used to share knowledge amongst participants and to increase the influence of the participating farmers on content, work process and evaluation. Surveys, meetings and farm visits were used to include farmers in defining the current weed management situation and in developing measures to improve it. This was complemented by literature studies and interviews performed by the author. Time constraint was the greatest limitation and decisive for which methods were chosen and to the level of influence of the farmers. The steps and methods of the process are described below.

2.2.3.1. Survey

As a first activity a survey was prepared and sent to 70 farmers. One aim was to find inspiration to possible weed management strategies based on ecosystem services. The second aim was to find contacts for interviews and possibly field visits.

2.2.3.2. First meeting

During the first meeting with the group the subject was presented and discussed. Three farms chose to participate. Together the work process was discussed. Due to time constraint there was more influence from the author than from the farmers. However all issues were discussed and agreed upon. The following contents and activities were decided:

- A description of the situation today and future expectations including: 1) the situation of the present farms, 2) climate change scenarios, 3) the use of oil, the oil peak and possible oil alternatives.
- Choice of focus and criteria. The following suggestions were made; 1) reducing fossil fuel consumption, 2) time efficiency, 3) cost, 4) solutions for today and for the future, 5) overall sustainability.
- A time schedule of the process was prepared in the form of a timeline.
- The following suggestions for finding inspiration to possible weed management strategies were suggested; 1) field visits, 2) discussing each others farms, 3) literature, 4) survey to farmers asking if they use any weed management methods which are based on ecosystem services.
- Development of suggestions for weed management strategies was to be made through a discussion between farmers and author.
- Implementation. It was estimated that there may be too little time to reach the stage of implementation. However if possible it would be encouraged.
- Evaluation. A participatory evaluation prepared by the author.

2.2.3.3. Preparation for farm visits.

Each farm household was handed a questionnaire about their farms and weed situations which was to be sent back to the author.

Before the visit to the participating farms the author prepared a summary of the expected climate scenarios of the regions were the farms were located to be used when deciding on future weed management strategies.

2.2.3.4. Farm visit

During the farm visits a farm walk was made for the author to get to know the farm and for issues related to the weed situation to emerge. The climate scenarios of the region were presented and shortly discussed in relation to future weed management. A timeline was made for the production season where the activities related to each crop were noted. The crop rotation, weed situation, previous weed management strategies and future possible strategies were discussed. Already here some basic ideas of which strategies to focus on were decided. At Senneby Trädgård it was decided to perform a field experiment with green mulching since the farmers had decided to try a method of spreading green mulch by tractor. At Sundvik

Trädgård it was decided only to discuss possible weed management strategies against summer annual weeds but not to make experiments due to the high workload of the farmer. At Stora Fårvallsslätten it was decided to find strategies against the perennial weeds.

2.2.3.5. Survey, literature study and field experiment.

The answers from the survey to farmers (other than the ones participating in the study) were processed and interviews were made with two of the farms. A literature study about the proposed strategies was performed. The strategies were discussed at several occasions with the farmers and new ideas emerged. A statistically designed field experiment was prepared together with the farmers. Both author and farmers decided how to set up the experiment and what to measure.

2.2.3.6. Symposium.

The field experiment was presented as a poster during the IV international symposium on ecologically sound fertilization strategies for field vegetable production organized by the International Society for Horticultural Science (ISHS).

2.2.3.7. Sustainability evaluation tool.

During a meeting it was discussed how the future weed management strategies could be evaluated from a wide sustainability perspective. The author prepared a suggestion of which sustainability criteria to use based on The Natural Step system conditions (see *chapter 2.6.1. The Natural Step Framework (TNS)*). Again due to time constraints most of the preparations were done by the author. Also a form of visualizing the sustainability evaluation in a spider diagram (see *chapter 2.6.2. Spider diagrams*) was suggested. The criteria and diagram were discussed and altered according to the comments from the farmers. Unfortunately there was very little time for this activity.

2.2.3.8. Field experiment and weed management strategies

During the production season most of the work was directed to the field experiment. Both quantitative and qualitative evaluations were performed by both farmers and author. Also weed management strategies were continuously discussed with the farmers based on literature, interviews with experts and the farmers experience and social situation.

2.2.3.9. Evaluation

A second farm visit was made by the author. The farmers were given the opportunity to read and comment the text about their farms and the weed management strategies which are a part of this thesis. The weed management strategies were evaluated from a sustainability perspective. The work process was evaluated and each participant reflected over what they had learnt during the study. Unfortunately there was only time to make the whole sustainability evaluation at Senneby Trädgård. With the other farms there was only time to discuss their impression of the sustainability tool.

2.2.3.10. Presentation

The thesis will be presented at the university and to the farmers. Also a popular version of the findings will be written within the project Climate Smart Agriculture.

2.3. Participating Farms

The farms are described from both a social and biogeophysical perspective including today's management. This information has been used in order to find improvement to the weed management which are found both desirable and viable by the farmers and will achieve a lower impact on climate change.

2.3.1. Sundvik Trädgård

The farm Sundvik Trädgård is located at the island Ljusterö east of Stockholm, Sweden and run by mainly Hillevi Rundström with some help from her husband Kalle Helmersson. During the growth season one person is employed to help out on the farm. Up until 1969 Hillevis parents had dairy cows on the farm and between 1969 and 1980 the fields were leased for cereal production. In 1980 Hillevi started producing potatoes (*Solanum tuberosum*) and vegetables. On the farm there is; a 1 ha vegetable field including an annual green manure ley of 0.3-0.4ha, 2 greenhouses 160 m^2 and 240m^2, 9 ha field crops, 3 ha leased arable land, 3ha semi-natural pasture, 11 ha old pasture, 13 sheep, 70 hens and 3 Icelandic horses. Horses and sheep are a good combination to keep the parasites down and to achieve an even grazing. The products are sold in the farm store and a few weeks of the year on the farmers market. The main diseases and pests are leaf sucker (*Trioza apicalis*) and carrot fly (*Psila rosae*) on carrot and several cabbage insects. The soils are sandy where vegetables are grown and richer in clay and stones were permanent grazing, cereals and ley is grown. There is sufficient water for irrigation.

Crop rotation: About 1/3 of the vegetable field is dedicated to green manure every year. For the rest of the vegetables there is no strict crop rotation. Last years success with weed control, this years precipitation and temperature and logistics are some factors deciding what to sow/plant on what field. However there is at least 4 years between carrots (*Daucus carrota*) and between cabbage (*Brassica oleracea*). The vegetable crop rotation is separate from the remaining crops and ley since not all soils are suitable for vegetable growing (stones, heavier clay, no irrigation) and since some of them are further away from the house.

Weed management: According to Rundström there were more problems with perennial weeds as Quackgrass (*Elymus repens*) and different Thistles (*Circium* sp.) at the start of the vegetable production. Today the most common field weeds are annual spring germinating weeds as: Fat-hen (*Chenopodium album*), Pale Persicaria (*Persicaria lapathifolia*), Black Nightshade (*Solanum nigrum*) and Pineapple Weed (*Matricaria matricarioides*). The last two weeds being the most troublesome.

Vegetables are sown/planted in beds of three rows with 30 cm distance. Between the beds alleys of 1 m are created. The weeds are controlled by crop rotation and by plowing, harrowing and bed-making at spring. After sowing and planting flame weeding and hand hoeing together with hand pulling when needed. During weeding and harvesting only the alleys and not the beds are used for walking. Sometimes green manure with for example Persian clover and annual ryegrass is sown in the alleys with 15 cm distance to the crops. The green manure is sown to increase soil fertility and to control weeds. Rundström has not experienced any competition between green manure and crop probably since the vegetables are planted out into the field at the same time when the green manures is sown and are therefore at advantage. The green manure is cut to keep it low. Where weeds have not been controlled in time it is sometimes necessary to use a mower. Crop rotation is used in the sense that if weeds had time to set seed one year then the next year a bare soil fallow is performed to give time for harrowing. The fallow is followed by a green manure sown in early August or a short season crop as lettuce. Frequent harrowing is performed before sowing green manure. Covering the vegetable rows with mulch has been tried but abandoned since it was too time consuming to do it by hand and there was no adequate machinery on the farm. Normally there are no problems in controlling the weeds up until the end of June. July is the main harvesting month requiring one fulltime harvest worker and one fulltime at the farm store. At that time it is difficult to keep up with the weeding which causes some weeds to seed and increase the seed bank in the soil.

2.3.2. Stora Fårvallsslätten

The farm is situated close to the town Skara not far from the large lake Vänern, Sweden. It was bought by Svante Lindvist 25 years ago and is today run by him and Béatrice Falsen. The main commercial crops are vegetables which are conserved by lactic acid fermentation. The family wants to take a brake from the intensive vegetable production at least for a while. They have already decreased the vegetable area considerably. They only produce cereals for their own consumption since it is difficult to compete with highly mechanized farms when it comes to cereals. The farm includes 7 ha crop fields, 6 ha pasture and 3 ha forest, 2 working horses a cow providing milk and meat, sheep for milk and wool and hens for eggs. Since the farm is horse powered and the horse tools are small and simple very little fossil fuels are used. Due to the horses there is a lot of ley in the crop rotation. A lot of ley also means less labor compared to more intensively managed crops. The ley is normally left for 4-5 years and contains much Lucerne (*Medicago sativa*), cock's-foot (*Dactylis glomerata*), common bird´s-foot-trefoil (*Lotus corniculatus*) and some white clover (*Trifolium repens*) since it is more resistant over the years compared to red clover. This production system with extensively managed leys, cereals and relatively small area of vegetables gives them more problems with perennial weeds as quackgrass (*Elymus repens*). If the weed situation is good after the ley vegetables are planted, if not, a short summer fallow follows where the soil is mechanically worked to control the quackgrass, docks (*Rumex longifolius, Rumex crispus*) and other perennial weeds. After the fallow either peas and oats (*Avena sativa*) or common vetch (*Vicia sativa*) and oats are sown as green manure. Vegetables are planted 1-2 years later and followed by cereals with legume ground cover. Sometimes a whole year fallow is necessary to control perennial weeds. All vegetables except for cabbage are grown in a crop rotation on 2.5 ha sandy soil with access to an irrigation pond. Cabbage is part of a different crop rotation on 1.4 ha clay soil which is too heavy for the other vegetables

Annual weeds are efficiently controlled by the mixed crop rotation and long leys. Frequent weeding once every week or every second week control the remaining weeds and increase mineralization of the nutrients. The major problem is quackgrass which they have struggled with for many years. Horses graze the ley which will be terminated the following spring. They do a good job destroying and eating the quackgrass. The combination of horses with sheep is good since they graze in different ways. More cows would be even better but there is not land enough to support more cows. However horses grazing on old leys give problems with docks and quackgrass. Horses graze very close to the ground and create patches with bare soil where these weeds thrive. They do not graze where they have left their dropping giving spot wise problems with the same weeds. Lindqvist has noted that the weed problems increase when the horses are left grazing for a longer time. Pigs are known to efficiently eat quackgrass however there is only one pig on the farm and no plans of buying more.

If there is time the fields are sometimes harrowed with a disc harrow or cultivator after the vegetable harvest. The soil is plowed and harrowed in spring. Other weed management strategies are delayed sowing and flaming, inter-row cultivation and hand weeding. The cabbage is planted with equally large distance within and between rows to allow horse powered mechanical weeding in both directions. During periods with more vegetables and less ley in the crop rotation there have been fewer problems with perennial weeds. This has however increased labor requirement and given problems with the nutrient balance on the farms.

Green manure and ley species are chosen to suit as fodder for sheep, horses and cow, to tolerate grazing, to be productive in long term leys, to be drought tolerant and to compete well against weeds. Species' that need frequent cuttings are unsuitable since there is no time to cut more than 1-2 times. The ley must dry in the field before it is transported to the hay loft. It is important to have time to cut as much as possible before the rain comes. There are only fuel powered schredders for horses. They use a mower which is less efficient for weed management since the ley must be higher at cutting and the cuts are longer than when using a schredder. The animals also do not manage to graze the whole area fast enough. In the farmers experience lucerne makes a good ground cover against weeds but is sensitive to grazing and too much gives problems with drying the hay with barn hay drier. Cock's-foot grows fast in spring and competes well against quackgrass but senesces very fast and is not so popular amongst the animals. Timothy (*Phleum pretense*) has been tried but has a scarce coverage and is hence an unsuitable weed competitor.

The most important pest and diseases are late blight (*Phytophtora infestans*) on potatoes and larvae and snails on cabbage.

2.3.3. Senneby Trädgård

Senneby Trädgård is located at Väddö north of Norrtälje, Sweden. The owners are Dan Johansson and Britt-Inger Nilsson. During the growing season trainees and school youth help out on the farm. Together they add up to two fulltime workers. The farm was taken over by the present owners in 1981 and it is today a diversified farm with 0,5 ha strawberry production, 2-3 ha of vegetables rotated with about 10 ha of the total 20 ha ley, 2 greenhouses mainly for tomato (*Lycopersicon esculentum*), cucumber (*Cucumis sativus*) and paprika (*Capsicum annum*), 10 ha cereals, 60 ha forest and 3 ha pasture. There are also about 40-50 sheep and 9-10 geese. The products are sold at the supermarket, local market and farm store as well as through pre-ordered boxes directly to consumers. There are many different soil types on the farm from loamy sand to soils with somewhat higher clay content. The largest problems with pest and diseases are; deer, larvae in cabbage and late blight in potato. The crop rotation is diverse due to the large amount of different crops grown on the farm. Johansson feels they should have more ley included in the vegetable rotation and will rent more land for that purpose. Today the vegetables are not rotated on all fields since some fields are inappropriate for vegetable production and more suitable from ley and cereal production.

The most common weeds are summer annuals and weeds that spread with the animal compost as fat-hen (*Chenopodium album*) and corn spurrey (*Spergula arvensis*). The owners have not noticed any shift in weed flora over time. The weeds are managed by soil tillage using; cultivator (sometimes a plow), harrowing and inter-row cultivator. Flaming and mulching is also used. A special weed management strategy of the farm is to use the 9-10 geese in the strawberry plantation. The geese seem to like the weeds but not the strawberry shoots. Unfortunately they are not fond of the scentless mayweed (*Tripleurospermum perforatum*). Silage and fresh ley cutting green mulch are used in the greenhouse and sometimes on small areas of cabbage. The green mulch is used to suppress weeds, maintain humidity and to fertilize.

2.4. Field experiment

At Senneby Trädgård the owners were interested in a more large scale application of green manure from fresh ley cuttings. They were planning to rebuild a manure spreader to mechanize the spreading of green manure in field vegetables. It was decided that a field experiment with green mulch in onion would be included in the study and performed at Senneby Trädgård. A completely randomized block design with two treatments (mulch and bare soil) and six replications was used. Onion weight, mineral and total nitrogen, diesel consumption and labor requirement was measured. The experiment had a participatory approach were the farmers were included in the design of the experiment and the evaluation of several qualitative aspects. For a full description of the experiment please read the separate paper in *appendix D*.

2.5. Survey

A survey (*appendix E*) was sent out to about 50 farmers asking for their experience using weeding methods which decreased the dependency on fossil fuels and took advantage of ecosystem services. Farms were chosen from a list of *Kärngårdar*[17] or through recommendation from extensionists and researchers. Twelve farms answered the survey.

The aim of the survey was to be a source of inspiration when the measures in this study were formulated. In two cases the methods used by the farmers were directly interesting for the measures on the farms and was therefore followed up by telephone interviews. The interviewees were Paul Teepen at Solbacka Gård about the method of growing vegetables between permanent strips of clover and Margareta Magnusson about green mulching.

Whenever the answers from the survey were used in the study were presented as personal communication stating the farmers' name. A complete list of farms answering the survey is presented in *appendix F*.

2.6. Sustainability Synthesis

When designing an improvement to a specific production problem it is important to evaluate the range of different options from a wider sustainability perspective where environmental, social and economic factors are included. Economic factors are often included however environmental and especially social issues are often omitted. The focus of this thesis will therefore be on the two latter factors. One of the objectives of this study was to find a simple tool which could facilitate this synthesis when the overall sustainability analysis is not the main objective but complementary information. Today there are various methods or tools for evaluating sustainability. Some are; Ecological Footprint (Holmberg *et al.,* 1999), Life Cycle Assessment (Baumann and Tillman 2004), MESMIS (Pino) and The Natural Step, TNS (e.g. Azar *et al.,* 1996; Robért *et al.,* 2002) and Emergy analysis (Odum, 1996). The main objectives of the evaluation in this study were 1) to guarantee that a more complete picture of sustainability criteria were used when measures are chosen in practice and 2) to identify gaps of information. Hence a fast and simple tool was needed. Also, the tool needed to be able to combine qualitative and quantitative data. It was decided to test if a combination of the

[17] Kärngårdar is a network of farms dedicated to developing farming which will be resilient in case of crisis. The farms are also maintaining local and traditional knowledge alive. (www.karngardar.se)

framework of The Natural Step and a simplified version of a spider diagram would suit the purpose of this study.

2.6.1. The Natural Step Framework (TNS)

The Natural Step (TNS) framework is based on four system conditions or principles of sustainability which should be met both locally and globally (Azar *et al.*, 1996; Helmfrid, 2002). TNS was chosen since it focuses on the very early activities in e.g. a production chain and not on the final environmental impact. Hence management decisions to prevent environmental damage can be taken at a very early stage. Since the framework is built on general principles it does not necessarily require experts and models to determine the causal chain and viable improvements. The suitability of using the TNS framework for evaluating the developed weed management strategies will be evaluated in *chapter 3.3*. The four system conditions or principles of sustainability of TNS are:

1) Substances extracted from the *lithosphere*[18] must not systematically accumulate in the *ecosphere*[19].
2) Society produced substances must not systematically accumulate in the ecosphere.
3) The physical conditions for production and diversity within the ecosphere must not become systematically deteriorated.
4) The use of resources must be efficient and just with the respect to meeting human needs without exceeding the level of impact on nature given by principle 1-3.

The ecocycle principle[20] has been used as a common analytical tool for the four system conditions. The use of this principle leaves some important related issues out as animal ethics and genetic engineering (Helmfrid, 2002).

According to Azar *et al.* (1996) TNS uses sustainability indicators for the four principles which are based on societal activities instead of the state of the environment which is the most common method. The indicators focus on the early part of the chain of causes in society that effect the environment. Societal activity indicators (that indicate activities occurring within society e.g.: the use of extracted minerals, the production of toxic chemicals, recycling of material) and environmental pressure indicators (that indicate human activities that will directly influence the state of the environment e.g. emission rates of toxic substances) may give an earlier warning than would environmental quality indicators (that indicate the state of the environment e.g. the concentration of heavy metals in soils and pH levels in lakes). The authors state two important reasons to why the indicators are constructed in this way.

1) There is often a long time lag between activities performed in society and their corresponding environmental impact. Hence environmentally based indicators will often give the warning too late to be able to change the impact.
2) Due to the complexity of ecosystems all possible damages from societal activities are not known. Still most indicators are based on known environmental damages.

Below the system conditions are described with examples of sustainability criteria for each condition. Which criteria should be used and where they fit is a social process and often

[18] Litosphere = the earth's crust (Helmfrid, 2002)
[19] The Ecosphere includes the biosphere, atmosphere, hydrosphere and pedosphere (Helmfrid, 2002).
[20] The circulation of material flows within the ecosphere.

decided between TNS consultants and different stakeholders (Helmfrid, pers. commun. 2008a).

System condition 1. Substances extracted from the *lithosphere* must not systematically accumulate in the *ecosphere.*

Increasing amounts of carbon dioxide in the atmosphere, sulphur dioxide leading to acid rain, phosphorus in lakes and heavy metals in soils and in our bodies are all examples of such accumulation (Azar *et al.,* 1996). The concentrations of these substances which originate from human activities should not be large in comparison to natural fluctuations (Robért *et al.,* 2002). Possible measures are to decrease the amount of extraction from the earth's crust, recycling and the quality of final deposits (Robért *et al.,* 2002). It could also imply substitution of abundant elements for scarce elements (Azar *et al.,* 1996).

System condition 2. Society produced substances must not systematically accumulate in the ecosphere.

These substances are waste resulting from human production processes where both lithosphere and biosphere raw materials have been used (Helmfrid, 2002). Some of them are long-lived and/or in amounts previously unknown to the ecosphere (Azar *et al.,* 1996). The substances should not accumulate in the whole ecosphere or in parts of it (Robért *et al.,* 2002). Examples of such substances are; DDT and PCB in biota, radioactive inert gases in the atmosphere and CFC molecules destroying the ozone layer. (Helmfrid, 2002:17). Possible measures are; reduce production volumes, change the characteristics of what is produced e.g. degradability, safe final deposits, recycling and incineration (Robért *et al.,* 2002).

System condition 3. The physical conditions for production and diversity within the ecosphere must not become systematically deteriorated.

Society is dependent on the ecosphere for the supply of food, raw materials and fuel (Azar *et al.,* 1996). Even with system conditions 1 and 2 fulfilled care must be taken not to take more resources from the ecosphere than are regenerated (over-harvesting) nor systematically reduce the natural productivity or diversity by manipulating natural systems (introductions, mismanagement and displacement) (Azar *et al.,* 1996, Robért *et al.,* 2002). Examples of such reductions are; deforestation, soil erosion, land degradation with desertification as an extreme form, extinction of species, exploitation of productive land for asphalt roads and refuse dumps, and destruction of fresh water supplies (Azar *et al.,* 1996).

Systems condition 4. The use of resources must be efficient and just with the respect to meeting human needs without exceeding the level of impact on nature given by principle 1-3.

In a social context efficiency means that resources are used where they are most needed which implies just distributions among human beings (Azar *et al.,* 1996). Human needs refer not only to the basic needs to sustain life but all needs to maintain health (Azar *et al.,* 1996). The Chilean economist Manfred Max-Neef identifies nine fundamental human needs that are consistent across time and cultures: subsistence, protection, affection, understanding, participation, leisure, creation, identity and freedom (TNS, 2008). Max-Neef emphasizes that none of these needs can be substituted for one of the other and that lack of any of them is a poverty of some kind (TNS, 2008). Robért *et al.,* (2002) point out that these needs should not be confused with the cultural means by which we satisfy them. The authors call for a need to change societal focus from commodities to services.

2.6.2. Spider diagrams

Spider diagrams (also called amoeba diagrams) are used to visualize an overall picture of the sustainability of the compared systems (e.g. Altieri, 2002; Bell and Morse, 1999; Guzmán and Alonso, 2007). For each sustainability criterion a relative scale is decided where the real values are related to an ideal or optimal value. Each criterion is represented on an axis in a spider diagram. The real value of each criterion is pointed out on the corresponding axis and all points are joined creating an amoeba like area. The larger the area the more sustainable the system.

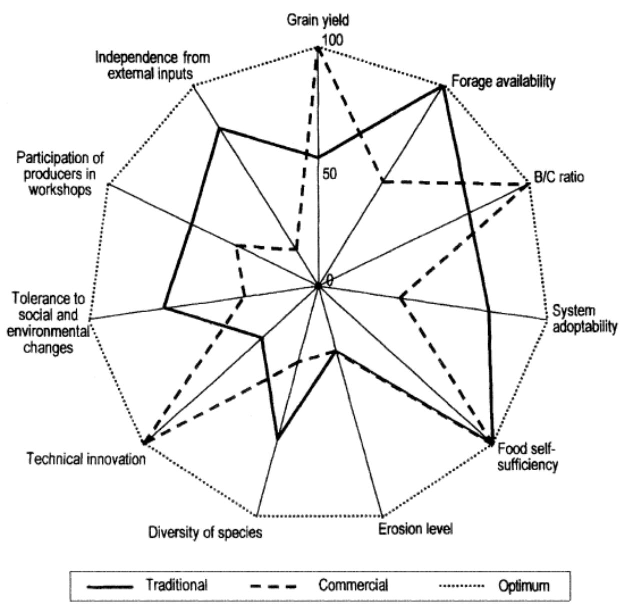

Figure 2.1. *Example of spider diagram (Altieri, 2002)*

2.6.3. In this study

In this study sustainability criteria chosen by the participants were combined with the system conditions of TNS and the spider diagram. The farmers were asked to mention which criteria they would like to use when evaluating the sustainability of the weed management strategies. These criteria were then compared to the four system conditions of TNS to see if something had been overlooked or if the system conditions did not cover what the farmers proposed.

After the relevant criteria were set each criterion was ranked on a 5 points scale comparing the new weed management strategy with the previous one used on the farm (*Chapter 3.2. table 3.3*). The scale was 1 = much worse, 2 = worse, 3 = equal, 4 = better and 5 = much better. For example if it was found that the nutrient circulation was better with the new strategy the criteria received 4 points. At the end all points were summed and divided by the amount of criteria. If the average was higher than 3 the weed management strategy improved the overall sustainability compared to the previous strategy. If it was lower than 3 the strategy had lowered overall sustainability. Of course this is a very rough estimation and should only be used as a guide.

The spider diagram was used to visualize all the criteria in one diagram. Each criterion formed an axis in a circle. Each axis was given 5 points starting from the centre and outwards and a dot was made on the corresponding point of each criteria. All dots were joined and an amoeaba like area appeared. An inner circle at point 3 showed where the separation between an improved or decreased over all sustainability was. If the area was mostly above the inner circle the weed management strategy was more sustainable. The spider diagram of Senneby Trädgård is shown in *figure 3.1., chapter 3.2*.

3. Research Findings and Discussion

In this chapter the information about expected climate change in the regions and expected weed flora change due to climate change is presented. This information together with the interviews with the farmers and literature review of weed management strategies is the basis for possible weed management measure to be taken on the farm. The measures have been developed in discussion with the farmers. Thereafter the sustainability evaluation of the measure on one of the farms, Senneby Trädgård is presented. Finally it will be described what the participants learned during the study about weed management strategies, sustainability evaluation and participatory research methodology.

3.1. Key Weed Issues and Measures to be taken on the Farms

In this chapter the weed management measures were developed together with the farmers taking into account the premises of the study as well as the properties of the farm and the social situation of the farmers will be presented.

3.1.1. Senneby Trädgård

The main weed problems are summer annuals and weeds spreading with the compost. Summer annuals are the predominant weeds due to a crop rotation dominated by annual vegetables (see *chapter 1.3.1.*). Three desirable measures have been identified together with the owners;

1) A composting system where the compost is covered to increase the heat during the decomposition and thereby kill more weed seeds.
2) Include more frequently cut ley in the vegetable crop-rotation.
3) Use green mulch in the vegetable rows.

Although the composting system may be an important measure against weed dispersal it was not investigated further in this study due to time constraints. As for including more ley the owners are looking into the possibility of renting more land which is also suitable for vegetable production.

Johansson and Nilsson had already plans on expanding and mechanizing their mulching practices. It was therefore decided that a field trial should be set up at their farm evaluating the viability of mechanized mulching as a climate smart and overall sustainable weed management strategy. The presentation of chosen weed management strategies at Senneby Trädgård is limited in this chapter since there is a separate paper in *appendix D* which describes the field trial. It is recommended to read the abstract of *Appendix D* before continuing to the next chapter.

3.1.2. Stora Fårvallsslätten

At Stora Fårvallsslätten the mechanical weed management is hand and horse powered. Here the challenge is not to decrease the use of fossil fuels but to make the weed management more efficient. As already mentioned the most troublesome weed is quackgrass (*Elymus repens*) and to some extent docks. This is caused by a crop rotation with long leys and few crops which imply soil tillage as vegetables and cereals (see *chapter 1.3.1.*). At the same time the family is interested in diminishing the labor requiring vegetable production and instead increases the amount of long term leys. Two main measures were identified:

1) To improve the coverage and thereby competitiveness against weeds of the long term leys over the season and over the years.
2) Include a year of with weed competitive annual ley. Keep horses grazing the grass from October-December to diminish quackgrass.
3) To increase the amount of crops which imply mechanical weeding and tillage.

3.1.2.1. Improve the coverage and competitiveness of long term leys.

To increase the coverage of the ley several measures can be taken:

1. Shorten the period of horse grazing to avoid overgrazing benefitting weeds.
2. Take soil samples to see if there are any nutrient deficiencies or unsuitable soil pH for ley growth.
3. Use ley species which are suitable for the system. They should be tolerant to grazing, drought, good fodder quality for sheep, cattle and horses, suitable for hay production and productive in long term leys (*Table 3.1.*).
4. Use species which cover the soil early in spring (*Table 3.1.*).
5. Use species which cover the soil well in summer and autumn (*Table 3.1.*).
6. Do not use species which flower early since there is little possibility to cut them all early in the season with the available equipment (*Table 3.1.*).
7. Do not let animals graze long term leys seeded the same year.

Furthermore a study by Steinbeiss *et al.,* (2008) showed that increased species diversity in the ley increases the soil carbon storage within four years and decreases the original soil carbon loss when a new ley is established. Hence maintained or increased species diversity in the ley may play a role in greenhouse gas mitigation.

Table 3.1. presents the chosen ley species which were identified as suitable for weed management through a literature review, interviews and according to the local experience of Lindkvist (Fogelfors and Lundkvist 1999:116-117; Källander 2005:124, 139-145, Olssons frö AB 2008; Olsson., pers. commun., 2008; Virtuella floran). For each species there is a motivation to why it was found suitable.

Tab 3.1. *Identified ley species mix*

Species	Suitability on the farm
Common birdsfoot-trefoil *Lotus corniculatus*, Käringtand	High fodder quality, tolerant to drought, poorly drained soils, soil compaction, low pH, and low nutrient soil status. Suitable for hay and grazing (intensive and extensive), good productivity in long term leys but lower productivity than other legumes.
Lucerne, *Medicago sativa,* Lusern	To achieve higher productivity of legumes. Good fodder, drought tolerant. Productive in long term leys. Not too much since it is more sensitive and need more frequent cutting than the one above to give good fodder quality. The cultivar Luzelle is more adapted to grazing but there are no organic seeds available yet. Sensitive to low grazing intensity but seems to work on the farm. High amount of seeds on N poor soils to assure enough N fixation.
Red clover *trifolium pratense,* Rödklöver	Included to create a security through diversity and to give good early spring coverage the first 1-2 years before the long term species have developed. Low productivity in long term leys.

	However red clover benefits dock and may therefore be questionable. If problems with docks mainly occur in old leys red clover can be used since it disappears in long term leys. Due to drought intolerance it should only be used on the more clay rich soil.
White clover *Trifolium crepens,* Vitklöver	More resistant in old leys and drought tolerant than red clover. Covers up in gaps. Should be used in the more clay rich soil due to some drought intolerance.
Cock's foot, *Dactylis glomerata,* Hundäxing	To get early growth and coverage in spring. Not too much since it is very competitive and needs higher levels of N and more frequent cutting to maintain good fodder quality. Today it is possible to buy late maturing varieties which may be more suitable since they can be cut later in the season. Bad taste may be compensated by tasty herbs.
Tall Fescue, *Festuca arundinacea* var. *arundinacea*, Rörsvingel	To get good coverage summer and autumn. Very resistant to grazing. Not liked by sheep summertime thereby need to combine grazing with cow/horses and/or mowing. Good productivity in long term leys. May need more N for better development in the ley.
Ribwort plantain *Plantago lanceolata*, Svartkämpe	High mineral value, re-circulates nutrients from subsoil, very good coverage and weed competition with time, drought tolerant. Suitable for hay production and grazing. Can improve taste of hay when less tasty grasses are used. Self seeded.
Caraway, *Carum carvi,* Kummin	Good growth especially cold springs, good productivity in long term leys, pleasant smell and taste in hay. Should possibly be avoided if carrots are close in the rotation since they originate from the same botanical family.
Black medic, *Medicago lupulina*, Humlelusern	Grows well in low intensive leys, drought tolerant, good fodder quality. Self seeded.
Salad burnet, *Sanguisorba minor*, Pimpernell/Pimpinell	Grows well in low intensive leys, drought tolerant, vitamin and mineral rich, tasty.
Red fescue, *Festuca rubra,* Rödsvingel	Suitable for grazing, week competitor but covers gaps in the ley when other species have disappeared. Not as tasty as timothy but keeps quackgrass and docks away in older leys.
Mix of ryegrass and tall fescue, Rajsvingel	Cultivar: Hykor (not Perun). Competes well against dock. High dry matter-yield, good cold, drought and water saturation tolerance.

For the sandy soil the following mixture and proportion of seeds were found suitable:

60% (12kg/ha) common birdsfot-treefoil (or lucerne)
20% (4kg/ha) ribwort plantain
10% (2kg/ha) cock´s foot
10% (2kg/ha) tall fescue

A smaller part of the common birdsfoot-trefoil or lucerne may be exchanged for black medic. Part of the grasses may be exchanged for a mix of the other grasses mentioned in *table 3.1.* Some of the grass seeds or ribwort plantain may be exchanged for herbs like salad burnet and caraway. The aim of the high amount of ribwort plantain is to suppress the weeds. A cheaper alternative is to increase the amount of cock's foot. According to the farmer Cock's foot is suitable for weed control but turns yellow very early. This is probably due to low N levels on the farm (Olsson pers. commun., 2008). If the tall fescue will be productive on the farm it may be able to replace the early yellowing cock's foot. For the more clay rich soil two kg of the common birdsfoot-trefoil or lucerne could be exchanged for one kg red clover and one kg white clover.

Implementation on Farm.
According to Lindqvist this measure fits well to what has been tested on the farm previously. The higher amount of ribwort plantain is interesting but needs to be somewhat lower to decrease the costs. The potential of tall fescue is interesting. Especially the good growth in autumn which allows for prolonged grazing period which decreases the labor requirement on the farm. Possibly a plot of tall fescue will be grown next year as the only grass species together with the other herb and N-fixating species recommended in this study.

3.1.2.2. Weed competitive annual ley combined with horse grazing.
Common vetch (*Vicia sativa*) and annual rye-grass (*Lolium westervodicum*) are two species which compete very aggressively against weeds due to their early and compact growth pattern. They grow fast and create a good ground cover in early spring (Olssons Frö AB, 2008). This may be favorable against quackgrass since it is at its most sensitive stage in late spring (Dock Gustavsson, 1994). Possibly a grazing at this point could further weaken the quackgrass. The mentioned ley species also grow until late winter (Olssons Frö AB, 2008). According to a personal communication from Olsson (2008) at the seed company Olssons Frö these species can be grown together but should not be grown together with perennial ley species since they are aggressive and will dominate all other species. Hence it is suggested to introduce a year of these competitive ley species in the crop rotation. Olsson also recommends a grazing or mowing of this ley during summer and then letting the horses and sheep graze from October to December which will efficiently diminish quackgrass. It should be investigated if horse grazing controls the quackgrass enough to replace the commonly used autumn stubble cultivation against this weed (Dock Gustavsson, 1994). If the method is efficient is has the positive advantage of reducing nitrogen leakage as well as nitrogen and CO_2 volatilization caused by soil tillage (Dock Gustavsson, 1994). It saves labor when the horses graze the ley in late autumn. It also offers two ecosystem services:

1) Competitive ley species suppressing the growth of quackgrass and
2) Horses controlling the quackgrass through grazing at late spring/summer and autumn.

Implementation on Farm.
This measure is very interesting to the farm owners since it combines several benefits. It introduces more opportunities to till the soil in the crop rotation than what is used at the farm today which may reduce the quackgrass. At the same time it requires less soil tillage than the commonly used short summer fallow/ whole summer fallow or autumn stubble cultivation (Dock Gustavsson, 1994).

3.1.2.3. Increase the amount of crops which require horse powered mechanical weeding and tillage.
At this farm horses perform ecosystem services by for example serving as drought animals. Hence all weed related soil tillage is performed with the help of horses and not by diesel driven tractors. A way of improving the quackgrass control would be to introduce more crops into the crop rotation which require or allow for horse powered soil tillage before, during

and/or after their cultivation. Since the family wants to take a brake from the vegetable production and lactic acid fermentation and since cereals are difficult to produce in a competitive manner with horses an alternative crop is needed. The green manure after the ley in the crop rotation may be exchanged for field bean (*Vicia faba*) and/or blue lupin (*Lupinus angustifolia*). Field bean is not a high income crop but could be used as fodder. A related cultivar, broad bean, with larger beans can be used as food for the family. Field bean stores about 70 % of its N in the roots and is thereby an efficient green manure even if the legume is harvested. Both are inefficient weed competitors but allow for inter-row cultivation and tillage before or after the cultivation (Olrog, 2004). Field bean can be harrowed until it has reached 10 cm (Olrog, 2004). Field beans are suitable as fodder for cows but not horses (Boström pers. commun., 2008). Blue lupins can become toxic to sheep (Boström, pers. commun., 2008). They can also be sold as a niche crop for human consumption. They are from different botanical families and will not cause problems in the crop rotation. Both are easily stored, transported and possible to cultivate with the equipment available for horses. However field bean may need irrigation (Olrog, 2004) which could increase diesel consumption. Also an efficient way of drying the two crops must be found.

Implementation on Farm.
The benefit of cultivating field bean at this farm is small since it is not suitable for horses and does not give a high price. It does only grow well on the somewhat more clay rich soils. Blue lupin was tried this year but gave a very poor harvest. It needs to be grown for more years to evaluate its suitability since this year was exceptionally dry. The farm has been contacted by an herb company to grow garden thyme (*Thymus vulgaris*) and basil (*Ocimum basilicum*) for oil production. These are high value crops and could be a possibility for the farm. However the family has decided to decrease the amount of farm work for some time and has therefore not decided whether to accept the offer.

3.1.3. Sundviks Trädgård

The key weed issue on the farm is an abundance of summer annual weeds. Perennial weeds are no longer a problem probably caused by the change from cereal production and perennial leys with limited soil disturbance during the dairy cow production to annual vegetable production and more soil preparation, especially more pre-plant harrowing (see *chapter 1.3.1.*).

To control the summer annual weeds five possible strategies within the premises of this study have been discussed together with Rundström:

1) Introducing more autumn sown cereals or cover crops in the crop rotation to suppress summer annual weeds.
2) Consumer participation in weeding.
3) Left over silage as green mulch.
4) Strip intercropping vegetables and a permanent clover ley which will be root pruned and/or frequently mowed. Mowed mulch will be spread in the vegetable rows to smother weeds.
5) Sowing a winter annual legume cover crop which will be mowed at spring to avoid competition and transplant vegetables into the mulch.

3.1.3.1. Increase autumn sown crops and ley in vegetable crop rotation.

As indicated above it is important to mix annual spring sown and autumn sown as well as perennial crops in the rotation to achieve a good weed control. Hence it is suggested that the vegetable field should be extended with autumn sown crops and/or 2-3 years ley. A suitable winter cereal is rye since it is very competitive against weeds (Dock-Gustavsson, 2004). This means that more land is needed for the vegetable crop rotation.

Implementation on Farm.

The only piece of land which could be added to increase the vegetable crop rotation area is further away from the house. Since Rundström prefers to keep the labor intensive vegetable production close to the house this method is not suitable on this farm. It can however be viable on other farms.

3.1.3.2. Consumer weeding

Summertime a large part of the population are tourists with summer houses on the island. They are also the primary consumers at the farm store. Getting together to weed is thought to be offered to the consumers and other island inhabitants as a way of spending time together doing something practical and close to the earth. Rundström has sensed a need amongst some of the recurrent summer guests to take a brake from social obligations and chores of the summer and believes that weeding may be a good way for them to clear their thoughts. She also sees it as a pedagogical activity where people can learn about the work behind food production. The gain from organizing these events for Rundström will be some help with the weeding. When presented with the idea several summer guests found it to be an interesting idea. Similar systems were mentioned by other farmers in the literature study and are said to be used with success (Johansson, pers. commun., 2008a; Berlin and Berlin, pers. commun., 2008). This would also allow Rundtröm to get to know the persons before she chooses to offer them more frequent occupation on the farm.

Implementation on Farm.

The method will possibly be tested next season at Sundvik Trädgård.

3.1.3.3. Transplanting vegetables into silage mulch

It is not uncommon that farmers have left over silage. This silage can become a resource instead of a waste problem by using it as green mulch in vegetable production However it is questionable if it could be called an ecosystem service and be energetically efficient if the silage is produced for the purpose of green mulching. The benefit of using silage instead of fresh green manure is that it is available early in the season and can be spread by tractor over the field before the vegetables are transplanted. This allows an even spread and does not require any special equipment to protect the crop. Since the vegetables are transplanted into the mulch instead of spreading the mulch when the vegetables already are transplanted there is no need for raking the mulch closer to the plants. This saves a lot of time. Another benefit is that silage is more resistant to degradation and gives better coverage against weeds for a longer time (Larsson, 1997). Floating row-cover[21] should not be used since it increases the ammonia concentration which damages the plants (Johansson, pers. commun., 2008b). Covering the soil in early spring may also delay the warming of the soil.

Spoiled silage should probably not be used to avoid inhaling mould when working with the silage. The risk of the mold damaging the crops is assumed to be low since most species of

[21] A light weight polyester fabric used to extend the growth season by creating a greenhouse effect and to protect against insect damage.

fungi do not attack both dead and living plants. It is important to achieve a good growth of the seedlings as soon as they are transplanted into the field. Otherwise the time of harvest may be delayed and the crop will be weakened (Wien, 1997:48). If the C/N ratio of the silage is high it may cause immobilization of the N making it unavailable to the plants. Hence, the transplants should be observed and if they show sign of detained growth a liquid organic fertilizer with relatively easily available N should be added.

Implementation on Farm.
This measure will be tested on the farm. It is attractive due to the early weed control and since it may be simpler than spreading fresh green mulch by hand. The silage will be rolled out over the field. Rundström wishes to compare the effect of silage coverage applied in autumn and spring. The pace of silage degradation may differ a lot depending on the state of the silage at application. The silage should also be seen as a form of fertilization.

3.1.3.4. Transplant vegetables into mowed winter annual legume cover crop – hairy vetch.

Cover crops are known to reduce weeds either as mowed, naturally or chemically killed mulch or as living mulch intercropped with the main crop. Living mulch has been shown to suppress weeds more efficiently than dead mulch (Ilnicki and Enache, 1992, Teasdale and Daughtry 1993). However competition between the main crop and cover crop must be decreased. One way to achieve this is to synchronize the senescence of the cover crop with the maximum vegetative growth of the main crop. Brandsæter *et al.* (2008) explained that this can be achieved using winter annual legumes. Winter annual legumes are sown late summer, become dormant during winter and continue growing at spring. Late spring or early summer the legume senesces and dies. Hence competition is avoided with the vegetables that have been transplanted into the senescing mulch and are increasing their vegetative growth.[22]

A solution adapted to Nordic climatic conditions is to use winter annual cover crop species and cultivars that are mowed in spring before transplanting vegetables. As winter annuals they also experience natural senescence during summer but somewhat later when vegetables are transplanted. Hence, to avoid early competition with the main crop they need to be mowed (Brandsæter and Netlund, 1999). The method has mostly been used in non vegetable crops and rangelands (Putnam, 1990) however Abdul-Baki and Teasdale (1993) showed increased yield in tomato with this system and Brandsæter (1996) showed no difference in yield between cover crop and bare soil treatments in cabbage. The most promising cultivars found so far which are grown in a similar temperature zone as Sundvik trädgård are hairy vetch (*Vicia villosa*) cultivar Hungvillosa and then crimson clover (*Trifolium incarnatum*) cultivar Heusers Ostsaat (Brandsæter and Netland, 1999; Brandsæter *et al.,* 2000, 2002). They both showed good autumn establishment, early summer biomass and ground cover development and low crop re-growth after mowing but low ability to naturally reestablish

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[22] A cover crop which follows that growth pattern is subclover (*Trifolium subterraneum*). Subclover as living mulch in no-tillage system has been shown to greatly reduce weed biomass compared to conventional herbicide-tillage treatment in soy beans (*Glycine max*), snap beans (*Phaseolus vulgaris*), white cabbage (*Brassica olearacea capitata*), sweet corn (*Zea mays saccharata*), summer squash (*Cucurbita pepo*) and tomato (Lycopersicon esculentum) without adversely affecting the yield (Abdul-Baki and Teasdale 1993, Ilnicki and Enache, 1992). It has also shown a strong ability to naturally reestablish from seeds in the second autumn (Brandsæter and Netland, 1999). Unfortunately it has shown very poor winter survival in Norway and the long summer days seem to make it more frost sensitive[22] (Brandsæter *et al.,* 2000). Hence it is assumed that it will only perform well in the south of Sweden. Frost killed species as phacelia (*Phacelia tanacetifolia*), buckwheat (*Fagopyrum esculentum*), spring wheat (*Triticum aestivum*) and oat (*Avena sativa*) did not produce enough biomass before winter to give sufficient weed control at spring in Nordic conditions (Brandsæter, 1996).

from seed next autumn (Brandsæter and Netlund, 2002). Crimson clover had higher re-growth ability which was lowered if mowed in mid June. Though winter survival of the crimson clover was lower than hairy vetch, there are indications that it is less sensitive to delayed sowing in autumn (Brandsæter *et al.,* 2008). The same study showed that hairy vetch has a superior weed suppressing ability even with winter annual weeds geminating at the same time as the cover crop. Crimson clover showed lower and more varying weed suppressing ability. None of the cover crops could totally control *Poa annua* grass. In the experience of the farmer, Rundström, crimson clover has not survived the winters at her farm Sundvik Trädgård, but hairy vetch could possibly survive. Hence focus should be set on hairy vetch at this farm. Rye and hairy vetch/rye spring killed with glyphosate in conventional agriculture did not show any yield depression in white cabbage (Brandsæter 1996). However the weed control was too low at late summer, calling for a late summer weeding. Since early mechanical weeding is not necessary with a cover crop, higher planting densities of the main crop could be possible. This would allow the canopy of the main crop to cover a larger area during late summer and hence suppress weeds. In some crops it could also contribute to higher yield/ha. Higher planting densities may however increase the risk for fungi attack due to increased humidity.

According to Brandsæter *et al.* (2008) hairy vetch should be sown between early August and early September e.g. after harvesting cereals. The authors state that the earlier sown the higher the biomass at mowing next spring however, too early seeding may result in decreased winter survival. Seeding rate used by Brandsæter *et al.* (2008) was 75 kg/ha for hairy vetch. If the legume has not been grown on the land before, it is recommended to inoculate the seeds with appropriate *Rhizobium* bacteria. If the vegetable crop rotation at Sundvik Trädgård would be combined with the cereal/ley rotation, cover crop seeding could be done after winter cereal harvest or early termination of ley. In the vegetable/one year green manure rotation, the following crop rotation including hairy vetch cover crop is suggested:

Table 3.2. *Crop rotation with hairy vetch cover crop and vegetables.*

Year	Crop	Management	Season
1	Green manure	Sowing	Spring to spring
1		Green manure termination	Spring
2		Short summer fallow with tillage against perennial weeds.	Spring to summer
2	Lettuce	Sowing	Summer
2	Hairy vetch	Sowing	Early to late august
3		Mowing the cover crop. Adding small amount of liquid manure if needed, or compost into the growing cover crop at spring.	Late spring
3	Onions/pumpkin/squash	Planted into the mowed cover crop mulch	Late spring
3	Hairy Vetch	Sowed after vegetable harvest or into the vegetables 2 weeks before harvest	Early to late august
4		Mowing the cover crop. Adding liquid manure if needed. Or compost into the	Late spring

		growing cover crop at spring.	
4	Cabbage/flowers	Planted into the mowed cover crop mulch	Late spring
4		After harvest soil tillage against perennial weeds	Autumn
5		Repeated weed harrowing and possibly delayed sowing to reduce seed bank and prepare seed bed. Possibly adding solid manure to part of field.	Spring
5	Carrots/beetroot/lettuce/dill/ parsley/ leek	Sowing	Late spring
5	(possibility to sow rye as catch crop)	(Sowing)	Autumn
6	Green manure	Sowing	Spring to spring

Box 3.1. Benefits and Challenges of the method.

Together with Rundström the following challenges and needs for further investigations of this system have been identified;

- Winter survival of hairy vetch in this climatic zone.
- Production of enough hairy vetch biomass to efficiently suppress weeds. It has been shown that a biomass of 450g/m^2 is likely needed to reach an acceptable level of weed suppression (Almeida, 1985). At Sundvik trädgård most vegetables are sown or transplanted between the start and end of May. The study by Brandsæter *et al.* (2008) showed that the biomass in May was between 150-450 g/m2 for 'Hungvillosa' hairy vetch depending on the year and location. To postpone transplanting of the vegetables a whole month to achieve higher biomass, as suggested by the authors, is not seen as a viable option at Sundvik Trädgård. These and perhaps other cultivars must be tested locally to see how often they produce sufficient biomass for an acceptable level of weed suppression.
- The biomass production may vary greatly on a yearly basis. Heavy rains at late summer may make sowing of hairy vetch delayed or impossible. Vegetables may not be harvested before end of august when the cover crop must be planted. A possible solution is planting the cover crop into the vegetables about two weeks before harvest. Preferably hand harvested crops with low soil disturbance at harvest should be chosen. The rotation above has included this possibility. Prolonged winter or very dry spring may decrease growth. If the cover crop biomass is too low to suppress weeds alternative weeding may be needed which could be made difficult with the cover crop on the soil.
- Weeds which emerge when the coverage is reduced at late summer must be decreased to a minimum to avoid high labor requirement in July when the main harvest and selling of the products in the farm store occurs. This could possibly be accomplished with narrower plant spacing allowing a competitive advantage against the weeds. Plant spacing is often wider than necessary to allow weeding. If the cover crop eliminates that need plants can be grown closer.
- A crop rotation with decreased tillage could increase the amount of perennial weeds (Putnam, 1990) as quackgrass *and* thistles. It needs to be investigated if the amount of soil tillage planned for this rotation will maintain the perennial weeds on an acceptable level. Short summer fallow followed by salad and cover crop or autumn stubble cultivation followed by plowing are suggested measures against perennial weeds in this rotation (Dock Gustavsson, 2004). An autumn sown grass cover crop which is cut or grazed at late autumn may also have some effect (Dock Gustavsson, 2004).

Possible benefits with this method mentioned in a review by Ammon and Hartwig (2002) are: increased C sequestration in the soil due to less soil disturbance and more biomass production over the year, improved soil structure, retained soil humidity, less N leakage at autumn and spring, N fixation from the atmosphere, reduced soil erosion, reduced soil water pollution. According to a review by Smith *et al.* (2008) reduced soil tillage decreases CO_2 emissions. For N_2O emissions there is more variation and according to the authors reduced tillage can cause both increased and decreased emissions depending on soil and climatic region. Assumingly it will also lead to less diesel consumption due to less mechanical soil preparation and, if the method succeeds at this latitude, less labor due to less hand and mechanical weeding.

Implementation on Farm.
Cover cropping and the adapted crop rotation mentioned above will not be implemented as a whole on the farm. Rundström is slowly decreasing the production at the farm after 27 years of farming. Hence Rundström agreed to discuss the viability of different weed management strategies but not to introduce any large changes at the farm. However, she found the idea interesting and will perform a small scale observation trial possibly next season where some of the above mentioned challenges will be evaluated.

3.1.3.5 Strip intercropping with perennial cover crop legume

Perennial white and especially red clover have the benefit of surviving the cold winters of northern Sweden well (Mossberg, 2003). Being sown at autumn they compete well against summer annual weeds at spring. Strip intercropping vegetables with perennial clover can therefore be a viable weed control. In this case the legume is a perennial and there is no possibility of synchronizing its senescence with the maximum growth of the crop. Instead the legume is mowed and root pruned. A clover ley is sown year 1. Next year strips for vegetable plantation are opened. The vegetables are transplanted into the strips. Two forms of weed control are combined in this method 1) between rows through the competitive advantage of the perennial clover compared to annual weeds and 2) within rows by cutting the clover and placing the green mulch in the vegetable rows. After harvest and/or at spring the strips can be tilled to keep them open and manure can be added. This method has been tried by for example Paul Teepen (pers. commun., 2008) during two years using white clover. He emphasizes the importance of not having problems with perennial weeds when the method is introduced and the importance of a good establishment. Teepen recommends sowing the clover into a cereal crop and with a higher density than what is normal for leys to achieve a good establishment and coverage. He uses a between row distance of 0.5 m and a Dutch wheeled handhoe to open up the vegetable rows.

Box 3.2. Benefits and Challenges of the method.

Apart from being a weed control the clovers also contribute with the same benefits as mentioned under winter annual cover crops above. They have also been shown to decrease pest attacks from the cabbage root fly, (*Delia floralis*), and lygus bug (*Lygus rugulipennis*) (Rämert, unpublished). Normally the whole field needs to be tilled each year. With perennial clover intercrop only the strips where the vegetables will be grown need to be tilled. This reduces the need for tillage and thereby the energy consumption.

Compared to harvesting a ley on an adjacent field and *transporting* the dead mulch to the vegetable field several benefits are gained; less soil compaction, less energy consumption less labor (Schäfer *et al.*, 2002). If the long term ley is removed from the vegetable crop rotation then this method can provide the beneficial impact on soil microbial biomass and enzyme activity normally provided by ley (Elfstrand, 2007). Some disadvantages are: the ley area needed to cover the rows with mulch may differ from year to year depending on the climate while in this system the available area is fixed (Schäfer *et al.*, 2002). A field trial with white cabbage and redclover was set up to investigate the effect of the redclover on the turnip root fly (Rämert, unpublished).

According to personal communication from the coordinator Rämert the effect against weeds between the rows was very good. However there was not enough red clover cutting to cover the weeds within the white cabbage rows. It was found that there is a lot of competition between red clover and white cabbage.

To decrease competition trials were performed within the project where the clover was root pruned before planting and cut after the late generation of turnip root flies had passed. However more research must be done on combinations of cultivars in the intercropping system, the impact of different climate regions on the relationship between different cultivars as well as timing and frequency of root pruning and cutting to decrease competition to an acceptable level. It can be assumed that root pruning, cutting and spreading the mulch will require more fuel and labor than mechanical weeding. It needs to be investigated whether this is compensated by the reduced soil preparation in autumn and/or spring in clover strip intercropping.

Implementation on farm.
Rundström is more skeptical to this method due to the competition it may cause with the crop and the problems which might arise with perennial weeds. However Rundström did a small trial sowing a seed mixture in an alley between her vegetable beds which was thought to be tested as an intercrop in the method mentioned above. The seed mixture is sold by Prodana and is usually used for golf lawns. It contains 5 % white clover 'microclover', 20% perennial ryegrass (*Lolium perenne*) 'Greenway S', 30% perennial ryegrass 'Greenfair S' and 45% smooth meadow-grass (*Poa pratensis*) was sown and compared to a mixture of persian clover (*Trifolium resupinatum*) and annual ryegrass which are used on the farm. The alleys were not mowed as frequently as they should due to rains. This resulted in high growth and flowering of the persian clover/annual ryegrass mixture while the micro clover/grass was still quite low and not flowering. Although low it covered very well against the weeds. According to Rundström Persian clover is suitable since it grows fast at spring, covers well and can be frequently mowed. The microclover mix grew even better but needs to be grown more years to be properly evaluated.

3.2. Evaluation of the measures with the Sustainability tool

As mentioned previously under *Materials and Methods* there was only time to perform a sustainability evaluation at Senneby Trädgård. Please read the abstract of the paper about green mulch in onions (*appendix D*) before continuing this chapter. For a deeper understanding of green mulch and the field experiment the reader is also referred to *appendix D*.

The weed management strategy using green mulch from ley cuttings to shade out weeds was compared to the previous practice of inter-row cultivation. *Table 3.3.* presents sustainability criteria mainly chosen by the farmers for the evaluation. Each criterion is explained below the table. One of the objectives of the study was to evaluate whether The Natural Step framework was suitable for analyzing the overall sustainability of the developed improved agricultural practices. Hence the author, when possible, placed the criteria chosen by the farmers under one or more of the system conditions and corresponding human needs developed by Max-Neef (subsistence, protection, affection, understanding, participation, leisure, creation, identity and freedom) (TNS, 2008). In some cases the system conditions and human needs did not entirely cover the criteria. The motivation to why they do not fit is mentioned under each criterion. Finally a spiderdiagram was made by the author to overview and visualize the sustainability evaluation in one figure (*fig. 3.1.*).

Table 3.3. *Sustainability criteria and ranking at Senneby Trädgård.*

System Condition (corresponding human need)	**Criteria**	**Ranking**						
		much worse (1)	**worse (2)**	**equal (3)**	**better (4)**	**much better (5)**		
1	a) Non-renewable energy	1						
4 (subsistence and leisure)	b) Labor		2					
2	c) Nitrogen leakage		2					
3	d) Soil micro environment					5		
2	e) Land-use related climate change			3				
4 (subsistence)	f) Working environment		2					
3?	g) Nutrient circulation					5		
3 and 4? (Subsistance ?)	h) Flexibility of ley					5		
3 and 1	i) Soil carbon storage				4			
4 (subsistence and leisure)	j) Quality				4			
3	k) Quantity			3				
	Sum		6	6	8	15	**Total**	35
							Average	2,9

a) ***Non-renewable energy*** consumption was ranked very low due to the high consumption of non-renewable energy shown in the experiment and its importance to climate change. Attributed to system condition one since it includes accumulation of substances from the earth crust in the ecosphere.

b) ***Labor*** consumption was ranked low since the experiment showed that the method was more time consuming. Placed under system condition 4 since it is associated to the human needs subsistence (economy) and leisure (time off).

c) ***Nitrogen leakage*** was ranked low since the experimental samples and literature review showed indications of autumn leakage from remaining mulch after harvest. Attributed to system condition 2 since N is a substance produced by society due to increased amount of N fixing legumes in the ley and systematically accumulated locally through poor N efficiency.

d) The farmers estimate that the ***soil micro climate*** should be much better due to the higher humidity. The farmers have noticed that tomato roots grow much better in the top soil under mulch compared to bare soil. They therefore believe that the very top of the top soil is thought to be richer in nutrients and that there is an improved climate for soil fauna and flora. However no such strong tendency was observed in onion. Possibly placed under system condition 3 due to a more efficient use of resources which gives a better land use ratio compared to natural habitats and improved soil fertility and/or system condition 4 due to more efficient use of resources improves distribution of limited resources amongst humans.

e) ***Land-use related climate change***. Here land-use factors like emissions from ley cuttings were included. The indicator was ranked as no different since research has shown that there is no difference between nitrous oxide and carbon dioxide volatilization from mulch on ley or in vegetables. Placed under system condition 2 since the emissions are man made due to change in land use.

f) ***Working environment.*** The spreading of the mulch was experienced as heavy by Johansson due to constant changes of tractors to the mulching wagon. A more powerful tractor was used to harvest the ley and a less powerful for spreading the mulch in the vegetable rows. Hence the mulch wagon had to be reconnected between the two tractors. Placed under system condition 1 and human need subsistence which includes health.

g) Johansson believes that ***nutrient circulation*** is improved since the nutrients in the ley can be assumed to be more adequate to the crop needs compared to only animal manure. Some of the nutrients from the ley are incorporated into the animal and only the rests are passed to the plants. Possibly placed under system condition 3 due to a more efficient use of resources which gives a better land use ratio compared to natural habitats and/or system condition 4 due to more efficient use of resources improves distribution of limited resources amongst humans.

h) Johansson found that the ***flexibility of the ley*** was much better since a new option for the ley cuttings is created. The ley always needs to be cut to control weeds and to maintain a high fodder quality. The ley can be grazed or harvested and turned into silage or hay. With mulching there is a new opportunity to use the cuttings. This gives flexibility in the logistics of the farm. It was difficult to place this criterion within the systems conditions. The flexibility could be seen as the adaptability of the method to the circumstances. If it is adaptable and flexible it will strengthen the ecological aspects of the farm. E.g. instead of a surplus of silage production which in the end is only burnt the mulch can be included in the system as a weed control, improve soil fertility and nutrient circulation. The adaptability is also a form of economic and social (time) insurance. According to MESMIS (mentioned under *Material and Method*) adaptability is sometimes seen as part of the concept of resilience. Possibly the social and economic part of the resilience concept could be placed under the human need of subsistence in system condition 4. The ecological aspect of the concept is however more difficult to fit in under the system conditions. Possibly it can be attributed to system condition 3 since weak agroecosystem resilience could reduce the productivity.

i) By continually adding organic material the ***soil carbon storage*** will increase slowly over time. Attributed to system condition 3 due to improved soil fertility.

j) The ***quality*** of the products was estimated to be better at least from the visual point of view and is therefore ranked as better. In the qualitative evaluation made by the farmers the canopy of the onions was estimated as more luxurious. The farmers also believed that the internal quality can be improved with a better nutrient supply from the mulch. However only research showing higher vitamin C levels have been found. Some nutrients have been shown to increase and others decrease when mulch is used compared to bare soil but no connection to health has been performed. This is an area in need of more research. Placed under system condition 4, since health is part of subsistence and the experience of a more luxurious vegetable may be seen as leisure.

k) ***Quantity***, as onion weight, was not significantly higher in the mulched treatment compared to the bare soil and inter-row cultivated treatment. It was thereby ranked equal even though increased yield has been shown to be higher in many other studies in other crops. Placed in system condition 3 since higher yield would mean less area use.

The ranks were summed and the average was calculated to be 2.9. An average of three would mean that green mulch in onion does neither improve nor worsen the sustainability of the previous weed management strategy of bare soil and inter-row cultivation. Lower than three would mean that the measure is somewhat worse from a sustainability point of view and higher than three that the measure improves overall sustainability. Considering the robust nature of this comparison 2.9 can be considered as a status quo. The sustainability analysis is visualized in a spiderdiargram (*Fig. 3.1.)* where the pink circle represents the previous weed management strategy (bare soil/inter-row cultivation) and the green amoeba-like shape represent green mulch as weed control in onions. It can be seen that the area of the green mulch treatment is not much different from the previous weed management practice. Hence there is no large difference in overall sustainability. A larger area would have meant improved sustainability and a smaller reduced sustainability.

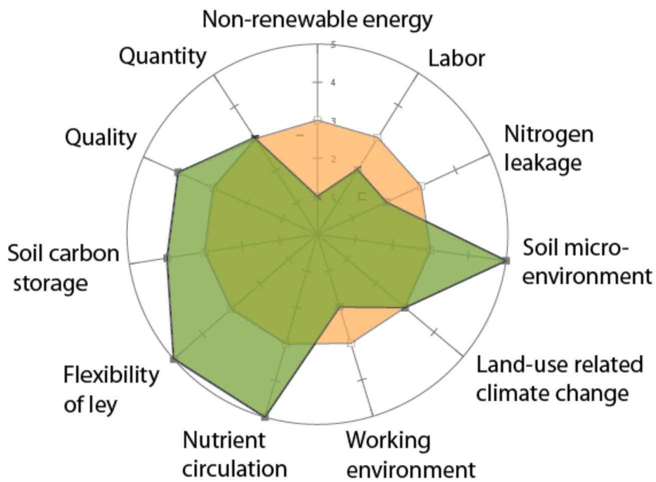

Figure 3.1. *Spider diagram comparing the overall sustainability of green mulch in onion (green amoeba-like shape) and bare soil and inter-row cultivation (pink round circle) as weed management strategies at Senneby Trädgård.*

3.3. What was learnt about measuring sustainability?

Even though the full sustainability analysis was only performed at Senneby Trädgård the other two farms also gave their impression of the joint tool of The Natural Step and the spider diagram. The tool of sustainability seems to have broadened the aspects included in the sustainability evaluation. However there was not time enough in this study to perform a thorough introduction to and discussion about the tool and its premises. The farmers did not find the four system conditions easy to grasp and use. It required a lot of time and help to know were to place different criteria. Lindqvist at Stora Fårvallsslätten had some previous experience of The Natural Step and believed the system conditions could be useful. Perhaps the system conditions could be useful if more time was given to understand them. On the other hand time and patience is often lacking and a useful tool should be easy to understand and use.

The fact that for example animal ethics and GMO are not included in The Natural Step is a drawback of the framework. An important social aspect of sustainability is the resilience or security of the system mentioned by Senneby trädgård. Resilience and security are however difficult to place within the fourth system condition. It could be argued that it is covered by system condition one and two since humans are part of nature but even naturally occurring toxins are damaging to human health and so is for example too heavy labor.

The conclusion is that the tool could be useful if there is enough time for a proper introduction. Once the method has been introduced it can probably be used more easily adapted to other situations. In order to find a practical sustainability evaluation tool more time is needed to develop the tool in a participatory way. Also other kinds of divisions of sustainability conditions, indicators or attributes should be tested.

3.4. Limitations of the study and suggestions for the future.

A limitation of the work process was that the study had to be concluded within the 30 weeks of the master project. Hence many steps of the process had to be rushed and the participation of the farmers was low compared to the author. During the evaluation Rundström stated that she had not understood that this was supposed to be a participatory research project. This shows the importance of good communication and enough time for the process of the participatory research. Possibly each participant should be asked to give their individual view of the aim of the project. In this study the aim and method of the study was only brought up in a group discussion during the first meeting.

Both Sundvik Trädgård and Stora Fårvallsslätten felt that the study was very theoretical and that their participation and the usefulness of the study would have been larger if simple experiments were performed and evaluated on their farms. They also felt that the author should have been more present on the farms. This was not mentioned by Senneby Trädgård probably since there a practical trial was preformed. By performing an experiment and an overall sustainability analysis the research process was taken a step further at this farm.

Perhaps the answer to all the encountered difficulties above is that a participatory research and development group probably needs a few years before all participants feel comfortable with the approach. Each actor must find its role and learn to appreciate what the other actors can contribute with.

The area of study was too extensive for the limited time available. The study could have been limited to only one farm and/or exclude the work on sustainability criteria and tools. For future participatory projects with very limited time (one year or less) the initiative should come from already organized participatory projects and the study area should be limited. For example if the group of Climate Smart Agriculture would have been more established they could have identified one or more measures which they were ready to evaluate on their farms. Students could be invited to participate in the evaluation of the measures as a part of their bachelor or master thesis's. Since the group was new no such projects were identified before the start of this study.

3.5. Limitations and strengths of participatory on-farm experiments and suggestions for the future

Performing an experiment with a statistical design was found to be too demanding on such a diversified farm as Senneby Trädgård. Possibly simple statistical experiments could be performed on large and more specialized farms with more homogenous environments. However, then the properties of other farms will not be evaluated. For example a high yield in a homogenous field and with the work load distribution of a specialized farm does not have to correspond to the yield which is obtainable under the circumstances of heterogynous soil conditions and the different logistics of a diversified farm. If the focus lies on the statistical design the method will not be fully integrated in the farming system and therefore the appropriateness of the method in the complex reality will be difficult to evaluate. The evaluation of the research process together with the owners of Senneby Trädgård resulted in two alternative suggestions of how to do participatory trials on farms;

1) First perform the trial on a research station or on a specialized and large or at least somewhat homogenous farm with full statistical design. If the fields are heterogonous the statistical design can be adapted as long as there is a large area enough to include the variability of the farm. On a small and heterogeneous farm the limitation could be (as in the experiment of this study) that there is not enough of the same cultivar planted to be able to perform a larger field trial. The main objective of these trials should be to improve the method and exclude some of the largest uncertainties. Variables which are difficult to evaluate on a commercial farm should be investigated on a research station. Thereafter a simpler version of the trial can be placed on commercial farms with different properties to include the real-life complexity. The aim of placing the trial on the farm is to evaluate the method from a systems perspective.

2) First perform a simple trial mostly based on observation on commercial farms. If the method seems to have some potential it is performed with full statistical design on a research station. The method can then again be evaluated on farms to incorporate what was learnt on the research station.

The second option is to prefer when possible. This way one can avoid years of study of a method which turns out to be limited by other factors than which were tested on the research station. The trial on station can be improved with the input from the farmers. Both approaches are possible to combine with external researchers or students performing a part of the research project.

3.6. Strengths of the study

The farmers expressed that by participating in this project they have developed the way they evaluate their practices especially concerning energy consumption. It has also strongly motivated them to try to do something more to improve. At Stora Fårvallslätten the farmers felt that by participating in the study the ideas they were working on concerning the choice of ley species and the role of the farm animals in suppressing quackgrass were further developed.

At Senneby Trädgård the study resulted in the above mentioned suggestions on how to work with on-farm experiments in participatory research. It also gave new insights concerning the use of green mulch. Both author and farmers at Senneby Trädgård became more skeptical to when green mulching may be a desirable weed management strategy. The study has shown that labor requirement and diesel consumption of mechanically applied green mulching was higher than what the participants would have expected. However the participants felt there is too little scientific knowledge about the various benefits of green mulch which the growers have experienced. Also some questions are left unanswered by this study as; what would the diesel and time requirement be if part of the animal manure would have been replaced by green mulch? Or if one or more irrigation could be avoided? What would the result have been under different local specific conditions or using a different crop? Hence through the study the participants were able to identify gaps of both scientific and practical knowledge which are mentioned below. It is also suggested how the participatory research project should be complemented in order to reach a more qualified evaluation of green mulch as a climate smart weed control.

- The project should be long term and include more on-farm experiences from different locations. Here it should be studied in which farming systems (choice of crops and green mulch, labor peak distribution, soil type, climate) there is a high chance of increasing the marketable yield and/or reducing the amount of irrigations and hence reducing diesel consumption and labor.
- The project should include a more complete systems analysis with direct and indirect resource use.
- It should also include more detailed scientific investigations of different aspect as food quality, pest and disease control, functional biodiversity and nutrient efficiency.

The study has also partly contributed to a discussion between Rundström at Sundvik Trädgård and Johansson at Senneby Trädgård concerning the overall sustainability of their production systems. The farmers concluded that the production of fresh vegetables for sale during the summer has a very low potential to be a sustainable system. The stated reason was that too many compromises must be done to get the vegetables ready for sale during the summer. This difficulty often came up when different weed management options were discussed together with Rundström. One example is the difficulty to find time for weeding as soon as the harvest and sale starts. Instead it was suggested that vegetables consumed during the summer should to a higher degree be produced in e.g. homegardens, allotments and community gardens by developing urban and peri-urban agriculture. Farmers should focus on producing vegetables which can be stored or conserved for consumption during the remaining season. In this way e.g. weed management and harvesting would not compete for the farmer's time.

During the final visit to the farms it turned out that the farmers had already tried parts of the measures discussed during the study. At Stora Fårvallslätten blue lupin was grown. At Sundvik trädgård a row of the micro clover/grass mix was sown between two rows of cabbage, wool from sheep which normally was burnt was now placed as mulch (inspired by the study visit at Mandelmanns Trädgårdar organized within the study) and a bale of silage was waiting to be tried as mulch. The study visits were also inspiring in other areas than weed control. Lindqvist and Fransén at Stora Fårvallslätten decided to establish a small forest garden by the road partly inspired by a study visit at Holma Stiftelse. This indicates that the study has contributed to a continued development of climate smart weed management strategies on the farms.

4. Conclusions

To avoid dangerous climate change and to quickly adapt food production to declining amounts of oil and other fossil fuels it is necessary not only to increase efficiency or replace the energy source but also to perform large reductions in the total amount of energy used. To develop weed management strategies based on reduced energy consumption through the help of ecosystem services an integrated approach is necessary. Many different issues must be addressed as; crop rotations, landscape elements, farm design, choice of crops and machinery, availability of labor (often skilled), economy, the goals of the farmers etc. The main difficulty may be that it requires the development of systems which will be sustainable in a future society with lower energy consumption while the wider system of society is still focused on high energy use (cheap long-distant transported food, lack of rural labor force, relatively cheap oil etc). There is therefore a need to find methods which are viable today but can be developed into a system which will be sustainable in a low energy future.

In the introduction to weed management it was shown that where yield can be increased without large inputs of resources (e.g. through narrower planting, intercropping, nitrogen efficiency) this can help reduce the total energy need per kg crop. Soil tillage should also be reduced in a way which will make the quack grass manageable.

Some of the weed control methods developed for the participating farms could easily be implemented on the farms already during the next growth season, for example: leftover silage as green mulch, seed mixture for extensive weed competitive lay, annual ley species combined with autumn horse grazing and consumer weeding.

Other methods the farmers thought needed to be developed and tested under different local specific conditions before they could be adopted, for example; cover cropping, mechanically spread green mulch from fresh ley and intercropping clover ley with vegetables. Some of them require larger changes on the farms.

A green mulch experiment was performed which showed the importance of performing experiments not only in experimental stations but also on commercial farms to discover benefits and challenges of the developed agricultural practices when used in a real world context. To achieve a realistic evaluation of the energy efficiency of a change in an agricultural practice it is essential to define and include all elements of the agricultural system which will be changed by the new practice. In this case the cutting of the ley and the irrigation need was included. In future studies one could include e.g. a decrease in energy consumption due to decrease in the use of animal manure which will be exchanged by the fertilizing effect of the green mulch.

Participatory research and development is a suitable methodology for the purpose of developing methods analyzed from a systems perspective and adapted to local specific conditions. Large amount of knowledge and practical experiences may be systematized jointly analyzed and shared amongst farmers, extensionists and researchers. A strategy should be developed for which kind of information should be created on farms and which on experimental stations. The evaluation of the participatory experiment at Senneby Trädgård resulted in the conclusion that on-farm experiments are suitable for evaluation of the methods on a systems level. Experimental stations may be used to perform more detailed experiments and experiments which are difficult to perform on a commercial farm. The experimental station could also perform high risk experiments after which the most promising techniques etc are tested on farms.

The sustainability tool used mainly at Senneby Trägård was able to evaluate the method from several perspectives, point to gaps in knowledge and give and approximation of its overall sustainability. The tool needs a period of introduction after which it more easily can be used to evaluate different methods. Other sustainability frameworks than The Natural Step should be tested to find out which is most comprehensive (also including e.g. animal ethics, resilience and GMO) and easy to grasp and use. The tool could be used in participatory research and development projects to compare different systems, to identify gaps of knowledge or to evaluate changes over time. Once they have been introduced to it, individual farmers could also use the tool when important decisions are to be taken.

The time needed for experimentation and development of knowledge and praxis means that the weed management strategies will not be widely spread yet for some time. However the oil and climate crisis may have motivated farmers and researchers to start experimenting on a wider scale. It also increases the interest of consumers which may open up for a closer integration of the consumers in the food production system. The consumers interested in helping out with weeding at Sundvik Trädgård are one examples of this. The government could contribute with financial subsidies as well as employment of persons who could organize and facilitate participatory research and development in how to re-design farm systems to be more resource efficient. This would help overcome some initial obstacles and push the development forward. In the meantime simple and fast measures to reduce the use of fossil fuels should be made (closer row spacing, efficient machinery, more hand labor, biogas when possible etc). However all investments should be made in accordance with the long term development of future low energy sustainable weed management strategies based on ecosystem services.

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Appendix A. Climate Change

Since the second half of the 1800th century to the year 2005[23] the global average temperature has increased with 0.76°C (IPCC, 2007a:36) and is estimated to rise with 1.1 to 6.4 °C from the year 2000 to 2100 (IPCC, 2007a:70) depending on the future scenario (*Box A.1.*). The rate of warming is twice as high over land as over sea and twice in the northern hemisphere compared to global average (IPCC, 2007a:37). The Intergovernmental Panel on Climate Change (IPCC, 2007a:25) has stated that this increase in temperature to a large extent is created by human activities. Since 1750 the carbondioxide (CO_2) concentration has increased by nearly 100 ppm. This should be compared to the 20 ppm rise during the 8000 years before industrialization (IPCC, 2007a:25). Global greenhouse gas emissions (GHG) have grown with 70 % between 1970 and 2004 (24% since 1990) (IPCC, 2007c:3). The far dominating source of GHGs is CO_2 from the burning of fossil fuels which represents 2/3rds of the total anthropogenic[24] CO_2 emissions (IPCC, 2007a:25). The warming has occurred during a period when natural forces as variation in solar radiation and volcanic activity should have caused a cooling and not warming (IPCC, 2007a:60). Without the cooling effect of human induced aerosols (which are now decreasing) the temperature rise would have been substantially larger (IPCC, 2007a:29, 60).

[23] The temperature change is calculated as a change in means of the years 1850-1899 and 2000-2005.
[24] Anthropogenic = human induced

A.1. The IPCC Emission Scenarios

The IPCC have developed four scenarios in their Special Report on Emission Scenarios (IPCC, 2000). According to IPCC the scenarios present different levels of greenhouse gas (GHG) emissions and related climate change depending on how the society will develop. The scenarios do not include any specific mitigation actions and are hence an estimation of what could happen if nothing is done about climate change. The four scenarios are named A1, A2, B1 and B2. In some cases there are subgroups as for example A1F1, A1T and A1B. The difference between the scenarios is mainly based on expected population growth, if development will focus more on economy or environment and whether the development will be globalised (assuming faster spread of environmental technology) or regional (locally adapted technology but slower spreading of environmental techniques globally). A summary of the assumptions and emission scenarios presented in IPCC (2000) and SOU (2007:60 p.150-152) are presented in *figure A1*.

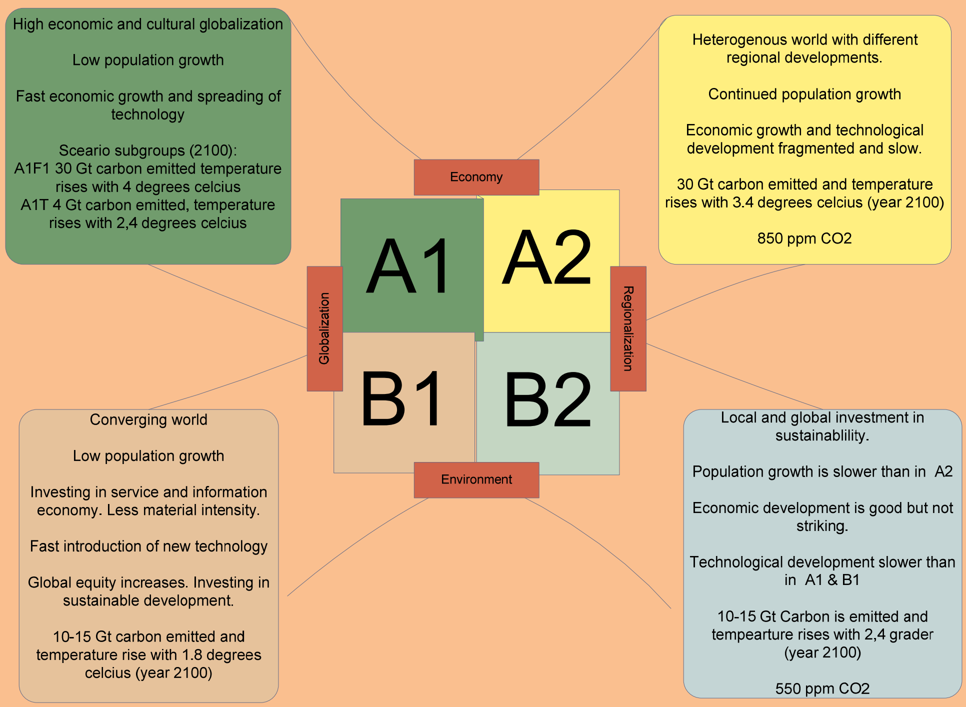

Figure A1. *IPCC emission scenarios if no specific mitigation actions are performed.*

According to the IPCC (2007b:66) already now the world is experiencing decreased water availability in mid-latitude and low-latitude countries and the opposite in humid tropics and high latitudes. However in the IPCC report "The Physical Science Basis" (2007a:54) it is stated that drought also has become more common in the tropics and subtropics since the 1970s (IPCC, 2007a:54). In Europe and Australia extremes in high temperatures and heat waves have been shown to be linked to climate change (IPCC, 2007a:54). There is also an increased amphibian and coral extinction, increased damages from floods and storms, increased morbidity and mortality from heat-waves, droughts and floods, changed distribution of some disease vectors, local retreat of ice on Greenland and West Antarctic (2007b:66). Increased temperature and other climate-driven changes in ice cover, salinity, oxygen levels and circulation has changed species abundance and distribution on land as well as in marine and freshwater environments (IPCC, 2007b:28). Increased temperature has caused ground instability in permafrost regions, rock avalanches, increase and enlargement of glacial lakes (IPCC, 2007b:28). Melting permafrost will accelerate methane emissions from tundra's (IPCC, 2007b:38). In the northern hemisphere the growth season has been prolonged (IPCC, 2007b:28). Ocean acidification is already a fact (IPCC, 2007b:28).

According to the human development report (UNDP, 2007/2008) 98 % of the people affected by climate disasters from 2000 to 2004 were found in the developing world. It was also stated that only one in 1500 people in OECD[25] countries were affected by climate disasters while one in 19 were affected in developing countries. With low social security and personal assets the poor are heavily stricken by climate disasters often leading to life-long cycles of disadvantage (UNDP, 2007/2008).

At 1^{o}C temperature increase above pre-industrial level the IPCC (2007b:66) predicts that 0.4-1.7 billion people will suffer from increased water stress, the burden from malnutrition, diarrheal, cardio-respiratory and infectious diseases will increase,.

Between 1.5-2^{o}C increase there will be decreases in some cereals in low latitude countries while the yields are expected to rise in high latitude countries, 20-30% of existing species will be at increasingly high risk of extinction, most corals will be bleached, 0-3 billion additional people will be at risk of coastal flooding (IPCC, 2007b:66).

At 2.5^{o}C increase the terrestrial biosphere will tend towards being a net carbon source, a long term commitment to several meters of sea-level rise due to ice-sheet loss, ecosystem change due to weakening of the meridional overturning circulation (IPCC, 2007b:66).

Once the temperature increase exceeds 2^{o}C above pre-industrial level climate impacts on food production, water supply and ecosystems are projected to increase significantly and irreversible catastrophic events may occur (EU commission, 2007; Steffen, 2006). The risk that poorly understood positive feed-back loops will be set in motion increases (IPCC, 2007b:66; 77-78, Steffen, 2006).

According to IPCC (IPCC, 2007a:70) climate change will also result in sea level rise between 0.18-0.59 m in 2100 compared to the year 2000 due to the melting of the glaciers and thermal expansion of the sea.

A1. Greenhouse Gases and Changes in Land-use.

About 2/3rds of the anthropogenic emissions originate from burning fossil fuels and the rest from land use change (IPCC, 2007a:25). Nitrous oxide (N_2O) is a GHG 296 times more potent than CO_2. Since the pre-industrial era humans have increased the N_2O concentration in the atmosphere with 18% mainly through agriculture and associated land use change (IPCC, 2007a:27; IPCC, 2001:47). Today 40 % of N_2O emissions are created by human activity. In the same period the atmospheric concentration of methane (CH_4), which is 23 times more potent than CO_2, has been doubled (IPCC, 2007a:27; IPCC, 2001:47). Methane emissions originate from wetlands, ruminant animals, rice cultivation, biomass burning and a small contribution from industrial processes including the burning of fossil fuels (IPCC, 2007a:27). After high growth rates from the late 70s the growth rate of CH_4 emissions are now slowing down (IPCC, 2007a:27). However there is large inter annual variation which is poorly

[25] OECD = organisation for Econoic Co-operation and Development.

understood but seems to be coupled to emissions from wetland and biomass burning (IPCC, 2007a:27). Methane emissions from wetlands are highly temperature sensitive and all models show increased emissions caused by climate change (IPCC, 2007a:27).

The affect of changes in land use can have a significant affect on local climate through shifts in radiation, cloudiness, surface roughness and temperatures (IPCC, 2007a:30). Changes in vegetation can cause a regional shift in water balance and surface energy (IPCC, 2007a:30). The scientific knowledge in this area is still low (IPCC, 2007a:30).

A2. Positive Feedbacks, Lack of Knowledge and Model Limitations.

It should be emphasized that with new knowledge and improved modeling, each new IPCC report has described the situations as worse than what was previously thought. For example, in the last IPCC report (2007a) it was found that the previously estimated rise in temperature in the A1 scenario should have been 1^{o}C higher. The stated reason is that now there are more climate-carbon cycle feedbacks included in the model. An example of a climate-carbon cycle feedback is increased temperatures causing forest fires which then release CO_2 which in turn increases the temperature. These feedbacks mean that less CO_2 emissions are needed to reach a certain temperature and larger reductions in emissions are needed than what was previously thought.

Over the history there have been abrupt changes in the climate. It is not known how these abrupt changes occurred or where the climate thresholds are. What is known is that feedbacks and non-linear relationships are the rule and not the exception in the functioning of the earth system (Steffen, 2006). This means that the models cannot be trusted to show how and when future abrupt changes in the climate might occur (IPCC, 2007a:85). Since it is not known when the threshold of the ecosystems will be crossed it is crucial not to exceed the limit of dangerous climate change which is currently believed to occur above 2^{o}C. This chapter will further explain:

1) The constraints of climate models
2) The current lack of knowledge which makes reliable prediction of climate change difficult.
3) Some of the feedbacks which are thought to be able to rapidly increase the speed of climate change.

Before going into more technical details it is important to mention that all scenarios are built on socio-political assumptions which do not have to be true. A large safety margin is therefore needed. The IPCC (IPCC, 2007a:51, 85-90) gives some examples of limitations:

1) There is no certainty of the magnitude of future climate-carbon feedbacks.
2) There is a lack of understanding of changes in key processes that drive global and regional climate changes as; El Niño Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), tropical cyclone distribution and land surface feedbacks.
3) There are no models addressing the key processes that could contribute to large, rapid, dynamical changes in the Antarctic and Greenland Ice Sheets that could increase the discharge of ice into the ocean and lead to higher sea level rises then previously estimated.
4) There is an uncertainty of the impact of climate change on melting and precipitation on ice sheets.

5) There are large uncertainties remain about how clouds might respond to global climate change.
6) There are problems with simulation of some modes of variability as the Madden-Julian Oscillation and extreme precipitation.
7) Systemic biases have been found in most model simulations of the Southern Ocean that are linked to uncertainty in transient climate response.

An uncertainty with huge implications for northern Europe is if the meridional overturning circulation (MOC) would shut down/substantially slow down or not. If it would it could imply cooling instead of warming in northern Europe (SMHI, 2008b). However according to the IPCC (2007a:89) " the likelihood of a large abrupt change in the MOC beyond the end of the 21st century cannot yet be assessed reliably. For low and medium emission scenarios with atmospheric greenhouse gas concentrations stabilized beyond 2100, the MOC recovers from initial weakening within one to several centuries. A permanent reduction in the MOC cannot be excluded if the forcing is strong and long enough."

An example of a land surface feedback is release of a vast amount of carbon from soil when bacteria increase their activity due to increased temperatures while biomass production levels stop increasing due to saturation of CO_2 in the photosynthesis (Cox *et al.,* 2004). It is estimated that one third of terrestrial contribution to CO_2 emissions during the 21st century will be caused by the drying and burning of forests (Cox *et al.*, 2004). This will start already at 2^{o}C temperature rise and escalate after 3^{o}C turning Amazonas, also called the lungs of the world and a hydrological engine, into a desert and huge clouds of smoke will make it difficult to live in large parts of the continent (Lynas, 2007:122). With it several ancient human cultures (Lynas, 2007:122) and a vast amount of the world's biological diversity will be lost (Cox, 2004). Fine soot particles from the fires can contribute to a further heating of the planet (Steffen, 2006). Recently Sitch *et al.* (2008) compared 5 global models in how they respond to climate-carbon cycles. All of the models showed a peak in the carbon uptake by land around 2050 and later decline. All models showed moderate to high loss of vegetation in Amazonia. The authors also emphasize that land can become a source of carbon to the atmosphere if the cooling effect of sulphates has been underestimated, and drops off as anticipated. Other recent articles on climate modeling show that there are still a lot of mechanisms which are not included in all models (e.g. Betts *et al.,* 2007; Sitch *et al.,* 2007; Cowling, Jones and Cox, 2007)

There are also important feedbacks from the sea. About 50% of CO_2 emissions end up in the sea where it lowers the pH and inhibits the building of calcium carbonate ($CaCO_3$) shells of some coccolitoforides (IPCC, 2007a:26, 48). This can happen already at a 2^{o}C increase (Lynas, 2007:67-68). The coccolitoforides are the largest producers of $CaCO_3$ in the world and contribute to a great extent to the removing of carbon from the atmosphere (Lynas, 2007:68-69). They also influence the weather by producing a chemical which benefits cloud formation (Lynas, 2007:68-69).

Increased temperature is already increasing the pest pressure on for example boreal forests, which has lowered their capacity to act as carbon sinks (Steffen, 2006). The rising temperature is increasingly melting the permafrost areas and drying out peatlands, leading to the emission of CO_2 and CH_4 to the atmosphere.

All these feedbacks are ”sleeping giants” or processes that have the potential to accelerate the rate of warming beyond what human emissions of greenhouse gases can accomplish (Steffen, 2006).

A3. Adaptation and Mitigation

Since pre-industrial times until the year 2005 the temperature has increased 0.76°C (IPCC, 2007a:36). If no climate change mitigation measures are taken the GHG emissions are projected to increase with 25-90% until 2030 according to the IPCC scenarios (2007c:4). In these scenarios carbondioxide emissions from mostly fossil fuel based energy would increase between 40-110% from the year 2000-2030. Two thirds to three quarters of those emissions would originate from what IPCC refers to as “*non*-Annex 1 countries”[26]. At the same time their per capita energy CO_2 emissions will remain substantially lower than Annex 1 countries.

According to the Kyoto protocol the global CO_2 eq emissions should be stabilized at a level below 550 ppm (Miljömålsrådet, 2008b). The IPCC reports have shown that in order to stabilize the temperature on 2 degrees[27] above pre-industrial levels the CO_2 concentration must be stabilized at 350-400 ppm the CO_2 eq at 445-490 ppm and emissions must peak between the years 2000-2015 and decrease with 50-85 % until the year 2050 (IPCC, 2007c:15). However even with more ambitious reduction plans suggested by the Greenhouse Development Rights (described further down) some aspects of climate change will still occur and the risk of exceeding the 2°C limit is 15-30 % (Kartha *et al.,* 2008). Several facts speak against the acceptance of higher rise in temperature:

- Once global warming exceeds 2°C above pre-industrial level, climate impacts on food production, water supply and ecosystems are projected to increase significantly and irreversible catastrophic events may occur (EU commission, 2007; IPCC, 2007b:66-67).
- Our limited knowledge of certain mechanisms and non-linear relationships in ecosystems
- The uncertainties and limitations of modeling.

The European Union and the Swedish Government have set 2°C increase in temperature above pre-industrial levels as a target ceiling (EU commission, 2007, Naturvårdsverket, 2007). In January 2008 the European Commission put forward a proposal of how to fight climate change and promote renewable energy up to the year 2020 and beyond. The EU committed itself to ***“****reducing its overall emissions to at least 20% below 1990 levels by 2020****,*** *and is ready to scale up this reduction to as much as 30% under a new global climate change agreement when other developed countries make comparable efforts. It has also set itself the target of increasing the share of renewables in energy use to 20% by 2020.”* (EU, 2008a). Member states that currently have a relatively low per capita GDP and thus high GDP growth expectations may increase their greenhouse emissions compared to 2005 while member states with a relatively high per capita GDP will need to reduce their greenhouse emissions compared to 2005. However, no country should be required to reduce its greenhouse gas emissions in 2020 to more than 20% below 2005 levels and no country should be allowed to increase its greenhouse gas emissions in 2020 to more than 20% above

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[26] Annex I to the Climate Convention (UNFCCC) lists all the countries in the Organization of Economic Cooperation and Development (OECD), plus countries with economies in transition, Central, and Eastern Europe (excluding the former Yugoslavia and Albania). By default the other countries are referred to as Non-Annex I countries

[27] Note that global mean temperature at equilibrium is different from expected global mean temperatures at the time of stabilization of GHG concentration due to the inertia of the climate system. For the majority of scenarios assessed by the IPCC, stabilization of GHG concentrations occurs between 2100 and 2150.

2005 levels (EU, 2008a). It was also suggested that the European Union should work for reductions of GHG emissions with 50% compared to 1990 years levels by the year 2050 (EU, 2008a).

In Sweden the total amount of GHG emissions was 65.7 million tons of CO_2 eq (Naturvårdsverket, 2008a). The total emissions include export products but *not* international transportation, import and land-use (Naturvårdsverket, 2008a). Emissions from land-use are generally negative meaning that GHGs are absorbed. Since 1990 the emissions have varied between -81.7 to 17.2 million tons of CO_2 eq (Naturvårdsverket, 2008c). However these data are normally not included in national statistics on GHG emission since they are very insecure (Abrahamsson, pers. commun., 2008). Land-use emissions show a large variation between different years which is not well understood and may be due to methodological problems (Abrahamsson, pers. commun., 2008). The Swedish government has decided to reduce the amount of CO_2 eq during the period 2008-2012 with 4% compared to the 1990 years level (Miljömålsrådet, 2008a). To the year 2050 the amount of CO_2 eq/person should be reduced to 4.5 tons or with 54% compared to 1990 year levels (Miljömålsrådet, 2008b). Between 1990 and 2006 the total amount of CO_2 eq was reduced with 8.7% (Naturvårdsverket 2008a). The GHG emissions per person were 7.2 ton CO_2 eq/person in 1996 (Naturvårdsverket, 2008b). If the reduction continues at the same pace only the aim of 2020 could possibly be reached. However the reduction does not have to be linear.

Since the range of the global emissions of CO_2 eq reduction until 2050 is 50-85% the aim of the European Union and the Swedish government to decrease emissions with approximately 50% fits within the lowest end of this range. A study by Naturvårdsverket made in 2007 emphasized that in order to have a 50% chance of stabilizing the temperature at a $2^{o}C$ increase, emission reductions of 85% must be made. This estimation was made assuming that the Swedish emission right per person in 2050 will be equal to the global average.

However an increasing amount of countries and persons are arguing that the reductions should be considering both the greater historical pollution of early industrialized and high income countries and the higher ability of financing reductions of these countries. There are at least two different models suggesting proportionally higher decreases in CO_2 eq for high income countries. The models are called Contraction and Convergence (IPCC, 2001c:90) and Greenhouse Development Rights (GDE) (Kartha *et al.,* 2008). Especially the later emphasizes that developing countries have not had the benefit of developing their standard of living the way the early industrialized countries did and should therefore be allowed a higher emission rate at the cost of the industrialized countries (Kartha *et al.,* 2008). According to this model the European Union should make greater efforts of CO_2 eq reductions than what has been mentioned.

Within the GDE model each country should be responsible for both emissions produced within its borders but also emission from imported goods and international transportation (Kartha *et al.,* 2008). According to a recent report from the Stockholm Environment Institute (Kartha *et al.,* 2008) the Swedish emissions would then increase with 17%. The report also shows that in accordance with Greenhouse Development Rights Sweden should decrease its GHG emissions with 122% by 2020 compared to 1990 years levels. The achieve this decreases must be made both nationally and through investments on international level. This is an undertaking of a whole different scale than what the European Union is preparing for at the moment and requires the same effort as when mobilizing for a catastrophe (Kartha *et al.,* 2008).

It can be concluded that the European Union is underestimating the need of emission reductions to 2050. If the aim is to guarantee that the temperature will not exceed 2^{o}C above pre-industrial levels the target emissions should be set at least at the highest level of the range given by the IPCC, namely 85%. Furthermore, if the aim is to share these reductions fairly amongst the nations of the world the high income countries, including Europe, should take a greater responsibility of GHG reductions.

Whichever the case it requires substantial and fast changes of our daily lives. IPCC suggest several mitigation technologies and practices (*Table A.1.*).

Table A.1. *Key mitigation technologies and practices by sector. Sectors and technologies are listed in no particular order. Non-technological practices, such as lifestyle changes, which are cross-cutting, are not included in this table (table according to table SPM3 in IPCC 2007c).*

Sector	Key mitigation technologies and practices currently commercially available	Key mitigation technologies and practices projected to be commercialized before 2030
Energy supply	Improved supply and distribution efficiency; fuel switching from coal to gas; nuclear power; renewable heat and power (hydropower, solar, wind, geothermal and bioenergy); combined heat and power; early applications of Carbon Capture and Storage (CCS, e.g. storage of removed CO_2 from natural gas).	CCS for gas, biomass and coal-fired electricity generating facilities; advanced nuclear power; advanced renewable energy, including tidal and waves energy, concentrating solar, and solar PV.
Transport	More fuel efficient vehicles; hybrid vehicles; cleaner diesel vehicles; biofuels; modal shifts from road transport to rail and public transport systems; non-motorized transport (cycling, walking); land-use and transport planning.	Second generation biofuels; higher efficiency aircraft; advanced electric and hybrid vehicles with more powerful and reliable batteries.
Buildings	Efficient lighting and day lighting; more efficient electrical appliances and heating and cooling devices; improved cook stoves, improved insulation ; passive and active solar design for heating and cooling; alternative refrigeration fluids, recovery and recycle of fluorinated gases.	Integrated design of commercial buildings including technologies, such as Intelligent meters that provide feedback and control; solar PV integrated in buildings.
Industry	More efficient end-use electrical equipment; heat and power recovery; material recycling and substitution; control of non-CO_2 gas emissions; and a wide array of process-specific technologies.	Advanced energy efficiency; CCS for cement, ammonia, and iron manufacture; inert electrodes for aluminum manufacture.
Agriculture	Improved crop and grazing land management to increase soil carbon storage; restoration of cultivated peaty	Improvements of crop yields.

	soils and degraded lands; improved rice cultivation techniques and livestock and manure management to reduce CH_4 emissions; improved nitrogen fertilizer application techniques to reduce N_2O emissions; dedicated energy crops to replace fossil fuel use; improved energy efficiency.	
Forestry	Afforestation; reforestation; forest management; reduced deforestation; harvested wood product management; use of forestry products for bioenergy to replace fossil fuel use.	Tree species improvement to increase biomass productivity and carbon sequestration. Improved remote sensing technologies for analysis of vegetation/ soil carbon sequestration potential and mapping land use change.
Waste	Landfill methane recovery; waste incineration with energy recovery; composting of organic waste; controlled waste water treatment; recycling and waste minimization.	Biocovers and biofilters to optimize CH_4 oxidation.

The highest mitigation potential is given to buildings. Thereafter agriculture, industry and energy supply are given similar mitigation potential. Transportation and forestry take a third position while waste management is given a very low potential. The suggested measures focus on energy efficiency and replacement of fossil fuels by biofuels.

In a study by Naturvårdsverket (2007) where it was shown that a scenario of improved technology in combination with carbondioxide neutral energy by itself will not be enough to reach the goal of $2^{o}C$ since it exceeds the emission target with 190%. The study concludes that change in behavior is needed. Mainly the increasing amount of consumption, travelling and transportation must be reversed

Appendix B. Ecosystem Services

Since ecosystem services are necessary for the survival of the human race it is important that human activities support and strengthen these services. The Millennium Ecosystem Assessment (MA, 2005) found that the contrary was true. Approximately 60% of the examined ecosystem services are being degraded or used unsustainably. MA resulted in four main findings:

1) Over the past 50 years, humans have changed ecosystems more rapidly and extensively than in any comparable period of time in human history, largely to meet rapidly growing demands for food, fresh water, timber, fiber and fuel. This has resulted in a substantial and largely irreversible loss in the diversity of life on Earth.

2) The changes that have been made to ecosystems have contributed to substantial net gains in human well-being and economic development, but these gains have been achieved at growing costs in the form of the degradation of many ecosystem services, increased risks of nonlinear changes and the exacerbation of poverty for some groups of people. Theses problems, unless addressed, will substantially diminish the benefits that future generations obtain from ecosystems.

3) The degradation of ecosystem services could grow significantly worse during the first half of this century and is a barrier to achieving the Millennium Development Goals.

4) The challenge of reversing the degradation of ecosystems while meeting demands for their services can be partially met under some scenarios that the MA has considered, but these involve significant changes in policies, institutions and practices that are not currently under way. Many options exist to conserve or enhance specific ecosystem services in ways that reduce negative trade-offs or that provide positive synergies with other ecosystem services.

Increased consumption and well-being in some parts of the world has had strong negative effects on other parts of the world. The MA (2005:2) states that the poor are the ones most affected by ecosystem degradation which is contributing to growing inequalities across groups of people, and is sometimes the principle factor causing poverty and social conflict.

According to MA (2005:2) there are two drivers to ecosystem change which are believed to become more severe and both are related to agriculture – climate change and excessive nutrient load.

Appendix C. Peak Oil and Oil Alternatives

Oil production (or rather extraction) in each country starts and ends at zero, reaching a peak in between when approximately half of the total has been extracted (Aleklett and Campbell, 2003, Hirsch, 2005). The more oil is extracted from a well the more difficult, and hence expensive, does it get to extract the remaining oil (Campbell and Laherrér, 1998). At some point extraction per time unit will stop increasing and start declining.

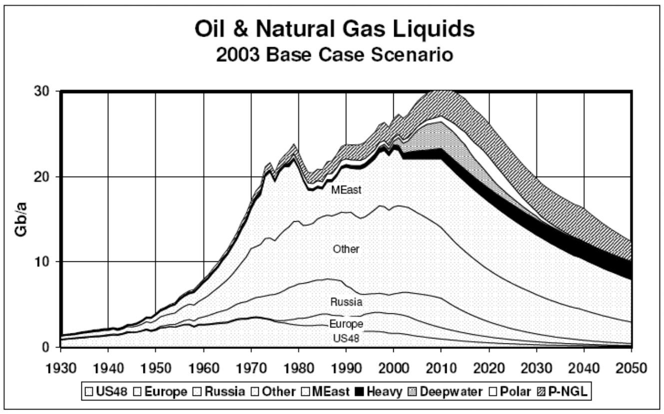

Figure C.1. *Approximated peak of oil and gas production according to ASPO (Aleklett and Campbell, 2003)*

Oil is providing 40% of traded energy and 90% of transport fuel, hence a peak will imply a historic turn point affecting all aspects of human life on Earth including agriculture, which means food (Aleklett and Campbell, 2003). Food production today is heavily dependent on oil not only as fuel during the production of agricultural inputs, driving tractors, food processing and storage, distribution but also as raw material in packaging, fertilizers, pesticides and herbicides (Johansson, 2005; Pimentel *et al.,* 2008). To adapt to such an immense change it would be an advantage to know when the peak is estimated to occur as well as the nature of the peak. The peak may be sharp, a soft roll-over curve or a plateau depending on amongst other things the demand, technology and politics (Hirsch, 2008). When we are forced to reduce our oil consumption there is a great risk for famine, military actions and social insecurity (Leder and Shapiro, 2008). To avoid part of these impacts mitigation must be initiated at least a decade before peaking according to the Hirsch report (2005).

According to many estimations we are in the middle of or about to enter the peak while few state the year 2035 or later and most believe it will occur no later than 2020 (Bentley *et al.,* 2007; Hirsch, 2005). Several authors have argued that the time of peak is underestimated since it is based on flawed information in public databases and poor analysis of what is reported due to;

- Misconceptions about what is measured and the kind of conclusions that can be drawn from different data presented in official reports (e.g. Aleklett and Campbell, 2003; Bentley *et al.,* 2007). Bentley *et al.* (2007) show that "proved plus probable" datasets held by industry to measure oil discovery indicate that the resource-limited peak in the global extraction of conventional oil is close. According to the Aleklett and Campbell (2003) it is more common to use the easily accessible but limited "proved reserves" data. These data only report 'market ready' quantities of oil (Meng and Bentley, 2008). Bentley *et al.* (2007) argue that it is the inappropriate use of proved reserves data which leads to the conclusion that no near-term threat against oil production exists.

- A historic under reporting of proved reserves. Often only the oil which is just about to enter the market is reported instead of the total oil discovered (Bentley *et al.,* 2007). Releasing conservative estimates reduced taxes and gave the impression of a well managed gradual growth (Aleklett and Campbell, 2003).
- A over-reporting during the 1980s due to the OPEC quota system where the size of the proved reserves of each country decided their allowable yearly export (e.g. Aleklett and Campbell, 2003; Bentley *et al.,* 2007).

The indications that the oil peak is close or already occurring were summarized by Schindler and Zittel (two scientific advisers to the German parliament) in 2002 (Heinberg, 2004);

- The peak of oil discoveries was reached in the 1960s.
- This peak in discoveries must be followed by a peak in extraction, since we can only extract what has been found before.[28]
- The extraction peak of individual fields is a historical fact, almost all large oil fields have already passed their extraction maximum and are in decline.
- The aggregation of the extraction profiles of individual fields (with their individual peaks) sum up to an extraction peak of individual regions. Historically, peak extraction was reached in Austria in 1955, in Germany in 1968 and in the USA in 1971, in Indonesia in 1977. Recent regions joining the club of countries with declining extraction rates are Gabon (1977), UK (1999), Austria (2000), Oman (2000) and Norway (2001).
- The aggregate decline of mature regions is getting steeper with every new "member of the club". In order to keep over-all extraction just flat, ever fewer regions have to increase their extraction.
- This pattern has been observed for more than thirty years. It is very likely that the peak of world oil extraction will be reached before 2010 at the latest.

To this summary it could be added that since the Second World War the oil extraction has increased every year while during the last few years it has remained on the same level of 84 million barrels (Aleklett, 2007).

Even if the IPCC scenarios may have overestimate the amount of fossil fuels available (Aleklett, 2007) there is enough to surpass the limit of 2^{o}C temperature increase (Brecha, 2008; Kharecha and Hansen, 2008). More importantly the continued use of fossil fuels increases the risk of climate-carbon feedbacks and non-linearity's which by themselves can cause the temperature to increase well above 2^{o}C without further human caused emissions of GHGs (Steffen, 2006).

[28] According to Aleklett and Campbell (2003) the world is now finding less than one barrel for every four it consumes.

C1. Oil Substitutes and Alternatives

Finding a satisfactory substitute for oil is not an easy task. Oil is not only used as fuel but also as raw material in industrial processes. It has the advantage of being a very concentrated, easily transported and stored fuel. Most alternatives fail in at least one of those properties. A lot of faith is put to natural gas and coal (IPCC, 2007b:10). However both are fossil fuels which not only are polluting but also non-renewable with their own extraction peaks in the near future. Coal has the additional disadvantage of emitting much more CO_2 compared to oil (Baumann and Tillman, 2004). According to an update on global reserves and extraction forecast by the energy watch group[29] (2007) coal is expected to peak in 10-20 years time. Natural gas is less polluting than coal (Baumann and Tillman, 2004) but also projected to peak approximately 2015 (Aleklett, 2007).

There are large amounts of unconventional oil as heavy oil, tar sand and shale oil. To be extracted high amount of energy is needed leading to low net energy gain or even negative net energy gain (Brecha, 2008). Furthermore these petroleum sources are very expensive and are thereby not seen as potentially important energy sources (Brecha, 2008). The extraction of unconventional oil is also associated with heavy environmental pollution as air pollution and heavy metal toxicity (Campbell and Laherrère, 1998).

Technology to remove CO_2 from natural fossil fuels called Carbon Capture and Storage (CCS) is still in developmental phase and projected to be commercialized before 2030 (IPCC, 2007b:10). However its importance is estimated to increase only after the year 2050 (Azar *et al.,* 2003). The time until it is commercialized and widely used is much later than both the estimated oil peak and the greenhouse gas emission peak between the year 2000 to 2015 set by the IPCC in order to stabilize the temperature at 2^oC (see *appendix A*).

Uranium for nuclear power is also a non-renewable resource which is expected to peak and decline probably by 2020 and in a very optimistic scenario no later than 2040 (EWG, 2006). According to the Energy Watch Group report (EWG, 2006) proved reserves of uranium would be exhausted in 30 years time with current demand while proved and possible uranium resources would end in 70 years time. The report states several reasons to why nuclear power probably will not be an important energy source in the next 25 years:

- To maintain current reaction capacity 15-20 new reactors per year would need to be constructed, while the current trend is 3-4 reactors.
- Old stocks of accumulated uranium will end in 10 years time which means that a 50% increase in production would be needed to match future demand with current capacity.
- The construction phase of a new power plants is 5 years and accumulation of uranium takes time.
- Problems with mining projects are slowing down the mining of uranium.

Even if nuclear power could play an important role it is associated with large risks. It also requires costly and energy demanding security arrangements which means that the energy-yield ratio (output-input) is low (Odum, 1996).

[29] The Energy Watch Group consists of independent scientists and experts who investigate sustainable concepts for global energy supply. The group was initiated by the German Member of Parliament, Hans-Josef Fell.

A possible oil substitute which is being developed is solar powered hydrogen gas as an energy carrier (Azar *et al.,* 2003). However, this technology is not estimated to be commercialized on a large scale until 2060-2070 while in the mean time coal and nuclear energy will be used as the energy source (Azar *et al.,* 2003). The major vehicle actors (Toyota, Ford, Daimler, Chrysler, GM/Opel and Honda) nowadays estimate that the fuel cell car may be commercialized some time during the period 2012-2020 (Commission on Oil Independence, 2006). The fuel cell car is more efficient than the internal combustion engine of today's cars. However according to Azar *et al.* (2003) this technology is very expensive and it will take some time before costs are brought down significantly. The authors also mention that platinum (used as catalyst) scarcity may imply higher cost.

Giampietro *et al.* (1997) studied the potential of large-scale biofuel production to replace fossil energy depletion on a global scale. Their conclusions were that biofuels are not able to replace current use of oil and it is not advisable to cover even a significant part of it. The authors found that none of the examined countries had enough land or water resources to rely exclusively on biofuel for energy security. If environmental cost would be included the potential of biofules would decrease even further. Pimentel and Patzek (2005) showed that when all direct and indirect energy costs are included many biofuels have an energy output which is less than the fossil energy input. Giampietro *et al.* (1997) concluded that heavy reliance on biofuels would make it impossible to guarantee food security because of the competition for arable land and water. Today less than 0.27 ha of arable land is available per capita for food production and fossil fuels are already used to reduce land demand for food security. The authors suggested that biofules could play a part in more rational and efficient use of biomass at the rural level but not at a large scale fuel production. A final reflection from the authors states that "*…biomass will be essential for other purposes. Specifically, the biomass of natural ecosystems will be needed to provide life support to the human species by stabilizing the structure and function of the biosphere. The diversity and health of natural communities existing in different types of ecosystem all over the planet will be the most important "capital" available to humankind to achieve sustainability…*"

Helmfrid and Haden (2006) estimated the potential of Swedish forestry and agriculture to replace the current fuel consumption with biodiesel and ethanol. It was concluded that at least 6.3 million ha arable land would be needed. The true area would be larger since in this calculation no indirect energy costs were included. Current arable land in Sweden is 2.6 million ha. Even if 1.1 million ha of previously cultivated land was added it would not be enough. Alternatively 80% of yearly forest production would be needed.

Reports from news agencies, civil society organizations etc. are already showing that biofuel production replace food production, raise food prizes, force farmers off their land, contribute to inhumane working conditions, increased water scarcity and environmental problems (e.g. Azar 2007; Bounds, 2007; Eklöf, 2007; Irin, 2007; Pimentel and Patzek, 2007). It can be assumed that there are great limits to which extent biofuels can replace oil without creating social and environmental damages especially in the south.

An important component is energy efficiency however so far the gain from energy efficiency has been lost through increased consumption in high income countries (Kartha *et al.,* 2008). Which mechanisms could prevent this from happening in the future (Helmfrid and Haden, 2006)?

Appendix D. Paper: Is Green Mulch in Onion (Allium cepa) Climate Smart Management? - Weeds, Diesel and Nitrogen

Weronika Swiergiel

D1. Abstract

The purpose of the study presented in this paper is to evaluate the viability of green mulch as a climate smart weed management in transplanted onion (*Allium cepa*) production. The aim of using mulch was to investigate its effect on diesel consumption and labor requirement. The effect on onion weight and the nitrogen (N) efficiency was also investigated. Spreading a 5 cm layer chopped red clover (*Trifolium pratense*)/grass mulch at one occasion sufficiently reduced annual weeds. However, it was crucial that the mulch cover was at least 5 cm in the whole field including close to the onion. Onion weight was not decreased by mulching which suggests that no severe N immobilization occurred. Compared to the Swedish average in 1995 of 24 kg N leakage/ha/year the N leakage was estimated to be high. Mulching in onion did not reduce diesel consumption or labor requirement per ha when used for weed control[30]. A more nutrient and water requiring crop as for example cabbage (*Brassica oleracea*) together with improved estimation of irrigation need adapted to mulched systems is suggested for further investigation.

D2. Introduction

Climate change and peak oil are probably the greatest challenges of our times. According to the UN climate panel we need to globally diminish our carbon dioxide emissions (CO_2) by at least 50-80% by 2050 (IPCC, 2007c). The purpose of the study presented in this paper is to evaluate the viability of green mulch as a climate smart weed management in transplanted onion (*Allium cepa*) production. The effect of mulch on diesel consumption and labor requirement in weed management and irrigation as well as onion weight and nitrogen (N) efficiency was investigated. No studies, prior to the present, have been found which evaluate the method from a climate change and peak oil perspective. The method has been shown to give positive results in many studies yet its on-farm implementation is scarce. To change this, the practical aspects including the spreading technique have been evaluated together with farmers within a participatory research project[31].

Previous studies have shown that mulching with organic matter suppresses the weeds by creating shadow, mechanical obstacle, decreasing temperature between day and night as well as through allelopathy (e.g. Mennan *et al.* 2006; Teasdale, 1993). Jaakkola (1995) achieved good weed suppression with three cm layer (220t/ha) of chopped red clover (*Trifolium pratense*) applied at three occasions. Schäfer (2005) reports that a five cm layer (3.1kg dry matter/ m^2) applied twice gave equally efficient weed suppression as three cm (2.5kg dry matter/m^2) applied three times. Larsson (1995) achieved 32 % weed reduction with a 5-10 cm layer (30 t dry matter/ha) of green mulch.

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[30] Since the yield increase in mulched treatment was not statistically significant there was no reduction in diesel consumption per kg onion either.
[31] Climate Smart Agriculture – Solutions for the future (www.schwartzstiftelse.se, in Swedish)

Green mulch has also been shown to increase the vegetative growth of black currant (*Ribes nigrum*) and humidity in the crop root zone (Larsson and Båth, 1996). Mulching as compared to bare soil has additionally shown a yield increase in tomato (*Lycopersicon esculentum*) (Abdul-Baki and Teasdale, 1993), red beet (*Beta vulgaris*) and white cabbage (*Brassica oleracea* var. *capitata*) (Riley *et al.,* 2003), cauliflower (*Brassica oleracea* var. *botrys*) and white cabbage (Larsson, 1995). Magnusson (2000) showed a relation between increased yield in cauliflower and broccoli (*Brassica oleracea* var. *asparagoides*) and increased availability of micronutrients with mulching. Båth *et al.* (2006) could not see any significant difference in the yield between mulched and un-mulched treatments in cabbage. However, as the experiment was performed on a heavy clay soil with 5% organic material the crop was probably not equally benefited by the mulch as would be on the sandy soil with 2.1% organic matter in this experiment, especially in a dry region.

In Cardina (1995) it is stated that onions should be kept weed free for a period of 12 weeks which is more than for most other crops. According to Ögren *et al.* (2003) onion fields should be weeded no later than five weeks after emergence and kept weed free for the next 10 weeks to avoid severe yield loss. Mulch from leys is only available about 4 weeks after transplanting the onion to the field and therefore needs to be complemented with other forms of weed control. However green mulching in onions should be advantageous due to the long critical weed period.

Magnusson (2000) has shown that green mulch benefits the crop by providing it with nutrients as well as improving the availability of nutrients in the soil. The author also found that green mulch was more efficient in increasing yield at a soil pH below 6.0 than above. At higher pH many micronutrients become unavailable. Mainly nitrogen (N), potassium (K), manganese (Mn) and zinc (Zn) are provided by the mulch but higher levels of Molybdenum (Mo) and cupper (Cu) related to higher yield in mulched crops has also been found (e.g. Larsson 1997, Magnusson 2000, Magnusson 2002). In the literature review of her doctoral thesis Magnusson (2000) presents that the availability of the following nutrients is improved by adding organic matter to soil. Zinc is highly associated with organic matter. Boron (B) but, only if the soil pH is not too high. For the same reason the acidifying effect of legumes is beneficial not only for B but also Zn, iron (Fe) and probably Cu uptake. However thick grass mulch may decrease solubility of Fe due to poor gas exchange. Calcium (Ca) availability is usually improved but can be decreased due to considerable amounts of K in grass or straw mulches. Carbon (C) in organic matter contributes to aggregation of soil particles. Chlorine (Cl) is added to soil by air and precipitation and increases with closeness to the sea. Plants close to the sea take up substantial amounts of Cl and mulching can therefore increase Cl concentration in the soil and crop. Further away from the sea both green and animal manure may contribute with too small amounts of Cl. Organic matter also decreases aluminum (Al) and sometimes Cadmium (Cd) and lead (Pb) toxicity. On farms where parts of the cultivated area are not suitable for a crop rotation with vegetables it may be a benefit to move the green manure[32] from one field to another.

Green manure of various constitutions can be applied as fertilizer to optimize the cropping system with minimal resource use. Hence it is important to estimate if mulch has similar nitrogen (N) efficiency as other forms of green manure. It has been shown that the N efficiency of green manure is low mainly due to unsynchronized release and uptake, leakage

[32] Green manure is term which includes not only green mulch but also leys which are directly incorporated without being moved or further processed.

and volatilization of the greenhouse gas nitrous oxide (N_2O) and ammonia (NH_3) which contributes to acidification and eutrofication (Larsson *et al.,* 1998; Glasener and Palm, 1995; Malgeryd and Torstensson, 2005; Baumann and Tillman, 2004). The volatilization of N is not only associated to the cropping system with mulched vegetables since all organic vegetable production should include ley or green manure in the crop rotation. Whether the ley is used as mulch or for some of the other above mentioned purposes the ley needs to be cut to decrease weeds, to keep a dense stand and to keep the ley fresh and nutritious for the animals. After cutting it can either be turned into silage or mulch on spot or transferred to a vegetable field. A study by Båth *et al.* (2006) showed that where the cuttings from the ley were left on the field the ammonia loss was equal to where it had been moved and used as mulch in vegetables. Unless there is a lack of other essential nutrients in the soil the nitrogen fixation and re-growth in the ley is benefitted by removing the mulch (Colwell *et al.*, 1989). This study does not include a full comparison where silage production all the way through the cattle to the meat and manure would have had to be included. However it should be mentioned that if the mulch was turned into silage it would result in a lot less N_2O loss from the field but only if it was not left for more than 4-7 days on the field to dry (Whitehead *et al.,* 1988). However N_2O losses from animal manure are assumingly high and should be included to achieve a full picture of the N efficiency of the two systems.

There are several reasons to why green mulch is used. As an addition to the already mentioned weed controlling and fertilizing effects green mulch has for example been shown to increase the vitamin C levels of cabbage (Lundegårdh, *et al.,* 2008). It is also used to make it easier to walk and drive between the vegetable rows on clay soils (Magnusson, pers. commun., 2008).

The efficiency of different forms of green manure can also be measured comparing the required ley area. Båth and Elfstrand (2008) investigated the area red clover ley needed as fertilization per kg leek yield in the form of: mulch, direct incorporation, biogas slurry and compost. The surface mulch treatment with similar N level as in the present study was more efficient than the highest level of mulch and biogas slurry and the two highest amounts of compost. No similar comparison has been found for manure from ley fed animals. However it can be assumed that the losses are large during silage production and storage of manure. Even though some of the nutrients are recovered in the meat, from an energy perspective a lot is used by the animal for life sustaining activities. Vegetables are often not part of the crop rotation on the whole farm area since some soils are unsuitable. Under these circumstances the mobility of mulch is more advantageous than direct incorporation. Biogas slurry is still unusual and it does not have the covering property of the mulch that controls weeds and retains soil humidity.

The application technique of the green manure is often mentioned as difficult and time consuming by growers (SJV, 1997, Källander, pers commun., 2008). Svensson (1995) added Danish compost spreading equipment to a manure spreading wagon and tried out different mechanical devises which would improve the coverage close to the crop. Prolonged rubber screens and inclined wheels showed promising results. Harvesting the ley with flail forage harvester was found to give an uneven distribution of the mulch hence a precision chopper was used. However this implies driving over the field at two occasions. Using a flail forage harvester, as in this study, may require less diesel and labor if coverage is found to be satisfactory. Also to use the compost spreading model special equipment must be bought and the manure spreader needed to be rebuilt.

The model used in the present study only requires a simple temporary and cheep modification of the manure spreader. A finish research team (Shäfer *et al.* 2002) investigating mulch spreading techniques evaluated a tractor-trailer mulch spreading prototype which was constructed in Sweden. However, several disadvantages were found; the heavy fully loaded trailer caused soil compaction, long transportation from ley field to vegetable field caused heating of the green manure, did not sufficiently protect the crop from being covered, difficult to manage the big tractor-trailer in the vegetable rows, the trailer had to be refilled before the row was ended. These difficulties caused the team to try out machinery for strip intercropped red clover ley instead. Strip intercropping may be a viable solution where there is no limitation to good vegetable soils. However this is many times not the case and strip intercropping vegetables with red-clover ley would be an inefficient land-use. Also it must be economically viable to invest in the special equipment used. To avoid long transportation and heating of the green mulch it is suggested that only leys close to vegetable fields should be used.

D2.1. Research questions

It was investigated whether the green mulch would impact the need for weeding and hence the amount of diesel and labor. The impact on onion weight was measured. Further more, it was investigated whether the higher humidity in the root zone would have an impact on the need for irrigation and thereby the amount of diesel and labor. This was especially important since the soils at the farm of the experiment are sandy and the area is exposed to dry summers. The precipitation during the summer is expected to decrease due to climate change (SMHI, 2008).

In this study a mulching wagon for spreading chopped ley from a neighboring field was tried and evaluated.

As additional information about the sustainability of the mulch system a *rough estimation* of the nitrogen efficiency was made using general samples of onion, mulch and soil with no replications. N release from the mulch, soil mineral N at harvest and plant uptake was measured and leakage and volatilization was estimated.

D3. Materials and methods

The experimental site was the farm Senneby Trädgård at Väddö north of Stockholm, Sweden. A general sample per treatment with two subsamples per plot was taken to analyze the total amount of nitrogen and structure of the soil by the Department of Soil and Environment at the Swedish University of Agricultural Sciences (SLU). The samples were air dried in 40^{o}C for a few days. Approximately 0,4g of ley was analyzed with CNS 2000 dry combustion for total nitrogen (Ntot) and total carbon (Ctot). The soil was found to be loamy sand (*Table D.1.*). No difference was seen in the soil nutrient status between the plots of the two treatments before applying mulch. A Spurway analysis (Modified Spurway Lawton method: 1:6 soil: HAc 0.1%, 0.5 h) of a general soil sample was performed by LMI soil laboratory (*Table D.1.*). The soil was kept cold in the field during sampling and then quickly frozen and sent frozen to the laboratory. No serious deficiencies were shown but Mg was low especially in comparison with K (Magnusson, pers. commun., 2008) (*Table D.2.*).

Table D.1. *Soil texture according to USDA soil classification system. Gravel was present but removed before analysis (Department of Soil and Environment, Swedish University of Agricultural Sciences).*

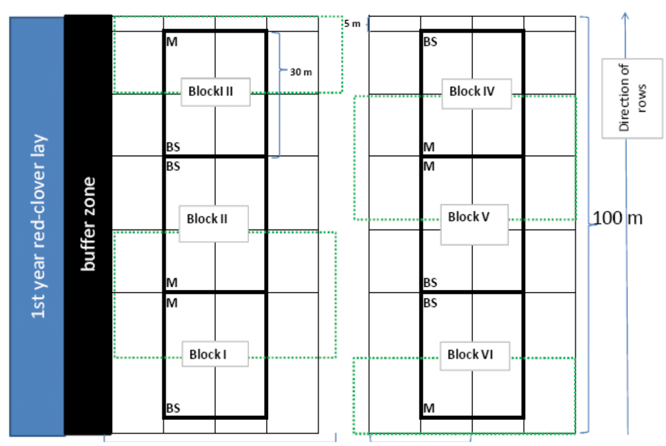
% Clay	% Silt	% Sand	% Gravel	% Organic matter
7	9	84	---	2.1

Table D.2*. Spurway analysis of the soil performed by LMI laboratory (mg/l soil, except EC and pH)*

Depth	EC	pH	NO_3^-	NH_4^+	P	K	Mg	S	Ca
0-30 cm	0.4	6.1	8	9	21	151	45	24	368
30-60 cm	0.2	5.9	0	4	4	76	21	6	199
	Na	Cl	Mn	B	Cu	Fe	Zn	Mo	Al
0-30 cm	32	25	2.3	0.3	1.5	127	7	0.2	2.9
30-60 cm	18	12	1.3	0.2	1.3	121	5	0	3.2

The climate is characterized by pre-summer and summer droughts. Two systems were compared for yield, soil mineral and crop recovered N, diesel consumption and labor. System 1 was onions mulched with cut red clover/grass ley (M) and system 2 was farmers practice with bare soil, hand and mechanical weeding and cut ley (BS). A completely randomized block design with 6 blocks and the two M and BS treatments was used. Each block was 3.5 m wide, 16 m long and included 5 rows of onions (se *figure D.1.*). Only the middle row was used for measurements. Each of the 12 plots was provided with individual irrigation by rectangular Gardena sprinklers. The measured results from 2008 were compared to two hypothetical scenarios.

Figure D.1*. Experimental design. M= mulched treatment BS = bare soil treatment.*



Onion was chosen as the experimental crop since it does not compete well with weeds due to 1) its very limited canopy which is not able to shadow out the weeds, 2) its slow growth which makes it easily outgrown by weeds and 3) its very superficial roots and low root density per unit soil which makes it a bad competitor for water and nutrients (Wien, 1997; Brewster, 1994). A harvest of 25 tons of onion removes 45 kg N, 6 kg P and 65 kg K from the field (Ögren *et al.*, 2003)

The field was fertilized with 20 tons/ha of liquid cattle manure before the planting of the onions. The red onion was sown in pots with 4-6 onions per pot in mid April and transplanted into the field the 14th of May. The experimental unit was hence an onion bunch defined as the bunch of onions planted together from each pot. The 16th of June mulch corresponding to 55 t fresh weight/ha (16 t dry matter/ha, 372 kg N/ha, C/N ratio 19) was spread on the experimental plots. The mulch originated from a one year old ley consisting of 69% red clover, 19% grass and 12% herbs on a dry matter (dm) basis. An older ley was not used to avoid possible initial N immobilization just at a time of vigorous growth of the onion. To spread the mulch a homebuilt modified prototype “mulching wagon” was used. The construction was inspired by a similar homebuilt model used at a farm in a previous study (Båth *et al.,* 2006). It is a covered frame attached behind a manure spreader. The green mulch is spread from the manure spreader over the frame. The onion rows are protected by long triangle formed caps. Three rows can be mulched at the same time. Thereby the green mulch only falls between the rows and is later adjusted by hand with a rake to cover the soil all up to the crop.

Rainfall during the period was: 10 mm in May, 35 mm in June and 17 mm in July. The field was irrigated with 15 mm at one occasion after planting. Late spring and early summer was unusually dry and the last weeks in July were very hot and dry. Two pre-mulching weedings were performed with inter-row cultivator and one within-row hand weeding with the help of a platform which is attached to the back of the tractor and carries 6 people laying down and weeding. The day after mulching a mechanical between row weeding was performed in the bare soil treatment. Two days after mulching an within-row hand weeding with the weeding platform was performed in both treatments. Ideally the weeding should have been done just before the mulch was spread. This was however not possible due to the wet soil after the rain. Also, the spreading of the mulch could not be postponed since the silage harvest had to be done urgently. This meant that the mulched treatment had one less between row weeding than the bare soil treatment. To assure that the bigger weeds not covered by the mulch between the rows would not benefit from the mulching all visible weeds were handpicked. Normally an additional inter-row weeding would have been performed in BS but was excluded this year due to time constraints and the additional difficulties associated with a block experiment. Qualitative observations of the weed development were made by the farmer during the experimental period and by the author at harvest.

At harvest 12 onion bunches per plot were weighed and a statistical two-way ANOVA analysis was performed. A 40 x 40 cm piece of mesh with whole size 0.25 cm was used to collect samples of mulch in order to achieve a rough estimation of where the mulch derived N was found. It was located at four places in each plot before it was covered with mulch. At time of mulch application and harvest a general sample of the mulch with twelve 25 x 25 cm subsamples and no replications was taken from each mesh and mixed. The sample was weighed and analyzed at the Department of Soil and Environment at SLU. A general sample was also taken of soil and onions with 12 subsamples per treatment at harvest and analyzed for soil mineral N and total N by the LMI laboratory in Helsingborg, Sweden.

An ocular description of the onions before mulching and at harvest was made by the author. An ocular comparison was made between the two treatments once a week by the farmer. The following parameters were compared and described as less, equal or more; onion growth, yellow tips of foliage, disease or pest infestation, color of foliage, soil humidity. A comparison of the above mentioned parameters including weed abundance was performed by the author at harvest. At this point each plot was compared to its vertical (between blocks) and horizontal (within block) neighboring plot. A qualitative blind test of the onion appearance (size, foliage vigor and shape) and taste was performed by the owners of the farm. The occurrence of "thick-neck" shape disorder was noted by the author after harvest as an indication of too high nitrogen levels in M. "Thick-necks" is a symptom of delayed maturity caused by too high or low N levels, water deficiency or other stresses (Brewster, 1994). Accept from being unattractive to customers (Johansson pers. commun., 2008b), "thick-necks" also lead to storage losses (Wien, 1997:606, Ögren *et al.,* 2003).

D4. Result and Discussion

D4.1. Yield and Weed Occurrence

Visual evaluation showed very few weeds were the mulch layer was at least 5 cm thick and no reduction in onion weight was observed in M. Hence it is concluded that spreading 5 cm layer chopped red clover/grass mulch at one occasion efficiently reduce annual weeds. The mulch layer was thinner within rows due to hand raking from between the rows into the rows. Hence more weeds grew close to the crop in M compared to BS where weeds were more scattered. Weeds in M may have competed more efficiently for nutrients due to their relative proximity to the onions compared with weeds in BS. Hence onion yield in M may have been reduced. In crops with limited canopy as onion it is crucial to achieve a thick and even coverage of mulch within the rows and/or increase the width of the within row weeding. This would be of less importance in a crop like white cabbage (Fredlund pers. commun., 2008).

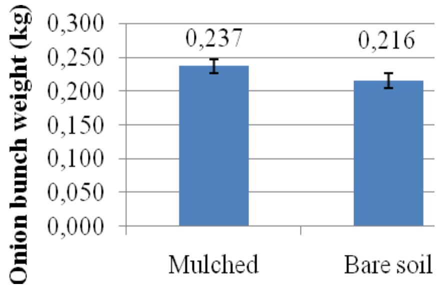


Fig. D.2. *Weight of onion bunches(2-5 onions) in mulched and bare soil treatments. Mean value ± SE, n = 12.*

The weight of onion bunches was not lowered by the mulch treatment (*figure. D.2.*) which contradicts a study performed by Boyhan *et al.* (2006). However the authors used mulch material with higher C/N ratio and an inadequate spreading technique leading to coverage of the onions. Although not studied here, this could indicate that no initial N immobilization, large enough to affect the onion growth, occurred at a critical moment in the onion development. Lack of weight increase in M may indicate that onions did not have any significant advantage from the mulch fertilization in terms of yield. Possibly part of the basic fertilizing could be excluded when mulch is applied in future research. A qualitative evaluation showed no difference in pest and insect attack or taste, shape or size of onions between M and BS onions. However the onions in M were judged to have more vital and luxuriant foliage and could result in an increased sale.

D4.2. Nitrogen recovery

The hypothesis that yield was not affected by immobilization is supported by the findings of Båth (2001) where the mineral nitrogen increased in the soil already 2 weeks after incorporation of red clover mulch (C/N ratio similar to the present study). Leek (*Allium porrum*) (Båth, 2001) and probably onion have low N requirement during early growth.

As additional information about the sustainability of the mulching system a *rough estimation* of N efficiency was evaluated as apparent N recovery (ANR) based on general soil, mulch and onion samples with no replicates. ANR was calculated according to the following procedure (assuming no priming effect of the soil): (Ntot in mulched onions (fw) – Ntot in bare soil onions (fw)) / total N (Ntot) applied with the mulch (*Table D.3.*). The N-yield of the roots was not measured due to time limitations. However the roots were dug up at two places and their biomass was estimated to be of very little importance compared to the above ground biomass. Assuming that the 4.3% higher dry weight of M onions was statistically significant the apparent N recovery with green mulching in this study was 0,32 % (*Table D.3.*). It can thereby be estimated that the onions took up a very small amount of N from the mulch. Båth *et al.* (2006) reported 25-28% ANR of mulch in leek compared to 15-70% ANR with mineral fertilizers in cabbage. Surface mulching was hence no less N efficient then most other fertilizers.

Table D.3. *Apparent nitrogen (N) recovery. M = Mulched and BS = Bare Soil treatment. All onion values are given in dry matter (dm) weight.*

Total N applied with mulch (kg/ha)	Total N left in mulch at harvest (kg/ha)	Released N from Mulch (kg/ha)	Onion yield in BS (kg dm/ha)	Onion yield in M (kg dm/ha)	N in BS onions (kg N/dm onion/ha)	N in M onions (kg N/dm onion/ha)	Apparent N recovery (%)
371,92	254,29	117,63	1324,80	1516,80	30,21	31,40	0,32

The amount of nitrogen released from mulch to the soil and air was calculated as: Ntot in mulch at the start of the experiment – Ntot in the mulch at the end of experiment on a dry matter basis and corresponded to 32% of applied N. A study by Larsson *et al.* (1998) showed an N release as low as 13%. Malgeryd and Torstensson (2005) and Ekbladh (1995) on the other hand showed 9-16% release only to soil, not including volatilization. Ekbladh (1995) reported that N uptake in leek was increased compared to bare soil with corresponding manure with 11-90 kg N/ha. It has been shown that 31-38% of mulch added N will be found in the organic matter of the soil 8 years later (Ladd *et al.,* 1985).

The amount of mineral N left in the soil at harvest at 0-30 m depth was 51 kg/ha in BS and 36 kg/ha in M while at 0.3-0.6 m depth it was 12 kg/ha in both BS and M. The added amount for 0-0.6 m depth is thereby 63 kg/ha in BS and 48 kg/ha in M. About half of the soil mineral N at 0-0.3 m depth was the easily leached NO_3^- the rest was NH^{4+}. No NO_3^- was found in 0.3-0.6 m depth. The onions did not show signs of “thick necks” which indicated that there were not excessive N levels for the onions at the end of their growth period (Brewster, 1994). Out of the 15kg less mineral soil N in M compared to BS (63-45 kg N/ha = 15 kg N/ha), 1.19 kg was absorbed by M onions. There are several possible pathways of the remaining N. It may have been incorporated into labile and recalcitrant soil organic matter due to higher microbiological activity under the mulch. The lower temperature under mulch may have caused less soil N to mineralize. It may also have been lost through denitrification (Smith *et al.,* 2008). More measurement would be needed to answer this question. Remaining 55 kg from the 118 kg N released from mulch may have been leached to soil layers deeper than 0.6 m or water. However since no NO_3^- was found at 0.3-0.6 m depth it is more likely that it volatilized. Since there was no NO_3^- between 0.3-0.6 m depth and since the onions continued to grow for another month taking up N the N leakage up until harvest was estimated to be low.

Although leaching of N from the soil was not measured the amounts of mineral N in the soil at harvest (end of July) and the amount of mulch left on the soil may indicate a risk of leaching with autumn rains, especially in sandy soil. The amount of soil mineral N after harvest in M shown in this study is in agreement with the reported 30 kg in leek and 100 kg in lettuce (*Lactuca sativa*) by Båth (2000). Magnusson (2002) found 20-30kg N/ha in cauliflower at the end of July. Adding mulch 2-3 times as in investigations by Jaakkola (1995) and Shäfer (1995) is not recommended since it resulted in 57-70 kg N/ha in autumn. Båth (2001) showed that the mineral N in soil can be decreased by 60-80% when changing from a 0.7 m between row distance to 0.5 m. Furthermore onion yield/ha is increased at higher densities (Brewster, 1994:66-68).

To estimate the risk of leakage with autumn rains a hypothetical calculation was performed using data on N loss from literature. Of the 372 kg/ha N applied with mulch 1.19 kg/ha was recovered in the onions and 48 kg/ha was found as mineral N in soil. A literature review show that about 1% is volatilized as N_20 and 2.7-39% as NH_3 (Båth *et al.,* 2006; Ladd *et al.,* 1985; Larsson *et al.,* 1998; Whitehead *et al.,* 1988). If we assume the N losses and N storages stated above then 3.72 kg N/ha was lost as N_2O, 10-145 kg/ha as NH_3 and 115-141 kg N/ha will be stored in the soil. This amount of N_2O-N equals 1153.2 kg CO_2 equivalents/ha (Baumann and Tillman, 2004:510). Subtracting those amounts we are left with 82-243kg N/ha. Some will be taken up by next year's crop and some may be leached out of the soil after harvest. Not knowing the amount taken up by next year's crop it is difficult to estimate the amount leached. However, compared to the Swedish average in 1995 of 24 kg N leakage/ha/year (SJV, 2000) the leakage in this experiment can be assumed to be high.

D4.3. Diesel Consumption and Labor

Due to an exceptionally dry spring the ley growth was extremely low and an area 10 times the size of the onion area was required for mulching. Other studies and experiences report ley areas of 2-6 times the crop field (e.g. Shäfer 2005; Fredlund pers. commun., 2008). Hence the experiment was compared to two scenarios assuming a reduction of the ley area needed to six times the onion area in scenario 1 (S1) and a ley area four times the onion area scenario 2 (S2). Through participatory evaluation simple optimization of machinery/technique has been assumed in the scenarios.

Table D.4. presents the diesel consumption and labor requirement of the two treatments. The seemingly high amount of diesel per ha for ley harvest is explained by the fact that the amount of diesel and labor required by the two treatments was calculated per ha onion. Hence for example the amount of diesel consumption during the harvest of 10 ha ley was allocated to the area of onion which the harvested mulch covered, in this case about one ha. In *table D.4.* it can be seen that the larger amount of diesel consumption (179%) in M compared to BS in the experiment was equal in S1 and increased to 185% in the S2. The larger amount of labor was decreased from 239% to 217% in S1 and 215% in S2. The area reduction of the ley did not decrease diesel consumption since thicker ley needs to be harvested more slowly and consumes more diesel per time unit. Spreading of the mulch required large amounts of diesel since the wagon had to be refilled after spreading about 30 m. However time used for harvesting was lowered. Since diesel for spreading the mulch remained the same other decreases in diesel consumption were too small to matter. Optimal machinery adapted to mulching, driving and spreading speed was not included in the scenarios but could further decrease the time and diesel consumed.

Raking the mulch into the rows was assumed to be much more efficient with increased experience in both scenarios. Specialized machinery which makes raking unnecessary was not included in the scenarios. Efficient raking will improve coverage and decrease the need for additional weeding. The construction of the mulching-wagon made it sensitive to wind which caused an uneven layer of mulch. The spreading ramp was therefore rebuilt to be lower and shorter. When tested it showed much less sensitivity to wind.

Table D.4. Diesel consumption and labor requirement in M (mulched) and BS (bare soil) treatment in the present experiment as well as in hypothetical scenarios 1 and 2 where the ley harvest, spreading technique and raking is increasingly improved.

		The experiment		Scenario 1		Scenario 2	
		Treatment		Treatment		Treatment	
Measurment	Activity	Mulched (M)	Bare soil (BS)	Mulched (M)	Bare soil (BS)	Mulched (M)	Bare soil (BS)
time (h/ha)	Inter-row cultivator	0,00	1,62	0,00	1,62	0,00	1,62
	Weeding platform	30,87	30,87	30,87	30,87	30,87	30,87
	Brush saw	3,82	3,82	1,27	0,00	1,27	0,00
	ley harvest/cleaning	47,19	47,19	33,68	33,68	17,46	17,46
	Mulch spreading	111,73		77,72		57,88	0,00
	Hand weeding	5,73	0,00	0,00	0,00	0,00	0,00
sum:		**199,34**	**83,50**	**143,54**	**66,17**	**107,49**	**49,95**
Diesel (l/ha)	Inter-row cultivator	0,00	1,95	0,00	1,95	0,00	1,95
	Weeding platform	13,67	13,67	13,67	13,67	13,67	13,67
	Brush saw	1,91	1,91	0,64	0,00	0,64	0,00
	ley harvest/cleaning	515,62	429,25	515,62	429,25	463,80	386,07
	Mulch spreading	266,70		266,70	0,00	266,70	0,00
Sum:		**797,90**	**446,78**	**796,63**	**444,87**	**744,81**	**401,69**
Diesel use in M compared to BS:		**1,79**		**1,79**		**1,85**	
Labor in M compared to BS:		**2,39**		**2,17**		**2,15**	

During soil sampling prior to harvest it was noted that the soil in BS was very dry even at 25 cm depth while in M it was humid at the soil surface under the mulch. According to the farmer the irrigation could be delayed for several days in the M treatment but not entirely avoided. This is of great help in the logistics of the vegetable cultivation were everything must be done at the right moment. It will become increasingly important since the Swedish summers are expected to become dryer due to climate change (SMHI, 2008). Possibly irrigation requirement has to be re-learnt when mulching is applied. Objective evaluations of irrigation need with potentiometer and more experience will tell if mulched vegetables are being watered in excess. Although it was not possible to measure in this experiment it can be assumed that avoiding one or more irrigations will decrease the diesel consumption and labor requirement significantly. This would be appreciated by the owners since irrigation is seen as a very time consuming nuisance.

During dry years mulch is very beneficial due to its humidity retaining property. However dry years the yield of ley is low. Depending on the proportion of ley on the farm it may not be enough for both fodder and mulching. Energy consumption will not differ much between dry and humid years as stated above but the labor requirement will increase somewhat since a larger field must be harvested for the same amount of green mulch.

Neither the experiment nor the improvements mentioned for the two future scenarios did result in a lower diesel consumption and labor requirement in the mulched treatment. Mulching in this system was not a more climate smart option for onion production. It is questionable whether green mulch spread by fossil fueled tractor can be regarded as an ecosystem service due to the high amount of external energy used. It is suggested that mulching should be used in a crop as e.g. cabbage that benefits more from the fertilizing and humidity retaining effect of the mulch. An increased yield will lower the diesel and labor per kg crop.

D5. Conclusions

Spreading 5 cm layer red clover/grass mulch at one occasion a month after planting was enough to efficiently reduce weeds from mid June until harvest. It was essential that the mulch cover was at least 5 cm also close to the onion. Yield was not affected by N immobilization. Compared to the Swedish average in 1995 of 24 kg N leakage/ha/year the N leakage was estimated to be high. Closer row spacing would increase yield/ha, N uptake/onion, reduce the required amount of mulch hence reducing volatilization and risk of N leakage. However if different distances are to be used in different crops it may cause difficulties with the tractor tools. Mulching in onion did not reduce diesel consumption or labor requirement per ha when used for weed control. A more nutrient and water requiring crop e.g. cabbage together with improved estimation of irrigation need adapted to mulched systems is suggested for further research to better understand under which circumstances green mulching may be beneficial from an energy perspective. Differences in storage loss, marketable yield and quality could influence the degree of climate efficiency of the method and needs further investigation. A complete comparison including silage and meat production as well as a system with permanent green manure and no animals is also suggested for future research.

Acknowledgement

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Keywords

Green Manure, Organic, Weed Control, Climate Change, Global Warming, Red Clover

Appendix E. Survey Questions

	Survey How ecosystem services can be used to replace fossil fuels in weed management.

Questions

1. What is the name of the farm/company?

2. How large is the farm and vegetable field in ha?

3. What do you grow apart from vegetables (e.g. cereals, green manure, ley, pasture, energy crops) and on how many ha?

4. Describe your crop rotation the last seven years (2008, 2007, 2006, 2005, 2004, 2003, 2002).

5. How many persons work on the farm and how much time goes to weeding?

6. How does the weed situation look like at your farm and what help do you have from other parts of your farming in the weed control (e.g. crop rotation, grazing and grubbing animals).

7. Have the weed species or abundance changed over the years?

8. Do you use weed control methods which are not dependent on fossil fuels (except for hand weeding)? Describe the method.

9. Which are the pros and cons of the method for the workers, the environment and the production. Have you noticed that the method has affected something else than the weeds (crop growth, diseases, insect, soil quality)?

10. How does this method affect your labor situation? Does the method use less labor than handweeding? Does the method use more time than mechanical weeding with tractor? Please also include indirect labor requirement (e.g. production of fodder or biofuels, less labor due to improved pest control or increased yield etc.). Please estimate how much the labor requirement has changed.

11. Are you planning other weed control methods which do not use fossil fuels?

Appendix F. Survey Participants

Name of farm	Name of farmer(s)
Högsta Grönsaksodling	Margareta Magnusson
Sörtorp	Karl Källander
Solbacka Gård	Paul Teepen
Bolstads Kleven 2:1	Karl-Ivar Karlsson
Växhuset	Ralf Pampers
Holmströms Krav odlingar	Bernhard and Gisela Holmström
Mälby Gård	Per Johansson
Hållsby station	Nils Karlsson
Hebo Trädgård	Henry Karlström
Gammelbo Gård AB	Peter Bergström
Hagalund	Barbara Hinsch
Tassemarken	Anna Lilljeqvist and Sigvard Andervad
Ramsjö Gårdsprodukter	Anders and Karin Berlin
	Göran Petersson