Research on pest control and pesticide reduction in Sweden, Denmark and the Netherlands

- ongoing work and new ideas for the future

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Introduction

During the last decade society has experienced a growing interest in organic farming partly due to the public debate about environmental degradation and contamination of soil and water. The drawbacks with pesticide use has been recognised and a wide range of projects have been initiated to identify and minimise the negative impact of pesticides (eg Kreuger, 1999). Representatives from science and society have pointed out that a sustainable development of the society and particular the agricultural sector, cannot be based on use of high amounts of agrochemicals. However, the agricultural systems used today are in general not designed for a production without pesticides. Thus, we need to change the production techniques towards systems with low or no input of pesticides. Such a change naturally requires an identification of problems that might occur and development of new methods for pest control.

Aims and limitations of the report

The objectives of this report are i) describing available and future methods for pest control without agrochemicals and discuss their applicability, ii) studying trends concerning pesticide use and research in Sweden, Denmark and the Netherlands. Based on the obtained findings recommendations for future research are given - both in the near future and in a longer perspective.

The report has been carried out during five weeks in autumn 1999. Recent literature has been studied and interviews with scientists and civil servants in Sweden, Denmark and the Netherlands have been performed.

What's the problem ?

The society of today has based its crop production on the use of pesticides and fertilisers. However, we experience that this cropping system has major drawbacks. Contamination of ground waters, pesticide residues in food and an increase of herbicide resistance of weeds are some of the problems that have been recognised (Bichel, 1999).

Generally, scientist and political representatives are aware of the problems that pesticide use - and misuse - can cause and a number of efforts have been made to reduce the negative impact of pesticides in the environment. However, several target conflicts can be identified in agriculture and society concerning pesticide use. The consumers demand cheap, high quality food, originating from Swedish farmers, available all the year around and produced without any negative impact on the environment. Government policy was to adapt agriculture to a "European" production and regulation system as well as keeping special rules and regulations for Swedish agricultural production. The farmers are interested in high yields and sale prices, low production costs and cropping reliability. The food industry demands high quality products, delivery reliability from the farmers and a low price of raw materials.

These partly contradictory demands can sometimes be quite difficult to meet at the same time. One way to solve the pesticide problem is organic farming. At present, about 2.8 million hectares are used for agricultural production in Sweden (Anon., 1998) of which 200 000 ha are used for organic production. A governmental goal is to reach 10 % organic farming by the year 2000, a goal that partly will be accomplished. Organic farming generally yields less than

the conventional farming, and thus the price of the product is higher for the consumer and food industry. The input of manual labour -especially for weed control -is generally higher in organic farming which is a major drawback. The labour requirements effect both the possibility to enlarge the productive area and of course, the price of the product.

Another way to reduce pesticide use is to develop the conventional cropping system. Pesticide use in row crops can be reduced by band sprayers and introduction of resistant crop varieties. More efficient pesticides and further development of low dose compounds can also decrease the amounts used in field.

Pesticide use in Sweden

In 1998 about 8400 metric tonnes of pesticides (measured as active ingredient) were sold in Sweden (Anon. 1999a). The main part (76 %) is used in industry to preserve wood and other materials. Agriculture, including commercial horticulture, used about 20 % or 1688 tonnes. The main part of the pesticides used in agriculture is the herbicides (1277 tonnes). Fungicides (271 tonnes) and seed dressings (74 tonnes) are the second and third largest groups.

In comparison to many other countries Sweden has succeeded in reducing pesticide use quite well. In e.g. the Netherlands pesticide use has today (1998) been reduced to about 55 % of the average in the period 1984-1988, but Dutch agriculture still uses about 9800 tonnes of pesticides (Anon., 1999b), i. e. about six times more than Sweden.

The National Chemicals Inspectorate decides whether a pesticide is approved for use in Sweden or not. Their decision is based solely on the physical and chemical properties connected to the pesticide and not the possible need of the product in Swedish agriculture.

Insecticides

In Swedish agriculture, insecticides generally play a minor role in arable crop production. The total use was about 35 tonnes in 1998, mainly compounds to control aphids in cereals and *Phyllotreta nemorum* and *Meligethes aeneus* in rape-seed. In the mid 1990's pioneer experiments were carried out to remove insects in strawberries and potatoes by the use of a vacuum cleaner (Arvidsson, 2000 pers. comm.). However, no further development of this kind of technique was carried out due to high costs and lack of interest from the farmers.

The main problem with insecticides is the high toxicity for humans and animals.

Fungicides

The main part of the fungicides in agriculture, about 95 tonnes are used to control *Phytophthora infestans* (potato late blight). The use of fungicides to a large extent dependent on the weather conditions during the season

Herbicides

At present weed control is mainly carried out with agrochemicals although an increase of physical methods in use is observed. The most common active ingredient is glyphosate used for weed control of e.g. *Elymus repens* L. before ploughing in the autumn . In 1998, about 468 tonnes of glyphosate were sold in Sweden which is approximately 30 % of the total amount pesticides used or, 37 % of the herbicides (Anon., 1999a). Glyphosate is also used for weed control in private gardens and for weed control on hard surfaces in public urban areas.

Agriculture without pesticides - a possible future ?

Only a handful of reports have been published discussing whether agriculture could be maintained at a national scale without use of pesticides. The most recent one is that of the Danish Ministry for Environment and Energy (Bichel, 1999) where the effects of a total phase-out of pesticides in Danish agriculture are evaluated and recommendations for future work are presented.

The most important recommendations of this report are summarised below.

Concerning non-chemical pest control there is a need of :

- Research on development of the alternative methods of pest control to become economical competitive to pesticides.
- Research on new techniques/methods for physical weed control.
- Self-propelled weeding robots.
- New pest-preventive cropping strategies.
- New pest-resistant crop varieties.
- In pesticide related research areas there is a need of:
- Systematic investigations of how pesticides effects flora and wild life.
- Research on atmospheric transport of pesticides and the impact on the environment.
- Improved systems of chemical and physical weed control in row crops.
- Further development of pesticide application techniques to reduce spray drift caused by wind.
- Research on how to minimise pesticide leakage when filling and cleaning sprayers.
- Further work on precision agriculture and decision support systems for plant protection.

At present (January 2000) the Danish Ministry for Environment and Energy is preparing an action plan concerning pesticide use. In the draft of the plan the objectives are to reduce pesticide use in general, increase the area of organic farming by 170 000 ha to 230 000 ha in 2003 and to prohibit pesticide use along lakes and rivers with an area greater than 100 m^2. The action plan shall run during the period 2000 - 2003 and has a total budget of about 250 million DKK. The available documents do not specify any time-table or details of possible participants. However, it is reason to believe that the aim is to start the pesticide reduction programme in late 2000 (Anon. 1999f).

An earlier report concerning reduction or elimination of agrochemicals in farming was published in 1997. (Anon., 1997). The aim of this EU-project was to produce: i) a system to control weeds in small grain cereal crops in northern Europe using significantly reduced inputs of herbicides by precise targeted application, and ii) a system to control weeds in salad and vegetable row crops in southern Europe using a precise non-chemical method.

The suggested non-chemical weeding system was based on a mobile robotised arm with vision-based tracking and inertial guidance systems. An electrical discharge weed control method was used via a precision end-effector on the robotised arm. Detection, tracking and weed control were carried out in real-time. An important conclusion of the report was that the non-chemical method was applicable across the whole of Europe. The equipment would be especially interesting in horticultural crops due to their wide row spacing, greater unit value and the great concern about the impact of herbicides on crop quality. Moreover, the authors estimated that the non-chemical approach would almost completely eliminate the use of herbicides. It was pointed out that further research and development should be carried out in:

- Weed detection, both determining weed density and weed species.
- Non-chemical methods of weed control including different weed/crop combinations and other precisely positionable energy delivering systems such as lasers.
- Autonomous guided vehicles.
- Image analysis systems, in order to reduce the sensitivity to variable levels of illumination.
- Sprayer control methods in order to achieve the greatest advantage in terms of reduced chemical use and minimal environmental contamination.

Alternatives to conventional insecticides

Several strategies have been investigated in order to reduce insecticide use. In commercial greenhouse production of e.g. tomato and cucumber biological agents such as other insects, bacterias and nematodes are successfully used. The commercial sale of biological agents has increased the last two years. The sale of *Amblyseius cucumeris*, a predatory mite, had a 100 % increase to 716 millions individuals in 1998 compared to 1997 (Anon. 1999a). Nematodes such as *Steinernema feltiae, S. carpocapsae* and *Heterorhabditis megidis* are available for control of insects in green houses and on field crops (Anon., 1999e).

The use of micro-organisms such as *Bacillus thuringiensis* and *Trichoderma harzianum* has gained terrain the last years in control of insects and fungi diseases.

Bio-insecticides such as neem (Sjölund & Gripwall, 1999), is another option for insect control. Is it well known that substances originating from various kind of trees, flowers and animals can be used to control unwanted pests.

Fungi control without conventional fungicides

Biological agents are also used to control or prevent fungi diseases. Recently it has been shown that oils originating from garlic, peppermint, rosemary and thyme could reduce storage diseases in potato and in some cases increase yield with about 30 % (Bång, 1998).

Long-term storage of apples can often result in great losses in quality and quantity due to fungi diseases such as *Gloeosporium*, *Botrytis cinerea* and *Penicillium expansum*. Swedish experiments in 1997-1998 showed that vinegar and calcium chloride could be used to minimise damages caused by fungi. Ericsson & Tahir (1999) showed that vinegar could reduce the percentage of rotten apples (cv Aroma) to about 3.5-5.0 %. In the untreated fruit about 82 % where assessed as rotten.

Non-chemical weed control

Until the introduction of modern herbicides in the late 1940s early 1950s, farmers had to rely on physical weed control. Mainly three methods were used: weed harrowing, row cultivation and hand weeding. These methods were commonly used by the farmers and recommended by the agricultural experts (Korsmo, 1926). The interest in further development of physical methods faced a depression after World War II but has revived since the early 1980s.

Several methods for physical weed control have been investigated and developed in the last decade. Recently, a thorough review of physical weed control techniques was presented by Kurstjens (1998) discussing the benefits and drawbacks of various methods. The most common physical methods such as weed harrowing and row cultivation are well known by the farmers. Although the potential for a further technical development of these methods is limited there is a great potential to use the methods in new applications. Harrowing can possibly be used in crops other than cereals and row cultivators can be combined with automatic guidance systems into self-propelled machines operated without human labour.

Mechanical methods

Weed harrowing

Weed harrowing in cereals was a known technique already in the late 1920's (Korsmo, 1926) and is still one of the commonly used methods in organic cereal production. The method has been thoroughly studied by e.g. Rasmussen (1990; 1991; 1992). The general control effect of a harrowing is 30-60 % (Lundkvist & Fogelfors, 1999). Due to the low price of the harrows in combination with high working capacity the technique has been accepted by farmers as a simple way to control annual weeds. It is most likely that harrowing can be used in crops other than cereals. Some successful experiments have been carried out in other crops (Kudsk, 1996), but we still lack knowledge of the possibility to perform harrowing in vegetables and rape-seed. Experi-ments on weed efficacy, impact on crop quantity and quality should be initiated in these crops.

Row cultivation

Weed control in row crops can be divided into inter-row and in-row techniques. In the first case weeds that are present between the crop rows are controlled generally leaving an untreated strip of 5-10 cm on-the-row. This control can be performed with various kind of shares, rotating ground driven wheels, pneumatic driven knives etc. Reviews of different methods can be found in Kurstjens (1998) and in Dieraurer & Stöppler-Zimmer (1994).

The present development of row cultivation techniques is generally focused on precision or automatic steering devices in order to improve accuracy of the control treatment, reduce costs for labour, and increase working capacity. Accurate steering enables intensive mechanical weed control treatment on 92% to 95% of the total surface in row crops. Some recent plant and row detection systems mounted on hoes are found in app. 1. At present there seems to be no obvious area of research concerning tools for inter-row cultivation.

In-row weeding

A special case of row cultivation is weed control in the row, i.e. between the crop plants. This operation can be carried out by rotating nylon brushes on vertical axes (Fogelberg, 1998; Kouwenhoven, 1997), by vibrating steel rods, torsion weeders (Hallefält *et al.*, 1998) or by other ground driven implements such as spinners, spyders or finger weeders (Schweizer *et al*., 1992; Bowman, 1997). In-row brush weeding is possible to perform in most row crops but is mainly carried out in sugarbeets, carrots and maize. In-row weed control is an essential part of a non-chemical weeding system. In general the inter-row weeds i.e. the weeds between the crop rows, can easily be controlled by well-known tools such as duck-foot hoes while the weeds on the row must be either hand weeded or controlled by the methods mentioned above. Unfortunately brush weeding is a rather expensive technique due to high machine costs and low working capacity. There are no ongoing projects concerning in-row weeding in Sweden at the moment.

A partly new concept for in-row weed control in row grown crops is the "Smart Hoe" developed at the Wageningen University and Research Centre (van Asselt, 1999 pers. comm.; Bontsema *et al*., 1999). Crop and weed plants interrupt one or more light beams that cross the row on several levels. A digital signal processor processes the interrupted signal and filters the regular crop frequency from the irregular weed frequencies. Spring-loaded hoe knives are mounted on a rotating disc and when the rotational speed exceeds a certain value the knives moves into the row and cut the weeds. When the signal processor detects a crop plant the rotational speed is rapidly decrease so the springs withdraw the knives.

Based on the achieved results the method is interesting for further research. However, there seems to be little interest from farmers and machine industry to develop the experimental equipment available today. Possibly, a joint project between the Dutch agricultural university in Wageningen (WUR) and the Swedish University of Ahricultural Sciences (SUAS) could be started to evaluate the method for Swedish agriculture.

Thermal weed control

Freezing

Freezing of weeds using CO_2 or liquid nitrogen (N_2) is a method based on the principle that vegetation is damage by frost and application of a cold medium should thus severely effect the viability of the weed plants. However, investigations by Fergedal (1993) have shown a low efficacy and high energy consumption, which makes this method unattractive for commercial use. The potential for further development seems to be low and no recent literature has been found on this topic.

Flame weeding

Flaming of weeds either as a pre-emergence technique or in row crops (selective flame weeding) has been thoroughly investigated in the 1990's (e.g. Ascard, 1995; Bertram, 1996). Flame weeding can be carried out by heating weeds with flames from burning LPG (gasol) or by an indirect heat transfer (infra-red weed control). In the latter case, electricity, LPG or other fossil fuels are used to heat a ceramic shield which then transfer the heat to the weed plants (Kurstjens, 1999). Flame weeding is commonly used in organic production and several commercial manufacturers of equipment can be found in Europe. Today, there are no obvious needs for further research of the method. A further technical improvement of field equipment and development of machines for urban weed management and possibly home gardens should be carried out, but this development can probably be achieved by the manufacturers.

Hot water

Another thermal method possible for weed control - especially on hard surface areas - is treatments with hot water. The method acts mainly on above-ground plant parts and the effect is similar to that of flame weeding and foliar applied herbicides (Hansson, 1999a; Hansson, 1999 pers. comm.). Using water of about 120°C under pressure applying 400 -1300 kJ m^{-2} a control effect of about 90 % was obtained for *Sinapis alba* L. at the two-four leaf stage (Hansson, 1999b). Studies in Denmark (Hartvig *et al.*, 1997) have shown that although the hot water was effective against small weeds (90 % control) the amount of water was considerable, 6000 - 30000 l ha^{-1}. The high water need and thus the energy consumption was considered a problem and further experimental work to develop the method was recommended. Hot water weeding is currently being investigated at the Dept. Agricultural Engineering, Swedish University of Agricultural Sciences, Alnarp. Today the methods need further development - reduction of water consumption and machine costs - in order to be an attractive alternative to other non-chemical weeding method. Hansson (1999, pers. comm) has pointed out that the energy consumption in practice is about five times higher than the calculated theoretical one. Thus, there is an obvious need for optimisation of the method by improving the existing machines.

Steam

Steam as a weed control method is currently being investigated at the Dept. Agricultural Engineering, Swedish University of Agricultural Sciences, Alnarp. Experiments have also

been conducted at the Danish Forest and Landscape Research Institute. A commercial machine for steam weeding is available for urban areas (WR Damp ApS, Hedehusene, Denmark)

Steam has an effect similar to that obtained in flame weeding. An advantage with steam is the low risk for fires and the high weed control effect. In experiments by Hansson (1999c), an effect of about 90 % was obtained on 2-4 cm high weeds using 630 kg steam per hectare. The energy consumption for steam weeding is considered to be lower than that of flaming and hot water (Hansson, 1999 pers. comm.).

Today steam weeding is used to control weeds on hard surface areas but a possible new application of steam could be to control potato leaves before harvest instead of using Reglone® (a.i. diquat) or other defoliation herbicides.

Electromagnetic methods

Electricity and electroporation

Basically, there are two types of electrical weed control: i) electrical discharge and ii) direct electric shock. A third type is electroporation which however, can be considered as a variety of electrical discharge (e.g. Mattsson, 1995; Diprose & Benson, 1984; Vigneault, 1985).

Electrical discharge means the discharge of a quantity of electricity into the plant from a high voltage electric energy source. The discharge electrodes need not necessarily touch the plant if very high voltages are used, since the discharge can jump across an air gap. Direct electric shock treatment is a continuos process where a generator is physically connected to the plant by an electrode, the ground being used as the other electrode.

Electroporation is a phenomenon in which the membrane of a cell exposed to high-intensity electric field pulses can be temporarily destabilized in specific regions. The cell membrane is then permeable to exogenous molecules (Chang *et al*. 1992). When a cell is placed in a electric field of high magnitude, the pores in the membrane will be irreversible and thus lethal to the cell. This method has recently been used for cancer treatment (Engström, 1999) and is currently being investigated as a method to control weed seeds in crop production.

The use of electrical weed control methods is currently being investigated in two projects in Sweden. At the Institute of Agricultural Engineering, Uppsala, the direct electrical shock method is used to control *Cirsium arvense* L. in cereals (Lundin, 1998). This project aims at finding new strategies for control of *Cirsium* in organic cereal production. Electrical control is one of five investigated physical methods.

At the Dept. of Agricultural Engineering, Alnarp, electroporation of weeds is studied as a possible method for weed seed control in vegetable production (Fogelberg, 2000 pers.comm). Pioneer experiments on electroporation have shown that seeds of Sinapis alba L. can be controlled to 100 % using 25 pulses of 3000 V cm-1 (Bengtsson, 1996). The reported experiments were, however, conducted with seeds in water filled cuvettes germinating in petri dishes. Further experiments in peat or in soils from arable fields have resulted in a less pronounced effect of about 50 %.

At present electroporation seems to be a promising technique for weed seed control, however, much additional work must be performed in order to evaluate factors of importance for the control effect and to construct field operable machines. Little is known of how soil moisture, seed size and soil composition influence the outcome of a electroporation treatment. Moreover, the effects on soil flora and micro fauna have not been investigated. Further work on the method is recommended to be carried out.

Microwave radiation

Basically, microwave weeding is a particular form of thermal weeding. In this case the weed seeds in the soil are boiled by the heating process caused by the microwaves. During the 1970's and 1980's research was performed on microwave as a weed control method (e.g.. Lal & Reed, 1980; Diprose *et al.*, 1984) but the method has not been put into practical use. The main drawbacks of the method are the low capacity, large energy requirements and heavy equipment. A Swedish review study on the possibilities to use microwave radiation for soil treatment was presented in 1993 (Mattsson, 1993). This study pointed out a potential to use a stationary equipment for soil treatment e.g. in construction of urban areas. No further research on microwaves for weed control was however, conducted. The method cannot be considered to be of interest for further research.

Laser

Laser has recently been recognised as a method for weed control (van Asselt, 1999 pers. comm.; Kurstjens, 1999; Heisel, 1999 pers. comm.) and pioneer experiments are ongoing or will be started in early 2000 in the Netherlands and Denmark. In these cases the laser (CO_2-type) will be used as a kind of knife cutting the weeds above the surface. Only a handful of studies on laser weeding have been found regarding this technique (Bayramian, 1993; Winge, 1998). There is probably a great potential to use laser in combination with vision guided weed control machines. A pioneer project on the applicability of laser, UV-light and cutting water technique will be carried out at the Dept. Agricultural Engineering in spring 2000. Further research is recommended to investigate the potential of this method.

UV-light

The possibility to use UV-light as a weed control method has recently been studied in Denmark (Ogstrup-Pedersen, 1997; Andreasen *et al.*, 1999). When plants are irradiated with UV-light almost all energy is absorbed in the outermost plant tissue layer. This results in a heating of the tissue and the effect is thus similar to that obtained by flame weeding. At present only a handful of papers and reports have been published, mainly originating from Denmark. It has been suggested that UV-light could be used as a rapid and easy-to-use method for weed control on hard surface areas (pavements, railway embankments). However, the reported successful experiments have been carried out on grass surfaces or under greenhouse conditions. The method can be considered as interesting for weed control, mainly in urban areas, but further investi-gations should be initiated to study efficacy, weed selectivity and possible health risks. A pioneer project on the applicability of laser, UV-light and cutting water technique will be carried out at the Dept. Agricultural Engineering in spring 2000.

Other techniques for weed control

Water cutting

Water under high pressure (3000 bar) is used in industry to cut steel, plastics, wood, fabrics etc. (Borgström, 1999. pers comm.). The pressurised water beam contains no harmful additives and uses limited amount of water. No research has been conducted using water cutting as a weed control method although the idea has been discussed at the WUR in the Netherlands. At present it is not possible to judge whether water cutting could be used in agriculture. However, a pioneer project on the applicability of laser, UV-light and cutting water technique will be carried out at the SUAS, Dept. Agricultural Engineering, Alnarp in spring 2000. Further research is recommended to investigate the potential of this method.

Solarization

Soil solarization is a technique of controlling soil pathogens, weeds and nematodes by covering the soil for sufficient time with thin transparent plastic film, during hot summer months for sufficient time to raise the surface soil temperature to the levels lethal to soil-borne pests (Yaduraju & Ahuja, 1996) This method is used successfully in Mediterranean or tropic countries to control annual and perennial weeds. Weed reductions of about 75 % have been recorded in Indian experiments (Yaduraju & Ahuja, 1996).

Solarization is a technique adapted for countries with warmer climates than Sweden. However, in theory it should be possible to use solarization as a part of an integrated production of vegetables. A pioneer study should be initiated to investigate the potential of the method under Scandinavian conditions.

Cropping techniques

Apart from the physical control methods of weeds, various cropping techniques are in use to control weeds. The aim of these methods can be to prevent weeds from emerging by the use of night-time soil cultivation (Hartmann & Nezadal, 1990; Jensen, 1995; Fogelberg, 1998) or to accelerate emergence and growth of the crop by seed priming (Brocklehurst & Dearman, 1983; Bujalski *et al*., 1991; Pill & Evans, 1991; Schipper, pers. comm, 1994). The effect of night-time soil cultivation varies between zero and about 75 % control effect on annual weeds. This great variation is the major drawback of the method in practical use. However, in organic farming night-time soil cultivation might be used in a system of non-chemical weeding operations (Fogelberg, 1998).

Priming is a technique where crop seeds are soaked in aerobic polyethylene glycol (PEG) or weak salt solutions of high osmotic potential for a period of up to three weeks, which have the effect of controlling the water uptake of the seeds until they reach the brink of germination, but visible germination does not occur (Bujalski *et al*. 1991). Mean emergence times can be reduced by priming and the crop stand is often more uniform. For carrots, celery and onions emergence times have been reduced by 3-5, 5-8 and 3-9 days respectively (Brocklehurst & Dearman, 1983). For carrots, priming can improve plant stand giving up to 12 % more usable plants (Schipper, 1994. pers. comm.).

Although seed priming cannot be considered as a method to control weeds, it may be a part of a cropping system less dependent on herbicides. A reduction in field emergence time will in most cases improve the competition ability of the crop thus reducing the need of herbicides. The priming technique is today mainly used for vegetable seeds. At present, there are no ongoing projects concerning primed seeds in cropping systems at the SUAS.

Allelopathy

The use of allelopathic substances as natural herbicides have been thoroughly investigated in Hungary (Brückner & Molnar, 1999), Italy (Casini, 1999), Bosnia and Herzegovnia (Dikic, 1999) and UK (Wilson *et al*., 1999). The control effects have in some cases been very high e.g. (95 % inhibition of germination using extracts of *Anthemis arvensis* [Dikic, 1999]). However, the interest for allelopathy in the Nordic countries seems to be low. Johansson (1992) experimented with mustard residues as a bio-herbicide in vegetables, but no further work was carried out although the results were at least partly quite promising.

The use of bio-herbicides opens an interesting perspective for the future. On the one hand, these herbicides are "natural", sometimes easy to obtain, and effective. On the other hand, they may be highly toxic, have effect on few weed species and be costly to produce. Our knowledge of the bio-herbicides, how they effect pests and environment is limited. Several projects concerning bio-herbicides are however, ongoing in Europe (Bürki *et al.*, 1999) and a number of scientific papers have been published concerning control of *Chenopodium album, Orobanche cumana, Senecio vulgaris, Convolvulus* spp. and *Amaranthus* spp. The general approach in these studies have been to control the weeds by use of fungal pathogens (Bürki *et al*., 1997; Frantzen & Hatcher, 1997; Scheepens *et al*., 1997; Pfirter & Défago, 1998; Müller-Schärer & Scheepens, 1997). Biological control instead of herbicides will most likely be method for weed control in the future.

Pesticide research in some European countries

In order to catch the current trend of pesticide research in general, representatives from Denmark, the Netherlands and Sweden were interviewed concerning ongoing and future research on pesticide use.

Sweden

In Sweden eight persons at the Swedish University of Agricultural Sciences (SUAS), the National Board of Agriculture (SJV) and the National Chemicals Inspectorate (KEMI) were selected for discussions. These were:

Dr Jenny Kreuger, Dept. Soil Science, SUAS, Uppsala.
Prof. Lennart Torstensson, Dept. Microbiology, SUAS, Uppsala.
MSc Björn Isacsson, KEMI, Solna.
MSc Peter Bergquist, KEMI, Solna.
MSc Gunnar Karltorp, KEMI, Solna.
MSc Sylvia Jarl, KEMI, Solna.
MSc Ingemar Nilsson, SJV, Alnarp.
M Sc Karin sahlström, SJV, Alnarp.

Dr Kreuger and prof. Torstensson pointed out that pesticide research in Sweden has difficulties to obtain funding for long-term studies. They stressed the need of research in:

- Monitoring pesticide leakage in agriculture.
- Handling of pesticides on farms and in field .
- Development of methods for analysis of strobiluriner (a group of fungicides).
- Studying the effects of pesticides on flora and fauna.
- Optimising of the available biological breakdown facilities on farms.
- Reducing the use of pyretroids.
- Introduce varying limits of pesticides in e.g. water, based on toxicity .

The scientists considered it important to decrease the amount of pesticides in general, but pointed out that a reduction must take into account that the toxicity of pesticides, among other characteristics, varies. Thus a reduction shall not be limited to reduce the amount but on the total environmental load. Torstensson and Kreuger have taken part in several projects concerning pesticide use, biobeds and pesticide leakage (e.g. Kreuger, 1999; Torstensson, 1997; Torstensson & Asplund, 1997).

The representatives from the KEMI clarified that the aim of the inspectorate is not to supply Swedish agriculture with pesticides, but to allow or prohibit chemicals in general. Only about 1% of the chemicals used in Sweden are pesticides. Although the inspectorate has no funding for research, several areas where of interest for KEMI. The inspectorate asks for more research concerning:

- Whether it is possible to reduce fungicides in e.g. strawberries by thinning of the plant stand.
- A further development of mechanical weed control methods in sugarbeets.
- A development of new methods for potato leaf topping in order to phase out sulphur acid.
- New crop varieties resistant to insects and fungi, especially in apple and potato.
- Integrated production technique

Moreover, according to the representatives of KEMI the use of Topas C 50 WP® (a.i. penkonazol and kaptan), Phaltan® (a.i. folpet) and Benlate® (a.i.benomyl) in fruit production should be phased out due to their high toxicity. The use of pesticides in form of powders was also considered as a problem that should be solved by phase-out.

M Sc Ingemar Nilsson at the SJV mainly works with chemical weed control in agriculture especially the use of glyphosate. He pointed out that the use of glyphosate has increased in

Sweden the last years due to competitive aims for the farmers; reduction of nitrogen and reduction of herbicides. There is a general trend towards increased winter wheat production which causes a more intense use of glyphosate. The regulations in Sweden do not allow the farmers to plough stubble or fallow fields until October 20th and especially in the southern part of Sweden this rule leads to chemical instead of mechanical weed control of the fields. Moreover, Nilsson pointed out that a compulsory function test of sprayers would be preferred instead of a general recommendation of such a test. Nilsson also mentioned that a possible way to reduce the risk for pesticide leakage to the environment, would be to start collecting old pesticides stored at the farms.

According to Nilsson, further efforts in research should be focused on:

- Monitoring of pesticides in water.
- Further work concerning handling of pesticides.
- Development of non-chemical weed control methods, investigations of effect, limits of use and mode of action.
- Development of "environmental load index" for each agro-chemical (Nilsson, 1999 [app. 1]).

In discussion with M Sc Sahlström it was pointed out that organic farming is a growing sector in Sweden and in order to develop this production there is a need to monitor the conventional agriculture, develop and render more effective the food production and last but not least raise the important question of what's the benefit of organic farming. The weeds are a major problem in organic farming and thus there is a need for:

- Development of new non-chemical weed control methods.
- Research on organic seeds.
- Keep research experts in organic farming (weed control).

Denmark

Three representatives of the Danish pesticide research were interviewed concerning their ongoing projects and future work. These were:

Dr. Svend Christensen, Dept. Crop Protection, Danish Institute of Agricultural Sciences
M Sc Bo Melander, Dept. Crop Protection, Danish Institute of Agricultural Sciences
M Sc Torben Heisel, Dept. Crop Protection, Danish Institute of Agricultural Sciences

The Research Centre Flakkebjerg has about 200 employees and is a part of the Danish Institute of Agricultural Sciences. The research group of weed ecology and non-chemical weed control has about 15 members (scientists and technical staff). The objectives of the group are "to create results and knowledge that assists the process of minimising herbicide use in conventional farming and add to the development of weed management in organic farming". Research is carried out in four areas:

Crop/weed competition
- Variety weed suppression
- Seed rate
- Sowing date
- Nutrient placement
- Critical distance between crop and weed

Weed seed production and dispersal
- Population dynamics
- Crop rotation
- Soil seed bank

Non-chemical weed control
- Weed harrowing
- Hoeing
- Brush weeding
- Thermal weed control
- Mulching
- Weed cutting

Weed maps and position specific weed control
- Weed monitoring
- Spatial variable herbicide application
- Decision algorithms
- GIS and GPS (geographical information systems and global positioning systems)
- Computervision

Several projects concerning pesticide reduction, physical weed control and organic farming are ongoing. The staff are highly motivated and are generally well supported by their institute board - economicly as well as scientificly. The Danish government has since the mid 90's supported the research centre Flakkebjerg with new office premises and additional research facilities. In total 120 millions DKK have been invested.

The interviewed scientists considered high-tech weed control to be interesting, especially development of a self-propelled weeding robot. A number of projects were ongoing concerning decision algorithms for patch spraying, automatic guidance systems etc., but few results were presented. Future areas of interest were:

- Control of perennial weeds.
- High-tech weed control.
- International projects in co-operation with developing countries.
- Automatic guidance systems for hoes.
- Physical weed control in cereal crops.
- Studies of root competition between crop and weeds in order to improve the crop stand.

The Netherlands

In the Netherlands ten persons at the Wageningen University and Research Centre (former Wageningen Agricultural University) and Ministry of Agriculture, Nature Management and Fisheries were selected for discussions. These were:

Dr Jan K Kouwenhoven, Agrotechnology and Food Sciences, Soil Technology, WUR
Ing. C. J. van Asselt, Agrotechnology and Food Sciences, Systems and Control Group, WUR
Dr. L. A. P. Lotz, Research Institute for Agrobiology and Soil Fertility, WUR
MSc Dirk Kurstjens, Institute for Agricultural and Environmental Engineering, WUR
Dr Ben J. Post, Dept. Theoretical Production Ecology, WUR
Dr. Leo Vleeshouvers, Dept. Theoretical Production Ecology, WUR
Ing. A. J. W. Rotteveel, Ministry of Agriculture, Nature Management and Fisheries
Ing. Diana van der Stelt, Ministry of Agriculture, Nature Management and Fisheries
Ing. A. J. Nieuwenhuijse, Ministry of Agriculture, Nature Management and Fisheries
Dr. Her de Heer, Ministry of Agriculture, Nature Management and Fisheries

In general, there are few ongoing projects concerning new technology for non-chemical weed control at the WUR. An experimental equipment for in-row weed control (The Smart Hoe) has been developed by van Asselt during the last seven years (van den Brand, 1999; Bontsema, 1999). This machine operates in the row using a rotating wheel guided by photocells and is able to control in-row weeds in ornamental production. Although new and efficient, the interest from farmers and machinery manufactures seems to be low, mainly due to a low working capacity and high cost compared to herbicide us. In the beginning of year 2000 a minor project using laser as the cutting tool will be started.

The applied science is mainly performed at the research institutes or at the experimental farms. At present the Dutch government supports a multi-year crop protection programme carried out by the Dutch research institutes (DLO). The aim of the programme is to reach 60 % decrease of chemical crop protection agents, decrease in emission and decrease in reliance on agro-chemicals by the year 2000. The government supports the budget of the programme with approx. 10 million NLG per year (1998-2001).

Sub-programme	Research head	Budget (M NLG y^{-1})
Weeds	Lotz, AB-DLO	1,7
Fungii	Bonnekamp, IPO-DLO	6.2
Insects	Smits, IPO-DLO	3.5
Virus	Huttinga, IPO-DLO	1.8
Nematodes	Spoorenburg, PAV	1.6

At the AB-DLO, an institute working with crop production and product quality, soil-plant-environment and multifunctional and sustainable land-use, Dr Bert Lotz is chairman of the sub-programme "weed control and management" (app. 2) with a budget of 1.7 million NLG per year (approx. 6.8 million SEK).

In the weed programme projects are carried out concerning:

Preventive measures such as stale seed bed and weed suppression cultivars
Soil coverage of weeds
Mechanical weed control
Biological control
Innovative physical techniques (heat, micro-wave, water-jet)
Minimum lethal herbicide doses (MLHD)
Site specific application
Resistance and adaptation management
Weed management in urban areas

The multi-year programme will end in 2000 and shall, according to the Ministry of Agric. Nat. Manag. Fish., result in scientific and farmer press papers, workshops for farmers and demonstration projects. A new programme based on the present one will be started in the beginning of 2001. Probably, the new programme will contain projects concerning development of environmental indices, crop protection licenses, water quality management and knowledge transfer from scientist to farmers. The decision in the Dutch parliament will most likely come in the second half of 2000 (van der Stelt, 1999, pers. comm).

A growing problem in the Netherlands is the potato late blight - a problem that has been caused by a new and more aggressive fungi variety. About 180 000 ha are used for potato production and 70 % of the fungicides are used in potatoes. There is a need to change the whole production system towards a more sustainable system. At the moment a multi-year project is running to minimise the environmental load from potato production, i.e. reduce fertiliser and pesticide use. One of the goals is a fungicide reduction of 50 % in 2005 compared to 1998 (Dogterom, 1999).

In the discussions with representatives of the WUR, DLO and the Ministry it was obvious that the future policy of pesticide use in the Netherlands probably will be "no chemical control, unless..." This policy means that pesticides in general will be banned unless there is a pest problem which cannot be solved without agro-chemicals. The use of agro-chemicals has decreased to a level of about 55 % in 1998 compared to that of the period 1984-1988. The main part of this decrease is due to a reduction of soil desinfection chemicals. The use of fungicides has however increased to 5127 tonnes in 1998 compared to 4039 tonnes in 1984-1988 (Anon.1999b). This increase is mainly due to a new and more aggressive potato late blight variety.

For the near future the Dutch representatives pointed out several research subjects of interest. In order to reduce pesticides and their negative impact, further work should be initiated on:

- Plant detection and low-tech weed control.

- Laser and water jet technology for weed control in urban areas and in row crops. These ideas seem promising and pioneer projects will start in early 2000 (van Asselt; Kurstjens).

- Research concerning how to limit the negative effects of agro-chemicals is another important subject for the future.
- Precision agriculture in general.
- Develop the pesticides to be more target specific.
- Education of the farmers how to make non-standard decisions in pest control.
- How to limit the negative effects of pesticides in sensitive areas.
- Reduction of pesticides in water.
- Reduction of fungicide use in potato production.

Can pesticides be reduced in future agriculture ?

The public demand for safe food and environmental friendly productions methods puts conventional agriculture in a somewhat problematic position. On the one hand, the farmers should produce without pesticides and fertilisers in order to minimise environmental impact, on the other hand, the produce shall be of the same quality and quantity as before at the same costs. Will agriculture be able meet these demands in the future? In my opinion agriculture both can and must meet these demands from society. There are however, several question-marks that must be straightened in the discussion.

Strategies for pesticide reduction

Several methods or strategies for pesticide reduction have been identified and we can thus set up some possible scenarios. One is to focus on a general reduction of the total amount of pesticides in Sweden. In this case herbicides and the industrial use of wood protection chemicals should be considered for reduction. The chemicals used for preservation of wood generally contains arsenic, creosote, chromium and copper - compounds which all have a severe negative impact on the environment (Sundström, 1985). On the one hand, it seems reasonable to reduce the use of these chemicals in particular. On the other hand, impregnation of wood and other materials is concentrated to a number of sites where e.g. leakage to groundwater can be monitored. Moreover, the areas where impregnation is or has been carried out, are not used for crop production why the negative impact of the wood preservation chemicals do not directly affect human health through food. The agrochemicals do however, affect human health and environment at a larger scale due to their geographical spread in Sweden. In my point of view, a significant herbicide reduction is possible to achieve using the wide range of physical weed control methods available today. The new "high-tech" weeding methods could be interesting to use in combination with advanced precision agricultural technique such as vision guided weed detection robots.

Another way to cut pesticide use in Sweden could be to focus on the handling of pesticides. By avoiding leakage from sprayers on farm yards, to collect old and/or prohibited pesticides from the farms and to develop "environmental load indices" for each pesticide we would certainly minimise the environmental damages and lower the risk for ground water pollution. It is well known that a significant amount of pesticide residues found in drinking water or rivers originates from weed treatments on hard surface areas and farm yards or spill from

sprayers due to incorrect handling, bad maintenance of equipment or lack of knowledge how to use the sprayer. Moreover, a kind of index showing the impact on environment (effect on humans, animals, biodiversity) for each pesticide could be a useful tool for the advisory service and authorities to minimise pesticide use in regions/communities/fields considered to be particularly sensitive to certain pesticides.

The above-mentioned ways to cut pesticides are probably quite easy to introduce in agriculture. However, they do not answer some of the fundamental questions - are pesticides in the environment really a problem, which pesticides are the problem and where do we find them ?

As pointed out by representatives in Sweden and abroad there is a need to monitor pesticide leakage. I consider a national monitoring programme to be fundamental to fulfil society's demand for pesticide reduction. Without knowledge of where pesticides are present in environment and what kind of chemical substances we find in water, air and soil we have little possibility - if any - to understand the impacts of pesticides in nature. Moreover, our chances of minimising the nega-tive effects of pesticides are quite small if we lack information about what the real problem is.

New techniques for future agriculture

Several projects concerning precision agriculture (e.g. automatic guidance systems, patch spraying, GPS-controlled and/or self-propelled agricultural machines) have been initiated in Europe the last years (Baerveldt, 1999; Lang, 1998; Bontsema, 1999; Anon., 1997). In Sweden work is currently being carried out at the University College of Halmstad in co-operation with the sugar manufacturer Danisco Sugar AB regarding vision-guided mechanical weed control (Baerveldt, 1999). Also the Dept. Agricultural Engineering, SUAS, Uppsala have ongoing projects related to precision agriculture.

It can be discussed whether a "high-tech" approach is the most beneficial way to solve the pesticide problems. It seems possible to develop machines that can identify and remove a majority of the weeds present in e.g. row crops. On the contrary, this technique will probably be, at least in the initial phase, expensive and dependent on good weather conditions. A recent EU-project (Anon., 1997) investigated the use of a mobile robot using a camera to find and separate weeds and crop plants, to control weeds by either patch spraying or electric discharges. Although partly successful, the technique needed further substantial research on weed detection, image analysis systems and sprayer control to be useful.

Going "low-tech" is another option to solve the pesticide problems in agriculture. The torsion weeder (Hallefält *et al*. 1999) is a good example of a cheap tool with high efficacy which even can be made by the farmer himself.

In my opinion, there is a need for high-tech methods as well as low-tech technique. The agricultural production system varies greatly between crops, regions and farms and can thus not be considered as one homogenous system needing only one type of machine or method to solve the pest problem. Agricultural research must supply agriculture with a number of pest control methods suitable for small and large farms, as well as high-tech farming and low-tech farming.

Recommendations for future research

Based on the findings in recent literature and the current research trends in Sweden. Denmark and the Netherlands a number of recommendations for future research are given. These overall aim of the report has been to point out possible ways to make society in general and in particular agriculture, independent of pesticides. The overall aim of the recommendations is thus to support this development. However, it should be emphasised that the recommendations not only focus on further development of non-chemical pest control methods, but also take into account research topics necessary to support our understanding of the impacts of pesticides in the environment.

Near future (1-5 years)

The present knowledge of where and what kind of, pesticides have been found in soil and ground water is limited. Detailed results of this kind have been presented for only one geographical area in Sweden (Kreuger, 1999). In order to understand the magnitude of pesticide impact on e.g. ground water, *a national pesticide monitoring programme should be initiated.* It is important to collect the results of those single pesticide analyses of soil, drinking water and surface water, that are carried out in the Swedish communities. Moreover, *a standardisation of sampling techniques - including choice of pesticides to monitor, should be developed for use by the communities and drinking water suppliers*.

It is believed that a substantial amount of agrochemicals, no longer in use or even banned by the authorities, are stored at farms all over Sweden. These pesticides are or will become a problem to the environment due to e.g. the slow degradation of the packing material. *It is thus suggested to start an inventory of the occurrence of phased-out pesticides at farms and a program to collect and destroy these pesticides.*

Since the main part of the agro-chemicals are herbicides *further research on non-chemical weed control methods should be carried out.* It is important to notice that this research aims at developing new "high-tech methods" that can reduce herbicide use in conventional agriculture as well as improving "low-tech" methods or methods already used in organic farming. *New physical weed control methods of interest are electricity, laser, UV-light and, possibly, water cutting.* It is important that the present knowledge of these methods in Denmark, the Netherlands and Sweden is carefully studied, and their potential risks evaluated, in the initial phase in order to reduce costs for e.g. technical equipment in the pioneer experiments.

The Dutch smart hoe might be interesting for Swedish agriculture (for use in row crops), possibly in a joint Dutch-Swedish project. However, the present status of the ongoing work needs to be carefully studied before any further work can be initiated.
Further research should also be carried out on how weed harrowing can be used in crops other than cereals. Such research can be done in co-operation with the Danish Institute of Agricultural Sciences, Dept. Crop Protection, Flakkebjerg.

Solarization might be a useful method for seed bank reduction in vegetable production. The method is adapted to warmer climate conditions than in Sweden. However, a pioneer project on effect, costs and possible use under Scandinavian conditions should be carried out.

As pointed out by the National Chemical Inspectorate, there is a need for new methods for potato leaf control before harvest. *Steam defoliation instead of Reglone® and Basta® could*

be one option to reduce herbicide use. A modified version of the existing commercial steam weeder could probably be used for this purpose.Moreover, there is a urgent need of research funding for long-term as well as short-term projects. At present the Swedish research concerning pesticide use and its impact on the environment, development of new cropping systems and agricultural technology is down-sized to a level which cannot meet demands of society and agriculture representatives.

In the longer perspective (5-10 years)

Changing the present system with spraying licenses for farmer towards a system with "crop protection licenses" might be a way to reduce the amount of pesticides used. This change does however, require a change in science too. Multidisciplinary research projects with scientists from disciplines such as weed ecology, soil science, plant protection science and agricultural engineering, will probably be the most efficient way to get a holistic view on sustainable cropping systems.

There is a general interest among scientists to develop the precision farming concept. Several projects are ongoing concerning image analysis for patch spraying in agriculture or in urban areas. *The use of various physical weed control methods in combination with technology for automatic weed detection and automatic-guided or GPS-guided steering equipment for precision farming should be investigated for row crops*.

In the long run there is a need to develop cropping systems for potato and sugarbeets which minimise input of fungicides and herbicides. The use of pesticides can most likely be reduced with new crop varieties - a kind of research that mainly is carried out at plant breeding companies. *It is recommended that a scientific discussion begins on the selection of on plant properties for commercial crop varieties. It is likely to believe that organic or integrated farming need crop varieties selected on other criteria than in conventional farming.*

Concluding remarks

In my point of view, there is a general need of research on ”pesticide reduction” and subjects connected to that area. Moreover, we need to strengthen the research by an increase of economic as well as scientist support. In my opinion, the Danish research conducted at the Research Centre Flakkebjerg generally meets the questions put up by farmers and society better than in Sweden. Moreover, there seems to be a better understanding in Denmark that answers to questions of how sustainable agriculture should be developed which cannot be determined without long-term economic support by the government and market. I found that project ideas *discussed* in Sweden are being *carried out* in Denmark. In the long run we can probably expect a substantial advantage for Danish research compared to Swedish research as well as in the number of published papers as the number of skilled research groups.

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