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Weed Biology and Weed Management in Organic Farming

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1. Introduction

Weed biology, including the ecology, physiology and population dynamics of weed species, does not differ from plant biology apart from the notion that the plants under investigation are considered to be "unwanted". Weeds are unwanted and undesirable plants which interfere with the utilization of land and water resources and thus adversely affect human welfare (Rao, 1999). Weed biology research consequently aims to generate knowledge that is expected to be applied in the practical control of weeds, and should include integrated research, from basic to applied, with all elements contributing to real improvements in weed management (Moss, 2008). Management of weeds is performed for the benefit of different interests, ranging from clean and non slippery pavements, to minimizing yield losses in agriculture. The occurrence of weeds in agricultural crops leads to substantial yield reductions causing economic losses all over the world. Crop damage from weeds generally is larger than from other pests (Oerke, 2006). According to FAO (the Food and Agriculture Organization of the United Nations) and the environmental research organization, Land Care of New Zealand, weeds caused yield losses corresponding to $95 billion in 2009. This may be compared with yield losses caused by pathogens ($85 billion), and insects ($46 billion). The economic losses may even be larger if the costs for weed control measures are included (FAO, 2011).

The main reason for controlling weed abundance in agricultural crops is the risk for qualitative and quantitative reductions in crop yields. Black Nightshade (*Solanum nigrum* L.) is a problematic weed in crops such as peas (*Pisum sativum* L.), beans (*Vicia faba* L.) and soybean (*Glycine max* (L.) Merr.), where it not only causes a yield reduction in the crop, but also reduces crop quality by means of contamination with its poisonous seeds (Defelice, 2003). Common ragwort (*Senecio jacobaea* L.) is another poisonous species which does occur in temperate grasslands and pastures where it may lead to death of cattle and other livestock (Suter et al., 2007). Not only the fresh herbage is poisonous, but also its hay and silage remains toxic (Lüthy et al., 1981; Candrian et al., 1984).

A quantitative reduction in crop yield due to weeds foremost is ascribed to the ability of weeds to compete for resources such as light, water and nutrients, at the expense of the crop. The relative competitive ability of weed species is determined by two groups of interacting factors. The first one consists of species characteristics, such as propagation and dispersal features and other life cycle characteristics, and potential growth rate. The second one is made up by the plant environment, which to a large extent is determined by the cropping system and its management. This implies that improvements in weed control in agriculture need to be based on both weed (and crop) ecology, and on the influence of the particular crop and management system on the population dynamics of weeds (Barberi, 2002). The influence of a particular management system may encompass both direct weed control methods such as different types of mechanical and chemical interference, and cultural weed control methods, such as crop choice and crop rotation (Bond & Grundy, 2001). The major difference with regard to weed control between conventional agriculture and organic farming is that the use of chemical weed control is prohibited in organic farming. Another difference is that artificial fertilizers cannot be employed, and thereby it is more difficult to adapt nitrogen levels to the immediate needs of a crop. This affects the relative competitive ability of crops and weeds, which interact with the immediate nutrient status of their environment. In conventional agriculture, chemical control may be employed with short notice and in a curative way, while in organic agriculture a longer time perspective should be taken to prevent yield losses due to weeds (Bastiaans et al., 2008). Direct and cultural methods need to be integrated in organic farming, with the long term goal to prevent the occurrence of weed-induced yield losses, while keeping down costs for weed control. This implies an integration of a complex biophysical system with an unpredictable market, thereby increasing risks for organic farmers.

What kinds of weed species do occur in agricultural crops and how can we control them in organic farming systems? Once we understand why particular weed species do grow abundantly in certain crop cultivation systems, we may alter the crops and crop management systems in such a way that long-term weed abundance decreases. In the following sections, a brief overview of important weed species and available weed control methods in organic farming will be described and some examples of progress in organic weed control are given from Sweden in the Northern part of Europe.

2. Classification of weed species

Given the fact that preventive rather than curative measures need to be used, weed control is one of the greatest challenges in organic farming. A first step for the organic farmer is to identify and recognize the weed species which actually are occurring on the fields, to be able to plan and perform effective short and long term weed control measurements. Weed species may be classified into groups for the purpose of planning and recording control measures against them in many different ways. Among those ways, a botanical classification (monocotyledons vs. dicotyledons) is useful in conventional farming, as selective, group specific herbicides are available. Weeds can also be grouped according to habitat requirements (preferred climate and soil types), invasiveness, economic importance or other criteria. Below, we use life cycle features and the mode of propagation to classify weeds for organic agriculture, as done for farmers in Sweden by Håkansson (2003) and by Lundkvist & Fogelfors (2004). An overview of the more commonly occurring weed species in Scandinavia and Finland, including classification criteria and cropping systems in which those species may occur as weeds, is given in Table 1. For more information about wild plant species that can occur as weeds in different environments, and means of controlling them, see the website 'Organic Weed Management' (Centre for Organic Horticulture, 2011), or for Nordic conditions the website 'Weed Advisor', developed at the Swedish University of Agricultural Sciences, Sweden, (Fogelfors, 2011) (under construction).

2.1 Annual species

Annual broad-leaved and grass weed species propagate by seeds. They grow and develop, flower, set seeds and die within a year after germination. Some annual species, such as *Erodium spp*. (Storksbill) may also display a biennial growth pattern, depending on the winter climate. The ability of short-lived plants to become successful weeds in different crops depends mainly on the germination biology of their seeds. An important seed characteristic is seed dormancy which gives weed species the ability to create a 'seed bank' in the ground. After seed shedding, the seeds may be dormant in the soil until the environmental conditions are favourable for germination. While being species specific and dependent on moisture and temperature, many weed species do have a seed bank with a half-life time of 5 years or more, which means that a fraction of seeds may be viable for many decades (Burnside et al., 1996). Annual weeds may also be classified according to the germination pattern of the seeds, which often varies through the growing season. Annual weed species may further be divided into winter and summer annuals, i.e. winter annuals have their main germination period in the autumn while summer annuals germinate mainly in spring.

In organic farming, both annual broad-leaved and grass weeds may cause yield losses since they are competing with the crop for resources like water, light and nutrients. Consequently, it is important to control them, early in the season before they start to compete with the crop or later in the season before they set seeds, to avoid an increase of the seed bank. For weed management methods, see section 3.

There are many important annual weed species which may lead to yield reductions in cropping systems. For example, the broad-leaved species Black bindweed (*Fallopia convolvulus* (L.) A. Löve), Cleavers (*Galium aparine* L.), Common chickweed (*Stellaria media* L.), Common ragweed (*Ambrosia artemisiifolia* L.), Fat-hen (*Chenopodium album* L.), Scentless mayweed (*Tripleurospermum inodorum* (L.) Sch. Bip), and grass weed species like Black-grass (*Alopecurus myosuroides* Huds.) and Wild oat (*Avena fatua* L) need to be controlled, foremost in annual crops.

2.2 Biennial species

Biennial species propagate through seeds and have a two year life cycle. They germinate and grow vegetatively during the first year, overwinter, and flower, set seeds and die during the second year. Soil cultivation effectively prevents biennial species to flower and set seed. Consequently, biennial species rarely are conceived as problematic weeds, except in perennial row crops and poorly established leys. An example of a biennial weed, occurring in more temperate regions, is Wild carrot (*Daucus carota* L.). Biennial species can be controlled in the same way as annual weeds, i.e. they should be removed early during the first season before they start to compete with the crop or later in the second season before the plants set seeds.

2.3 Perennial species

Perennial broad-leaved and grass weeds are more difficult to control compared to annual and biennial weed species since they propagate through both seeds and vegetative parts (roots and stems). A perennial plant may flower and set seed during several vegetation periods, by means of new shoots which are emerging yearly from the vegetative organs in the soil. These weeds may be divided in groups according to the way they propagate vegetatively, i.e. whether they have a stationary or a creeping root system.

2.3.1 Stationary perennials

This group overwinters by tap roots or by short below ground stem parts. Examples of important broad-leaved species are Curled Dock (*Rumex crispus L.*), Broad-leaved dock (*Rumex obtusifolius* L.), and Northern Dock (*Rumex longifolius* DC.). They often cause problems in leys and pastures, since they compete with the pasture species or arable crops and occupy area which could be utilized by more palatable crop species (Zaller, 2004). Although some vegetative regeneration takes place from underground parts, the vast majority of new plants develop from seeds (Cavers & Harpers, 1964). In leys and pasture, *R. crispus* is considered a very serious problem since it both decreases the quantity and the quality of the ley and pasture harvests (Cortney & Johnston, 1978; Oswald & Hagger, 1983). Dandelion (*Taraxacum* F.H. Wigg) is another example of a broad-leaved stationary perennial with stout tap roots, commonly found in pastures and lawns.

2.3.2 Creeping perennials

Creeping perennials spread vegetatively by means of roots, rhizomes or stolons, which elongate and produce new plants from reproductive buds on those organs. Rhizomes may produce roots and shoots from their internodes, while stolons do have their reproductive meristem at the apical end. Stolons often occur as areal runners, while roots and rhizomes spread below ground. Troublesome creeping perennial weed species in organic farming are Creeping thistle (*Cirsium arvense* (L.) Scop.), Field bindweed (*Convolvulus arvensis* L.), Perennial sow-thistle (*Sonchus arvensis* L.), and Common couch (*Elytrigia repens* (L.) Desv. ex Nevski).

Cirsium arvense is a deep-rooted, broad-leaved perennial that reproduces vegetatively and from seeds, but under most circumstances seed production contributes less to its weediness. The weediness of *C. arvense* can be attributed largely to its capacity for vegetative reproduction and regenerative growth from the numerous buds produced on the roots (Donald, 1994). *Cirsium arvense* is considered one of the world's worst weeds. This species causes problems in crop fields, grasslands and pastures as well as on fallow land and in nature conservation areas in temperate regions of both hemispheres (Holm et al., 1977; Donald, 1994).

Another broad-leaved species is *Convolvulus arvensis* which is a serious perennial weed found in many different crops (Weaver & Riley, 1982). After emergence of the seedling, a taproot is formed from which lateral roots are produced. They grow horizontally about 50-70 cm before turning down and forming secondary vertical roots. This growth pattern is then repeated. In this way, the species can spread rather rapidly over large areas (Centre for Organic Horticulture, 2011).

Sonchus arvensis is a competitive broad-leaved weed species with the main part of the root system 0-20 cm below soil surface (Lemna & Messersmith, 1990). The weed is usually found in spring sown crops (cereals, oilseed rape, potatoes and vegetables) where it can cause considerable yield losses. Compared with spring cereals, *S. arvensis* has shown to be very efficient in nitrogen uptake early in the growing season when nitrogen availability usually is quite low in organically managed fields (Eckersten et al., 2010). This is probably one reason for its increased abundance in organic farming in the northern parts of Europe.

A serious perennial grass weed is *Elytrigia repens*. Seedlings begin to develop rhizomes at the 4- to 6-leaf stage, around the time of first tillering (Palmer & Sagar, 1963). In most situations, vegetative reproduction is more important than propagation by seeds. The aerial shoots of the parent plant die back in the autumn and new primary shoots start to develop below-ground. These grow slowly until temperatures rise in spring, and shoots emerge above soil surface. New leaves are produced and previously dormant buds at the base of each shoot may grow out to form upright tillers or horizontal rhizomes. The rhizomes themselves form numerous lateral rhizomes, about two months after the first shoot emergence. *E. repens* usually occurs as a weed in open or disturbed habitats, rather than in closed plant communities. In compacted soil, the rhizomes grow more or less horizontally. Rhizome growth increases with nitrogen level. Rhizomes grow horizontally in summer before turning erect in autumn, ready to form new aerial shoots (Centre for Organic Horticulture, 2011**)**.

2.4 Which weed species are favoured in which crops?

Sutherland (2004) distinguished weeds from non-weeds by means of life history traits of plant species, and concluded that life span was the most significant life history trait for weeds in general: Weeds were most likely to be annuals and biennials and less likely to be perennials than non-weeds. From Table 1, we see that annual plant species mainly occur as weeds in annual crops, implying that there is a strong interaction with the environment provided by an actual cropping system and the environment which is needed by certain plant species, to develop into large populations of weeds. Most of the annual species are able to develop during periods in which the crop is not present or not yet competitive. Some species, for example Common chickweed (*Stellaria media*), does tolerate a fair degree of shading, and may compete for water and nitrogen while situated below a crop canopy.

With regard to creeping perennials, they all have seedlings which hardly will establish in dense, competitive crops. But once established, they all are efficient users of nitrogen, and are conceived as strong competitors in most cropping systems. These weeds may escape effects of soil tillage, due to a deep position of their root system, and if they do not, their roots may be fragmented, each fragment being viable and able to sprout new shoots.

Instead of putting the question 'Which weed species are favoured in which crops?', one may ask the question 'Which crops have the best ability to compete and suppress weeds?'. In general, fast-growing crops, which close their canopy early, do have a good competitive ability and tend to suppress weeds much better then slow growing crops with more open canopies. Oats (*Avena sativa* L.), for instance, is considered to be a good competitor, while peas are on the other end of the scale (Lundkvist & Fogelfors 2004). Consequently, the core of weed control in organic farming is the use of suitable crop rotations in which crops with a weak competitive ability are alternated with strongly competing crops, or crops which allow for weed control at relative high frequencies throughout the growing season (see section 3).

Weed species	**Monocotyledon, Dicotyledon**	**Annual (w/s), Biennial, Perennial**	**Crops in which the weed species mainly occur**
Alopecurus myosuroides Huds.	Monocotyledon	Annual (w)	Autumn-sown annual crops
Apera spica-venti (L.) P. Beauv.	Monocotyledon	Annual (w)	Autumn-sown annual crops
Avena fatua L.	Monocotyledon	Annual (s)	Spring-sown annual crops
Capsella bursa-pastoris (L.) Medik.	Dicotyledon	Annual/biennial	Autumn-sown annual crops
Chenopodium album L.	Dicotyledon	Annual (s)	Spring-sown annual crops
Cirsium arvense (L.) Scop.	Dicotyledon	Perennial	Both annual and perennial crops
Convolvulus arvensis L.	Dicotyledon	Perennial	Both annual and perennial crops
Elytrigia repens (L.) Desv. ex Nevski	Monocotyledon	Perennial	Both annual and perennial crops
Erysimum cheiranthoides L.	Dicotyledon	Annual (w)	Annual crops
Fallopia convolvulus (L.) A. Löve	Dicotyledon	Annual (s)	Spring-sown annual crops
Fumaria officinalis L.	Dicotyledon	Annual (s)	Spring-sown annual crops
Galeopsis spp. L.	Dicotyledon	Annual (s)	Spring-sown annual crops
Galium aparine L.	Dicotyledon	Annual (w)	Autumn-sown annual crops
Lamium L.	Dicotyledon	Annual (w)	Annual crops
Lapsana communis L.	Dicotyledon	Annual (w)	Annual crops
Myosotis arvensis (L.) Hill	Dicotyledon	Annual (w)	Annual crops
Persicaria lapathifolia (L.) Gray	Dicotyledon	Annual (s)	Spring-sown annual crops
Poa annua L.	Monocotyledon	Annual/biennial	All crops
Polygonum aviculare L.	Dicotyledon	Annual (s)	Spring-sown annual crops
Ranunculus repens L.	Dicotyledon	Perennial	Perennial crops, First year leys
Rumex crispus L., *Rumex longifolius* DC., and *Rumex obtusifolius* L.	Dicotyledon	Perennial	Perennial crops
Sinapis arvensis L.	Dicotyledon	Annual (s)	Spring-sown annual crops
Sonchus arvensis L. – Dicotyledon – Perennial – Annual crops.	Dicotyledon	Annual (s)	Spring-sown annual crops

Spergula arvensis L. – Dicotyledon – Annual (s) – Spring-sown annual crops.	Dicotyledon	Perennial	Annual crops
Stellaria media L.	Dicotyledon	Annual (w)	Annual crops
Taraxacum F.H. Wigg	Dicotyledon	Perennial	Perennial crops, First year leys
Tripleurospermum inodorum (L.) Sch. Bip	Dicotyledon	Annual (w)	Autumn-sown annual crops, first year leys
Tussilago farfara L.	Dicotyledon	Perennial	Perennial crops
Veronica arvensis L. *Veronica persica* Poir.	Dicotyledon	Annual (w)	Annual crops
Viola arvensis Murr.	Dicotyledon	Annual (w)	Annual crops

Table 1. Commonly occurring weed species in Scandinavia and Finland. w = winter annual, s = summer annual. (Hallgren, 2000; Salonen et al., 2001; Riesinger & Hyvönen, 2005; Andreasen & Stryhn, 2008; Andreasen, & Streibig, 2011).

3. Strategies for weed management

Most weed control strategies aim at changing and/or reducing the relative competitiveness of the weed species, thereby favouring growth and development of the crop in comparison with the weed flora (Zimdahl, 2004).

Weed control strategies may be categorized in different ways. Often used terminology is biological, chemical, cultural, direct, indirect, mechanical, non-chemical, physical, and/or preventive weed control methods (Centre for Organic Horticulture, 2011; Larimer County Weed District, 2011). Biological control may be defined as the use of living agents to suppress vigor and spread of weeds. Such agents can be insects, bacteria, fungi, or grazing animals such as sheep, goats, cattle or horses, and consequently, biological control always implies an interaction of weed plants with organisms from another trophic level. Chemical control includes the use of herbicides to suppress and kill the weeds while cultural control may be defined as the establishment of competitive and desired vegetation, which prevents or slows down invasion by weedy species and is a key component of successful weed management. Direct weed control includes methods that aim to damage and kill weeds by direct physical force, compared to indirect methods which indirectly influence the weed floras, such as the choice of crop rotation or crops. Examples of mechanical methods are stubble cultivation, weed harrowing and hoeing while non-chemical methods include all control methods except herbicide use. Mechanical and thermal technologies are included in physical methods while the term 'preventive method' usually is employed when trying to stop weed infestation from the neighborhood to newly disturbed ground.

Bond & Grundy (2001) describe two types of methods: cultural methods (including pre-crop and post-harvest soil cultivation, crop rotation, crop cultivar choice, crop establishment, and limiting the introduction and spread of weeds) and direct control methods (mechanical control, thermal control, mulching, biological control).

Hatcher & Melander (2003) separate weed control methods into physical, cultural and biological weed control, where physical control includes mechanical methods (weed harrowing and hoeing) and thermal methods like flaming. Cultural control includes for

example intercropping, weed cutting and mowing, and biological methods include the use of biocontrol agents like insects, fungi, and bacteria.
Below we have chosen to describe weed control methods in two major groups: cultural methods and physical weed control methods.

3.1 Cultural methods

Cultural methods aim at establishing a strong and competitive crop and thereby reducing the ability for the weed flora to grow and develop in the field.

3.1.1 Weed – crop competition

Competition is an interaction between plants which require the same limited resources like nutrients, water and light. Harper (1977) defines competition as ’An interaction between individuals brought about by a shared requirement for a resource in limited supply and leading to a reduction in the survivorship, growth and/or reproduction of the individuals concerned’, and thereby points to the effects of competition. The aim of weed control is to ensure that as much resources as possible are accessible for the crop and not for the weeds and to reduce or delay growth and development of the weed flora. This is a valid short term goal, but also a long term goal, achieved by a reduction in replenishment of the weed seed bank, and avoidance of further seed dispersal and vegetative reproduction.
To illustrate the effects of removing competitive weeds on the growth of crop plants, a greenhouse experiment was performed in Sweden 2011 (Lundkvist & Verwijst, unpublished data). Spring barley and Charlock (*Sinapis arvensi*s) were grown together in mixtures, where *Sinapis arvensi*s was considered to be the weed species and barley the crop. In each box, six crop and weed plants i.e. a total of 12 plants were sown on 15 April. As control, boxes with six and 12 barley plants were used. At 6 May, weed plants were removed from some of the boxes. The results showed that barley displayed a nearly linear increase in biomass over time, when grown together with white mustard (solid line, Fig. 1). Total dry weight of the six barley plants at 12 May was about 3.8 g, which is much lower than the total dry weight of the six and 12 barley plants of the same age grown in monocultures, having dry weights of 9.5 and >12 g, respectively. The simulated weeding, performed at 6 May by means of removing the six white mustard plants per box, caused the growth rate of the remaining barley plants to accelerate (dotted line, Fig. 1) and led to significantly higher total dry weights of the unrestricted barley plants, compared to those which were restricted by the weed. On average, the solid line displays a slope of 0.23, with 95% confidence limits of 0.184 – 0.273, while the hatched line has a slope of 0.68, with 95% confidence limits of 0.500 – 0.854. Consequently, unrestricted growth is faster compared to restricted growth, which illustrates the importance of weed removal in the field.
Relative emergence time also strongly influences the competitive outfall between crops and weeds. When crop plants emerge before the weeds, they may be able to acquire more of the limited resources available than the weed plants, which will give the crop a competitive advantage. In two outdoor box experiments in Uppsala, Sweden, in 2006 and 2007, the effects of relative emergence time were studied on spring barley and perennial sow-thistle (*Sonchus arven*sis) (Fig. 2) (Eckersten et al., 2010, 2011a, 2011b). When the crop emerged 4 days before the weed, the stand was totally dominated by the crop 2 weeks after crop emergence (90% of the total aboveground biomass consisted of crop biomass). The opposite occurred when the crop emerged 8 or 26 days later than the weed (50% and 10% of the total aboveground biomass consisted of crop biomass, respectively).

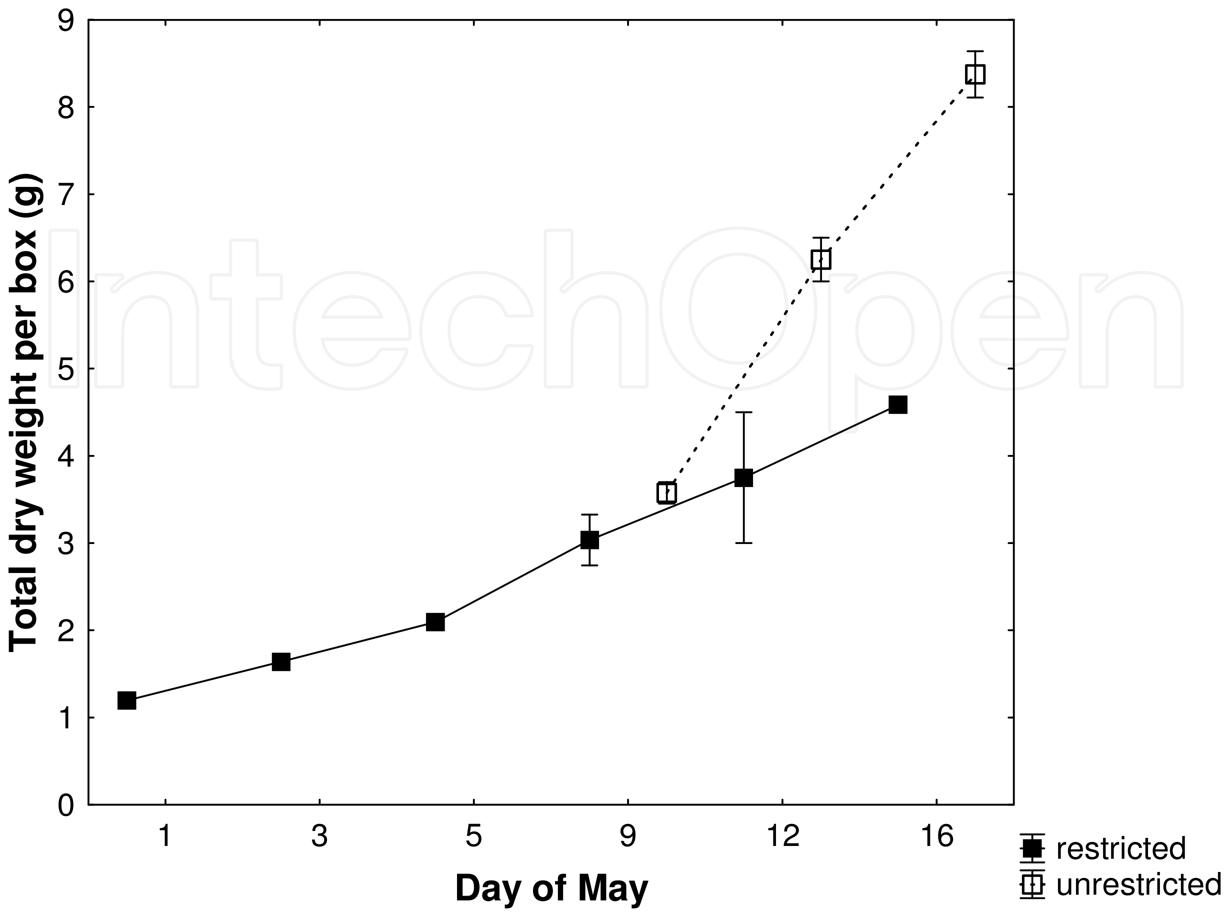

Fig. 1. Total dry weight of six barley plants per box over time. Growth was either restricted (six plants of white mustard were present over time) or unrestricted (the white mustard plants were removed on 6 May) (Lundkvist & Verwijst, unpublished data).

To assess the effects on *S. arvensis* competitive performance, its radiation and nitrogen (N) acquisition efficiencies and assimilate allocation were compared with spring barley at two N levels in the two outdoor box experiments mentioned above. First, shoot radiation use efficiency (RUE_{Shoot}) and nitrogen uptake efficiency (shoot uptake per soil mineral N per day; UPE) were estimated by calibrating a mechanistic model to above ground biomass and N observations (Eckersten et al., 2010). The RUE_{Shoot} was 44% lower whereas UPE was seven times higher in *S. arvensis,* than in barley. For *S. arvensis*, UPE was higher at the low N level than at high level, while the reverse was found for barley. Thereafter, it was tested whether the monoculture models could be applied to mixtures, assuming that intercepted radiation was partitioned between species proportional to their leaf area (Eckersten et al., 2011b). The mix-model was applicable to early stages, but underestimated shoot growth of both species grown in equal proportions, and overestimated *S. arvensis* shoot growth during late stages (415 -765 d°C after emergence). Conclusions were (i) that the growth of mixtures could be simulated as function of competition for radiation based on plant properties derived for monocultures, but needed additional modules for root/shoot biomass allocation, and (II) that the competitiveness of *S. arvensis* increased at low N supply due to a superior N acquisition efficiency compared to barley.

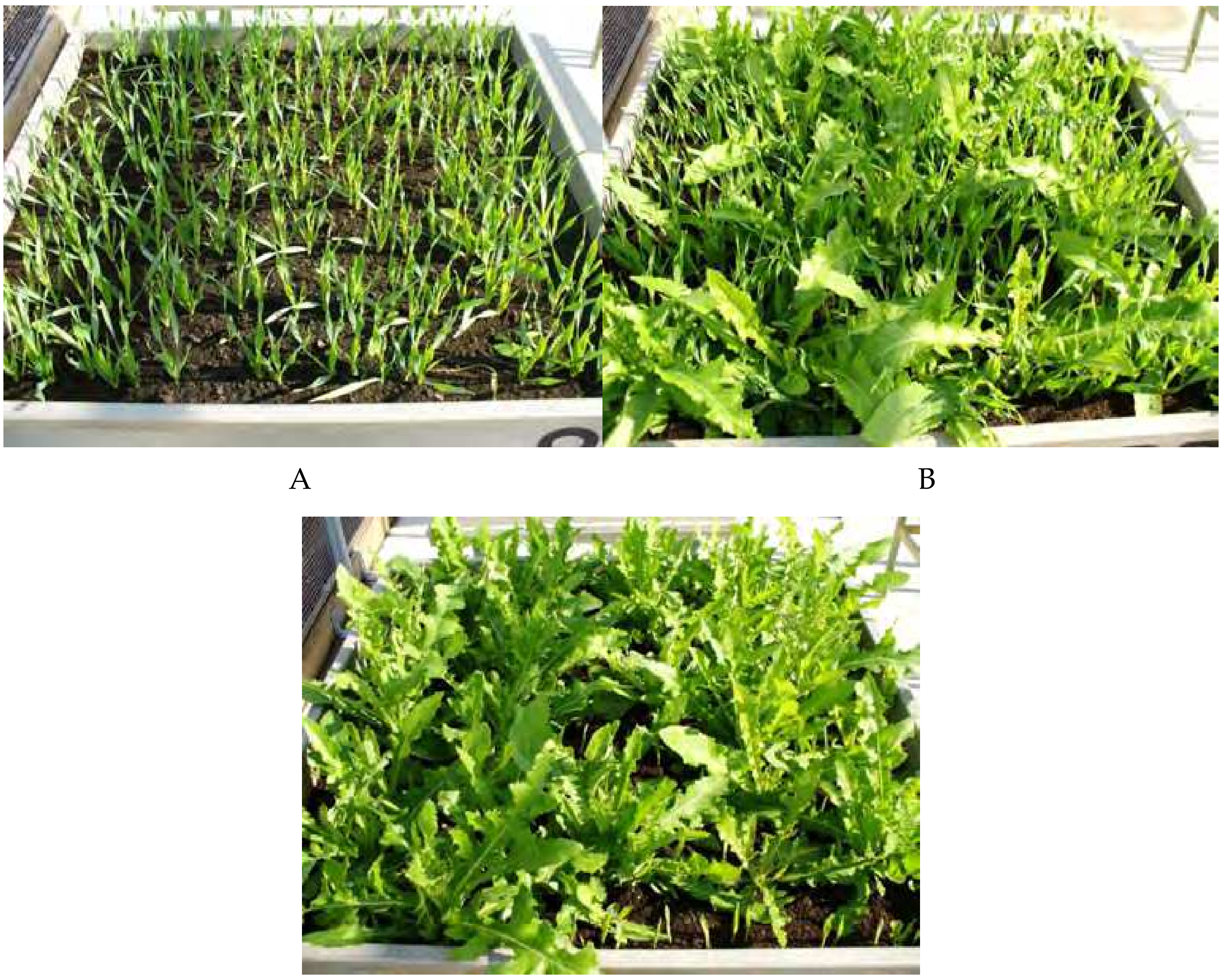

Fig. 2. Effects of relative emergence time on growth and development of spring barley (*Hordeum distichon* L.) and perennial sow-thistle (*Sonchus arvensis*). A) Spring barley emerging 4 days before *S. arvensis*, B) Spring barley emerging 8 days after *S. arvensis*, and C) Spring barley emerging 26 days after *S. arvensis*. Photo: Anneli Lundkvist, 2007.

3.1.2 Crop and cultivar choice

The choice of crops and cultivars also is an important indirect weed control method. Different crops have different competitive abilities. In annual crops, cereals are considered to have the strongest competitive ability against weeds followed by oilseed rape, peas and potatoes/vegetables (Håkansson, 2003). Lundkvist et al. (2008) showed for example that peas, a weak competitor, had significantly higher weed biomass at harvest compared with oats and winter wheat. Autumn-sown cereals and oilseed rape also seem to have a stronger weed suppressing ability compared with corresponding spring-sown crops. Well established perennial leys or pastures are usually very competitive against weeds, while first year leys or pastures may be rather susceptible to weed competition. The relative competitive power is also affected by seed rate (relative plant density) and also time of sowing (relative emergence time) which affects the emergence of the crop in comparison with the weeds, see section 3.1.1.

Crop cultivars may differ in weed suppressing ability, and which cultivar the farmer chooses may also influence the biomass production of the crop. Important plant competition parameters seem to be early vigour and season growth, straw length, leaf area index, and rate of root system establishment (Drews et al., 2009; Olesen et al., 2004; Cousens et al., 2003; Gibson et al., 2003). Bertholdsson (2011) reported that the weed suppressing ability in wheat varieties depended mainly on early season crop growth and allelopathy, see section 3.1.4.

3.1.3 Crop rotations

The choice of crop rotation strongly affects the abundance and diversity of the weed flora (Bond & Grundy, 2001). Since different crops favour different types of weed species, it is important to change between annual and perennial crops in the crop rotation. Autumn- and spring-sown annual crops also favour different types of weed species, which makes it important to rotate between such crops within a crop rotation.

An example of organic crop rotations, well adapted to the farm situation, was reported by Lundkvist et al. (2008). To study the effects of organic farming on weed population development and crop yields, two different crop rotations were designed. One rotation was adapted for animals, containing perennial ley (six fields), and one without animals, including green manure (six fields) on an organic farm established in Central Sweden in 1987. Each field contained a fixed 1 m^2 reference plot in which all the weed observations were done each year. During the period 1988-2002, number of weed plants in spring and weed biomass at harvest were recorded in the reference plots. No differences in these two parameters were observed between the crop rotations. Number of weed plants in spring did not differ between annual crops and did not increase over the 15-year period. Neither did weed biomass at harvest nor weed species diversity change over the 15 years. The two crop rotations kept weed pressure at the same level as under the previous conventional farming practice. General observations in the field suggested that invasion of *Cirsium arvense* was occurring along the field borders. Competitive ability of the crops showed to be important in weed regulation. They concluded that to improve weed management in organic farming, advisors and farmers should recognize the importance of individual field and farm analyses to design location-specific, farm-adapted crop rotations.

To study the effects of different crop rotations on the performance of the perennial weeds *S. arvensis* and *C. arvense,* a field experimental study was performed in Central Sweden (Lundkvist et al., 2011b). The overall hypothesis was that biomass production of the two weed species would decrease with competition from a crop. The development of *S. arvensis* and *C. arvense* under crop competition was assessed during 2005-2009 by means of two field experiments, which each included five crop rotations (two rotations with annual crops only, and three with a sequence of both annual crops and perennial grass-clover ley), and two cultivation techniques. Statistical analyses showed that at the end of the crop rotations with perennial leys, the weeds were effectively suppressed (71-98%, P=0.001) and the cereal yields were higher (51-70%, P=0.001) compared with crop rotations with annual crops only (Fig. 3). The results showed that the weeds can be controlled effectively under Nordic conditions by using crop rotations including competitive perennial ley crops.

A B

Fig. 3. Occurrence of the perennial weed species *Sonchus arvensis* and *Cirsium arvense* in two different crop rotations in central Sweden 2005-2009. A) Crop rotation with annual crops only, showing a high abundance of the two weed species. B) Crop rotation including both annual crops and perennial leys, with low abundance of the two perennial weeds. Photo: Anneli Lundkvist, 2009.

3.1.4 Allelopathy

Rice (1984) defined allelopathy as the effect(s) of one plant on other plants through the release of chemical compounds in the environment, and this definition is largely accepted and includes both positive (growth promoting) and negative (growth inhibiting) effects. Muller (1969) and Olofsdotter et al. (2002) considered allelopathy as the effect of chemical interactions between plants and described competition as the removal of shared resources. Studies with the aim to find crop cultivars containing allelopathic compounds for improving weed suppressing ability have been performed and are ongoing (Olofsdotter et al., 2002; Bertholdsson, 2011) but thus far, the uptake of allelopathic traits in breeding programs has been slow and no typical allelopathic crop cultivars are available on the market at the moment (Kruse et al., 2000).

3.1.5 Biological control

Biological control methods aim at suppressing growth and development of weeds by using living agents like insects, bacteria, or fungi. Grazing animals like sheep, goats, cattle or horses may also be looked upon as 'tools' for biological weed control. Natural enemies may be used to reduce the abundance of certain weed species. Many studies have for example been performed with regard to the control of *C. arvense* with rust pathogens (Guske et al., 2004; Müller et al., 2011). To be successful in the long term, small numbers of the weed host must always be present to assure the survival of the natural enemy. One of the most successful examples of biological weed control is the control of St. Johnswort (*Hypericum perforatum* L.) on rangeland in the USA and Canada, by means of the leaf beetle *Chrysolina hyperici* Forster (Harris et al., 1969). Morrison et al. (1998) showed that part of this success may be attributed to the fungus *Colletotrichum gloeosporioides* Penz., which is transferred by the leaf beetle. Thus far, few weed species can be controlled effectively by weed species specific pathogens, but there are good opportunities for classical biological control of weeds to be developed for Europe as well (Sheppard et al., 2006).

3.2 Physical weed control methods

Physical weed control aims at directly suppressing/removing weed plants in the field to enhance the competitiveness of the crop. Physical control methods include both mechanical and thermal weed management. Regarding mechanical weed control, weeds are affected by tillage and soil cultivation in different ways: i) growing weeds and perennating organs are uprooted, dismembered, and buried, ii) the soil environment becomes changed in such a way that germination and establishment of weeds is promoted, and iii) weed seeds are moved vertically and horizontally which will affect the emergence, survival and competition of the weeds (Mohler, 2001). In Table 2, weed control effects of different physical control methods are summarized and below, the weed management methods are briefly discussed.

Implement	Positive weed control effect	Negative weed control effect
Plough	Disrupts growth and seed production. Buries seeds produced this year and buries perennial weeds and their below ground root/stem systems.	Weed seeds from the seed bank are moved up to the soil surface.
Cultivator/Disc cultivator	Disrupts weed growth and seed production. Buries seeds produced this year and buries /fragments perennial weeds and their underground root/stem systems.	May stimulate shoot development from below ground root/stem systems of perennial weeds.
Harrow	Destroys/kills small weed plants. Fragmenting root/stem parts of perennial weeds near the soil surface.	Stimulates weed seed germination. May spread viable root/stem parts of perennial weeds.
Roller	Improves germination conditions for the crop.	Improves germination conditions for the weed seeds.
Weed harrow	Covers small weed plants with soil and/or uproots them.	Stimulates weed seed germination. May more or less damage the crop.
Inter-row cultivator	Covers small weed plants with soil, uproots them or cuts them off.	May damage the crop.
Brush weeder	Covers small weed plants with soil or uproots them.	May damage the crop.
Weed mower	Cuts of weeds in growing crops.	If used after stem elongation, the crop will be damaged.

Table 2. Weed control effects of different types of tillage implements (after Lundkvist & Fogelfors, 2004).

3.2.1 Stubble cultivation

Stubble cultivation gives good control effects against perennial weeds by fragmenting their root systems (Håkansson, 2003) (Table 2). Development of new shoots is then triggered, which may deplete the carbohydrate stores of roots and rhizomes. Annual weeds also are controlled by stubble cultivation, causing disruption of their growth and seed setting. In Sweden, stubble cultivation is usually performed in the autumn after harvest, by using cultivators/disc cultivators, and the soil is often cultivated down to 10-15 cm (Lundkvist & Fogelfors, 2004).

To simulate different intensities of stubble cultivation and to assess the effects of different intensities of root fragmentation (5, 10 and 20 cm) on *Sonchus arvensis* on sprouting and shoot development, an outdoor box experiment was performed in Sweden in 2008 (Anbari et al., 2011). Shoot emergence time, shoot numbers, rosette size, and flower production were quantified as functions of root length and weight. Emergence of the first shoot per root and of later cohorts was delayed with decreasing root length and weight (Fig. 4). Number of shoots per root increased with root length and weight, but per unit root length and weight, short roots produced more shoots. The first emerging rosettes were, for rosettes of a given age, larger for longer roots, and total rosette area per root five weeks after planting increased with increasing root length and weight. The number of flowers and production of mature seeds were positively related to root length and weight, due to delayed sprouting of

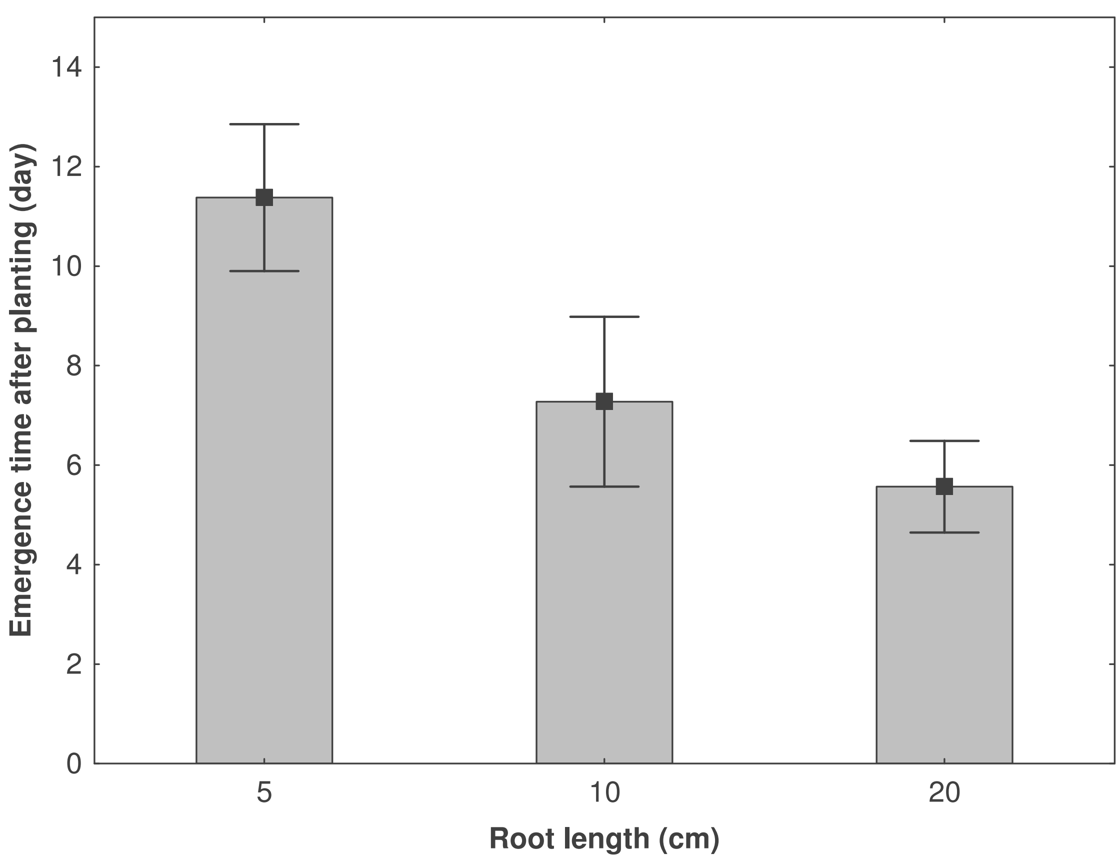

Fig. 4. Emergence time after planting (days) of the first shoot from *S. arvensis* roots of three length classes (5, 10, and 20 cm). Whiskers indicate 95% confidence interval (Anbari et al., 2011).

short and light roots. The proportion of flowers leading to mature seeds declined with shoot emergence time. By clarifying relationships between root size and growth parameters, this study showed that fractionating of *S. arvensis* roots delayed phenological development and hampered reproduction by seeds. The information may be used to refine mechanical weed control strategies for *S. arvensis*.

When farmers have large problems with perennial weeds in a field, fallow may be an interesting weed control method. During the fallow period, no crop is cultivated and soil cultivation is performed regularly. Fallow may be used during the whole growing season or parts of the season, combined with a crop grown before or after the fallow. Lundkvist et al. (2011b) studied the effects of short fallow on the performance of *S. arvensis* by means of field trials in Central Sweden. The overall hypothesis was that biomass production of *S. arvensis* would decrease with competition from a crop and with mechanical disturbance. To study the effects of short fallow in the spring, combined with competition of green manure crops, three field experiments were performed during 2005-2007, using short fallow techniques together with summer fallow and three green manure crops. Statistical analyses were done by ANOVA and comparisons were made by Student *t*-test. In the short fallow experiments the amount of *S. arvensis* was lower (75-93%; P=0.001) and the crop yields were higher (47-145%, P=0.001) in plots during the year after employment of short fallow together with green manure, compared with the control plots. Summer fallow was the most efficient method, followed by a combination of spring ploughing and disc harrowing. The results showed that *S. arvensis* can be controlled effectively under Nordic conditions by using short fallow.

3.2.2 Ploughing

Ploughing controls both annual and perennial weeds effectively (Table 2) (Lundkvist & Fogelfors, 2004). Perennial weed roots and/or belowground stem parts are cut off and buried in the soil. Since the plant parts are buried rather deep, shoots developing from those roots/stems usually have problems reaching the soil surface. Also annual weeds are efficiently controlled since the plants are buried in the soil, thereby interrupting their seed production. However, weed seeds from the seed bank will be moved up to the soil surface, and may eventually germinate and develop into new weed plants.

Early ploughing in the autumn is effective against annual weeds with late maturing seeds, and also against perennial weeds, since it stops their carbon assimilation and allocation of resources from shoots to storage organs. Late ploughing favours both perennial and annual weeds. Spring ploughing (which is often used on soils containing silt or fine sand) is also effective against perennial weeds like *C. arvense*.

3.2.3 Harrowing and seed bed preparation

In autumn, harrowing and seed bed preparation stimulate winter annual weed seeds to germinate while they stimulate both winter and summer annuals to germinate in spring (Table 2) (Håkansson, 2003). However, at the same time, weed plants that germinated early in the spring may be killed during sowing. During seed bed preparation, one aim is to avoid germination of weed seeds. Therefore, preparing a proper seed-bed implies killing of already emerged weeds, while applying as little soil cultivation as possible. Thereafter, sowing should take place as soon as possible to obtain an early crop establishment, thereby giving the crop and competitive advantage over the weeds.

3.2.4 Weed harrowing

The purpose of weed harrowing is to give crops a competitive advantage over weeds (Melander & Hartwig, 1995). Weed harrowing covers weeds and can kill weeds by uprooting them (Habel, 1954; Kees, 1962; Koch, 1964; Kurstjens & Kropff, 2001; Kurstjens et al., 2004). During harrowing, crop plants are sometimes covered with soil but often to a lesser extent than the weeds, and the crop usually recovers more quickly and out-grows the weeds before they have recovered from the harrowing (Bond & Grundy, 2001). Smaller weeds are easier to control via harrowing. Under favourable conditions, weed harrowing may provide similar efficacy as herbicides but usually the control effects from harrowing are lower than those which can be achieved with chemical control. Efficacy of harrowing depends on many factors including crop species and weeds present, the development stages of crop and weeds, weather, soil type and harrow type (Cirujeda et al., 2003; Hansen et al., 2007; Jensen et al., 2004; Rydberg, 1994). Weed harrowing may be divided into two categories; pre-emergence harrowing, and post-emergence harrowing. Pre-emergence harrowing (pre-wh) occurs after the crop is sown but before it emerges. This can be an effective control for early emerging weeds (Koch, 1959; Melander & Hartwig, 1995; Rasmussen, 1996) like *Sinapis arvensis*, *Galeopsis* spp., *Raphanus raphanistrum* L., and volunteers including *Brassica napus* L. Pre-wh may stimulate the germination of some weed species which can increase weed pressure (Kees, 1962). Post-emergence harrowing (post-wh) occurs after the crop has emerged and is challenging because both weeds and crop may be damaged by the harrow (Rasmussen et al., 2008) and the most sensitive development stage for mechanical disturbance often coincides for both the crop and the weeds.

A B

Fig. 5. The weed control effect of pre-emergence weed harrowing four days after sowing against *Sinapis arvensis* (B) in peas in 2003 compared with the control plot (A) where no weed harrowing was performed (Lundkvist, 2009).

Given the increasing need for harrowing as a means of weed control and the lack of information on the effectiveness of the many combinations of pre-wh and post-wh treatments that are possible, particularly with respect to field sites in far northern Europe, a project was initiated to study the effects of different combinations of weed harrowing before and after crop emergence on weed control in field sites in Sweden (Lundkvist, 2009). The major hypotheses were (i) that combinations comprising both pre-wh and post-wh provide better weed control effect against annual weed infestations than treatments containing only pre-emergence harrowing, and (ii) that pre-emergence harrowing alone or in combination with post-emergence harrowing provides better control of early emerging weed species versus post-emergence harrowing alone. The results showed that a pre-emergence weed harrowing treatment alone or combined with weed harrowing shortly after crop emergence in peas and spring cereals is most effective against the early emerging weed species *S. arvensis* and *Galeopsis* spp. Post-emergence harrowing alone usually has low control effect on *S. arvensis* (Fig. 5, Table 3). The late emerging annual weed species *C. album* and *Polygonum lapathifolium* were most effectively controlled when pre-emergence weed harrowing was combined with one or two weed harrowing treatments after crop emergence. The best weed control was obtained by a combination of pre- and post-emergence harrowing, but these treatments also caused yield losses of 12-14% in spring cereals, while no yield losses were observed in peas (Lundkvist, 2009).

Treatment	**En 2003 Peas**	**En 2004 Peas**	**Ua 2003 Peas**	**Ua 2004 Peas**
Control (no weed harrowing)	120 (20)^{a}	747 (55)^{a}	133 (24)^{a}	158 (37)^{ab}
Early pre-wh (2-4 days after sowing)	21 (8)^{b}	656 (65)^{ab}	110 (35)^{a}	151 (18)^{abc}
Late pre-wh (6-8 days after sowing)	-	613 (257)^{b}	135 (24)^{a}	181 (22)^{ab}
Early + late pre-whs	-	571 (114)^{b}	137 (33)^{a}	184 (28)^{ab}
Early pre-wh + post-wh at crop growth stage DC 12-13	13 (1)^{bc}	607 (67)^{b}	59 (14)^{b}	115 (26)^{abc}
Late pre-wh + post-wh at crop growth stage DC 12-13	-	556 (60)^{b}	33 (6)^{bc}	93 (31)^{c}
Early pre-wh + post-whs, at crop growth stages DC 12-13 & DC 15-16	10 (1)^{c}	304 (101)^{c}	13 (3)^{cd}	-
Late pre-wh + post-whs, at crop growth stages DC 12-13 & DC 15-16	-	320 (141)^{c}	7 (3)^{d}	-
Post-wh at crop growth stage DC 12-13[1)]	100 (1)^{a}			
Post-wh at crop growth stage DC 15-16[1)]	120 (1)^{a}			
Post-whs at crop growth stages DC 12-13 & DC 15-16 [1)]	100 (1)^{a}			

Table 3. Total number of weed plants (m^{-2}) in the 4 field experiments with peas treated with different combinations of pre- (pre-wh) and post-weed harrowing (post-wh) at Enköping (En) and at Uppsala (Ua) in 2003-2004 (Lundkvist, 2009). Values indicate mean (SE) with n = 3. Mean in the same column with different superscript letters are significantly different (P < 0.05). [1)] Post-wh, without pre-wh, was performed in one experiment (En 2003, peas). (-) treatment not performed in the experiment.

3.2.5 Inter-row cultivators

Inter-row cultivators are designed to control weeds between the crop rows to a depth of 5-10 cm through soil coverage, uprooting or root cutting (see for example Mohler, 2001;

Melander et al., 2005). The method is most efficient against annual weeds but may also give some control effects on perennial weeds with a rather shallow underground root/stem system. Inter-row cultivation is usually carried out in row crops (i.e. crops like sugar beet, potatoes and maize grown with relatively large row spacing) but also used in small grain crops like cereals sown with a row spacing of 20-30 cm in organic farming.

To study the control effects of inter-row cultivation on *Sonchus arvensis*, three field experiments in oats were performed in central Sweden during 2006-2007 with an inter-row cultivator. The immediate control effect was rather good which is illustrated in Fig. 6. However, at the end of the season no significant effects were obtained on either weed biomass or crop yield probably due to a rather low soil nitrogen content which favoured the efficient nitrogen absorbing *S. arvensis* (Lundkvist et al., unpublished data).

A B

Fig. 6. Effects of inter-row cultivation in oats with a large abundance of *Sonchus arvensis* in spring 2006. A) Control plot, B) Inter-row cultivation performed. Photo: Kurt Hansson.

3.2.6 Mowing

Mowing is a traditional weed control method by which growth and development of the weeds are disturbed by removing parts of their above ground biomass. Mowing is used in leys, near ditches and road verges and is often a rather efficient weed control method.

When mowing is combined with competition from a well established crop, proper weed control effects may be obtained (Graglia et al., 2006; Bicksler & Mausiunas, 2009). In Sweden, a selective weed mower 'CombCut' has been developed in such a way that it is possible to cut weed plants in a growing cereal crop without damaging the crop (http://www.jcs-innovation.se/enghem.html; Lundkvist et al., 2011a). CombCut combs through the field, down in the growing crop, cutting weeds which compete with the developing crop, while leaving the crop undamaged (Fig. 7). This is a novel weed control method since it is normally not possible to perform any type of mechanical weed control in cereals after crop emergence. Selective weed mowing is based on differences between the physical properties of crop and weed plants which - given a proper mowing timing, frequency and machine settings - can be used to control weeds in a growing crop without damaging the crop. Apart from counteracting vegetative weed biomass accumulation and competition with the crop, mowing may prevent weed seed formation, thereby preventing weed seed bank replenishment, and enhances the quality of seed crops.

The effects of the weed mower on weeds and crops are currently evaluated in an ongoing research project at SLU, Sweden (Lundkvist et al., 2011a). The hypotheses are that selective weed mowing (i) decreases the ability of the weeds to compete and reproduce in a crop, (ii) decreases the long term development of the weed populations, and (iii) increases the crop yields. To test these, we performed two field experiments and two outdoor pot experiments during 2008-2010 in Sweden. In the field experiments, the effects of selective mowing on *C. arvense* and spring wheat were determined by mowing at two different development stages of *C. arvense*. In pot experiment 1, effects of mowing two years in a sequence on *C. arvense* and spring barley were studied. In pot experiment 2, effects of different machine settings on spring barley were evaluated. Statistical analyses were done by ANOVA and comparisons were made by Student *t*-test. Preliminary results from the pot experiment 1 showed that growth of *C. arvense* was significantly reduced after mowing two years in a sequence (38-49%, P=0.001) compared with the control (Fig 8). When competition from spring barley was added, the reduction was even higher (66-79%, P=0.001). Also crop yields were significantly higher after mowing (76-94%, P=0.03) compared with the control (Fig 9). Machine settings had strong effects on the crop. A more aggressive setting caused stronger damage to the crop at later development stages. In the field experiments, no significant effects were obtained with regard to the crop yield due to large amounts of *C. arvense*. The results showed that selective mowing combined with crop competition seem to decrease the abundance of *C. arvense*.

Fig. 7. Weed mower CombCut (upper left and right). Close up pictures of the brush reel (lower left) and the knives (lower right). Photo: Jonas Carlsson, JustCommonSence AB.

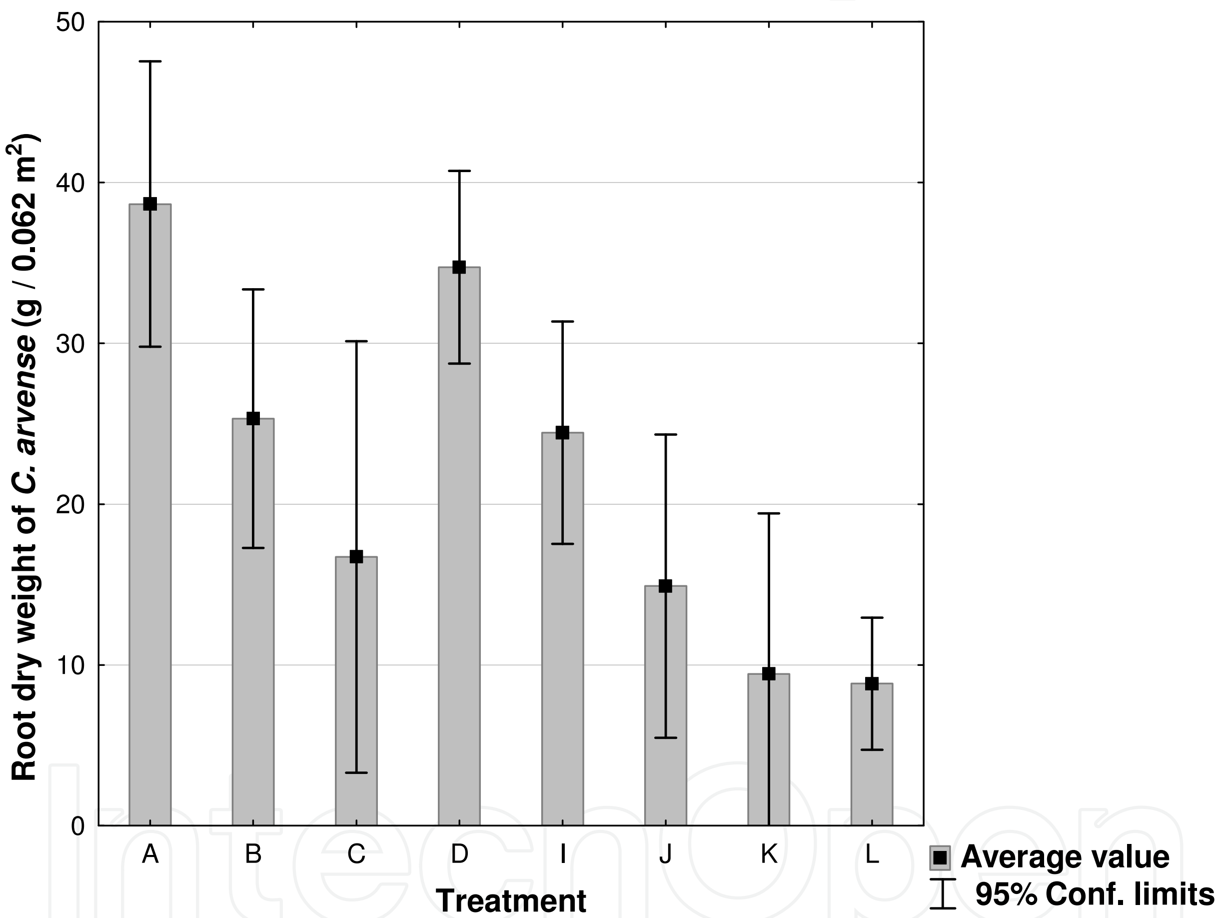

Fig. 8. Long term effects of selective mowing on *C. arvense* in pot experiment 1 in 2009

Root production of the weed (g/pot) in pots with *C. arvense* alone (A-D), and grown with spring barley (I-L). A, I = no mowing; B, J = early mowing; C, K = late mowing; D, L = early + late mowing; (Lundkvist et al. 2010).

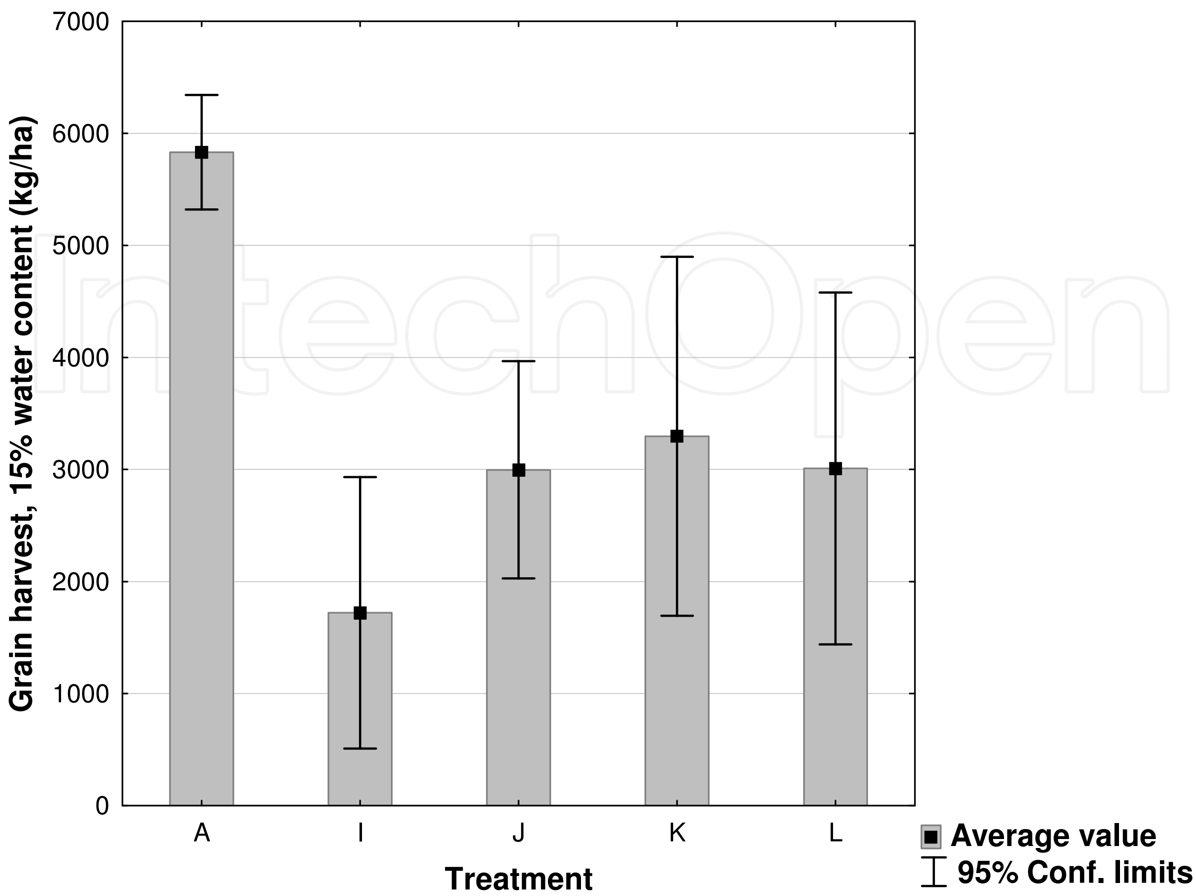

Fig. 9. Spring barley yield in pot experiment 1 in 2009.

A = spring barley, (without *C. arvense*), I = *C. arvense* + spring barley, no mowing, J = *C. arvense* + spring barley, early mowing, K = *C. arvense* + spring barley, late mowing, and L = *C. arvense* + spring barley, two mowings (Lundkvist et al., 2010).

3.2.7 Brush weeding

Brush weeding is used for controlling annual weeds through uprooting between and rather near the crop rows by using rotating brushes (see for example Mohler, 2001; Melander, 1997). This weed control method is mainly developed for post-emergence use in high-value vegetable crops, and further applications are restricted because of its low working capacity (Melander et al., 2005).

3.2.8 Ridging (potatoes and other row crops)

A ridger is a type of plough used to form ridges for covering the below ground parts of potatoes or other row crops, thereby protecting tubers from radiation and avoid greening. Ridging also works as a control method for annual weeds but also to some extent for perennial weed species by soil covering and/or up-rooting. The best control effect is obtained when the weeds are small, i.e. before they develop true leaves.

3.2.9 Flaming

When using flaming, weeds are briefly exposed to a propane or butane flame at 800-1000°C. The cell membranes are then disrupted and dehydration is rapidly occurring (Ascard 1995;

Ellwanger et al., 1973). This weed control method has a low working capacity and is mainly used against annual weeds before crop emergence in row crops such as onions, carrots, and sugar beets. Flaming may also be used after crop emergence (so-called selective flaming) when the crop plants have a protected terminal bud, like for example in cabbage (Holmøj & Netland, 1994).

4. Weed management strategies under climate change

A changing environment (either directional or with regard to parameter amplitudes) puts a selective pressure on plant species, and weeds are likely to be faster in adapting to changing environmental conditions represented by climate change than crops (e.g. Franks et al., 2007), due to their broader genetic variability. Altering crops to match changing environmental conditions is then one way to go, by means of devising appropriate crop breeding programmes which envisage climate change related to alterations of the environment. The geographic range of plant species is constrained by climatic limits, and changes in climate consequently will lead to alterations in the geographic distributions of weed species. For the temperate part of Europe, for example, a rise in temperature is favouring species from the Mediterranean region (Walther et al., 2002), and consequently, efforts have to be made to control invasive species (Sheppard et al., 2006). Ziska & Dukes (2011) recently published a book under the title "Weed biology and climate change" in which the major focus is on direct effects of elevated CO_2-levels on weed performance. Such effects have been proven to exist and have been quantified, including their interactions with plant water use and nitrogen uptake (e.g. Cotrufo et al., 1998; Poorter et al., 1996), However, from an agronomic point of view, not the direct effects of CO_2 on plant performance, but the globally changing precipitation and temperature patterns are the main causes of huge yield losses, and of changes in crop production systems and weed species distribution patterns.

While climate change already has been causing a number of catastrophic crop failures in many places of the world, the effects of a changing climate on crop production are expected to be less severe in the Northern parts of Europe. A significant climate warming is already occurring in Sweden (SMHI, 2006), and evaluation of existing climate scenarios (Eckersten et al., 2008) showed that a raise in air temperature by 4°C might be attained by the end of this century for the southern and middle parts of Sweden, and that an increase in growing season length is likely to occur due to an earlier temperature rise during spring. The actually monitored and for the future envisaged temperature rise will provide an enlarged time period to control annual and perennial weeds prior to sowing crops. A longer and warmer growing season also will lead to opportunities to grow other crops, including some that are commonly grown in rows. One such example is maize, of which the cultivation area in Sweden was increased with one order of magnitude only during the last decade. Due to shorter winters and longer vegetation periods, an increase of autumn sown crops also is envisaged in the Nordic countries. As outlined in section 2, specific cropping systems go along with a fairly specific weed flora, and consequently, choosing cropping systems in accordance with an increasing length of the vegetation period will bring about changes in the weed flora on the long run, favouring annual winter weeds in the Nordic situation. Frost-intolerant weed species may also be expected to shift their ranges further northwards with milder seasons, while milder seasons also provide opportunities for growing crops which under harsher conditions would be damaged.

In the context of climate change, the differences in photosynthetic pathways displayed by C_3 and C_4 plants may affect the competitive outcome between C_3 crops and C_4 weeds. An overall increase in atmospheric CO_2 would favour the C_3 crop over the C_4 weed, while an increasing temperature or reduced water availability would favour the C_4 weed. However, at Nordic latitudes, the growing season is characterised by long days, while most C_4 plants are short-day plants. This means that C_4 weeds will only flower if exposed to less than 12 hours of light per day, and consequently, are not likely to reproduce vigorously in a Nordic environment.

5. Conclusion

There are no simple standard solutions available for weed control in organic agriculture. While a conventional farmer may rely on herbicides, which can be applied with short notice to cure a field from an ongoing weed infestation, the organic farmer needs to take a long-term perspective while taking preventive measures to avoid yield losses. Direct and cultural methods need to be integrated in organic farming, with the long term goal to prevent the occurrence of weed-induced yield losses, while keeping down costs for weed control.

As certain crops do favour specific weed species, it is important to implement a crop rotation which suppresses the weed populations that have been expanding during a former cropping season. A proper crop rotation adapted to the actual farm situation is the core of organic farming. Early identification of an upcoming weed problem is necessary, and a wide range of control measures may be combined to keep weed populations at an acceptable level. Whatever crop is employed, soil bed preparation and management should be directed towards a rapid establishment and a maximum competitive ability of the particular crop under cultivation. Direct control measures need to be employed against weeds as early as possible, to prevent weeds from competing with a crop, but also in a later phase, to prevent weeds from replenishing the seed bank. Perennial weeds preferably should be prevented from establishment, but if they occur in fields, revising a planned crop rotation by, for example, employing a perennial ley, may contribute to a long-term solution.

Ongoing climate change in Nordic countries not only poses a threat to organic farming by means of favouring new and possibly invasive weeds. It also provides opportunities for prolonged weed control and use of new crops. Given the ongoing extension of the knowledge base for organic farming, the growing commitment of farmers devoted to organic farming, and national and European policies with clearly defined environmental goals, organic farming in the Nordic countries is well provided to meet its future challenges.

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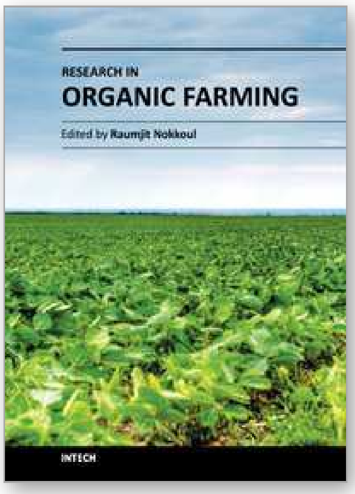

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This book has emerged as a consequence of the difficulties we experienced in finding information when we first started researching. The goal was to produce a book where as many existing studies as possible could be presented in a single volume, making it easy for the reader to compare methods, results and conclusions. As a result, studies from countries such as Thailand, Spain, Sweden, Lithuania, Czech, Mexico, etc. have been brought together as individual chapters, and references to studies from other countries have been included in the overview chapters where possible. We believe that this opportunity to compare results from different countries will open a new perspective on the subject, allowing the typical characteristics of Organic Agriculture and Organic Food to be seen more clearly. Finally, we would like to thank the contributing authors and the staff at InTech for their efforts and cooperation during the course of publication. I sincerely hope that this book will help researchers and students all over the world to reach new results in the field of Organic Agriculture and Organic Food.

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