Mechanisms of selective mechanical weed control by harrowing

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Abstract

Current weed control problems in organic farming and minor crops show that alternatives for selective herbicides need further development. Mechanical control methods such as weed harrowing are attractive because of the high capacity, wide applicability and low cost. However, the variable effectiveness and limited selectivity at early crop growth stages are major limitations for reliable weed control. In contrast to herbicides, there is little fundamental knowledge of processes and factors that influence selectivity and effectiveness of mechanical weeding. To provide a more basic understanding, the uprooting, covering and regrowth of three model plant species were studied in detailed laboratory harrowing experiments on sandy soil.

Uprooting appeared to contribute much more to weeding effectiveness than is commonly assumed. Although harrowing predominantly covered plants, covering killed few. In contrast, on average 47-61% of the uprooted plants were killed after six days without irrigation. Drier soil (5% as compared to 16% w/w) increased mortality of uprooted plants from 36 to 91%.

Soil moisture content greatly affected uprooting and covering selectivity. Covering selectivity could be manipulated by working depth and working speed, thus exploiting differences in plant flexibility and height between weeds and crop. Uprooting selectivity could be improved by precise working depth control and by precisely steering the tines along the crop rows. Small-scale spatial patterns and within-population variability of plant sensitivity proved to be very important.

This study indicated several opportunities for improving field experiment methodology and for modelling the efficacy and selectivity of mechanical weeding. A method to predict the relationship between crop and weed uprooting from measured plant anchorage forces was developed. This method could be used to quantify the selective potential of a crop–weed situation and the selective ability of harrowing independent of harrowing intensity.

Keywords: weed harrowing, mechanical weed control, selectivity, biomechanics, uprooting, soil-covering, recovery, plant damage, methodology

Contents

Account

Chapters 5 and 6 include references to published papers that are included as chapters in this thesis:

Chapter 3	Kurstjens & Perdok (2000)	*Soil & Tillage Research* **55**, 193-206
Chapter 4	Kurstjens *et al*. (2000)	*Weed Research* **40**, 431-447
Chapter 6	Kurstjens & Kropff (2001)	*Weed Research* **41**, 211-228

1 General introduction

1.1 Weed management

Weed management is an important aspect of soil-related crop production. Each cropping system requires a combination of weed prevention and weed control measures to prevent excessive loss of yield quantity and quality, and to stabilise the weed population at a sufficiently low level in the long term. In the course of the cropping cycle, several measures can be taken that act on different stages in the life cycle of weeds, such as:

- Manipulating the timing and amount of weed emergence relative to the sensitive stage of the crop by e.g. false or stale seedbeds (Shaw, 1996; Bleeker & van der Weide, 2000; Johnson & Mullinix, 2000), photocontrol (Hartmann & Nezadal, 1990; Ascard, 1994; Fogelberg, 1998), transplanting instead of sowing (Kouwenhoven *et al*., 1991), time of planting and seeding (Fernholz, 1990; Buhler & Gunsolus, 1996).
- Killing or damaging weed plants by e.g. herbicides, mechanical control, flaming (Ascard, 1995; Bertram, 1996), biological control (Cardina, 1995).
- Reducing weed growth and weed seed production by competition (Berkowitz, 1988; Kropff & van Laar, 1993) of e.g. intercrops (Liebman, 1988; Baumann, 2000), availability of nutrients (Fernholz, 1990; van Delden, 2001), soil cover and mulches (Calkins *et al*., 1996), competitive crop cultivars (Richards & Whytock, 1993; Jordan, 1993; Cosser *et al*., 1997; Froud-Williams, 1997), seeding density and row spacing (Malik *et al*., 1993; Roberts *et al*., 2001).
- Increasing weed seed mortality (Medd & Ridings, 1990), decreasing seed viability and disrupting rhizomes of perennial weeds in deeper layers by e.g. tillage (Lueschen *et al*., 1993), compost, cover crop and green manure (Gallandt *et al*., 1999), solarisation (Braun *et al*., 1986), allelopathy (Putnam, 1988).

Some methods can only be used when no crop is growing on the field (e.g. ploughing), whereas others can be used to control weeds between sowing and harvesting the crop. Of the latter methods, non-selective methods aim to control all plants in the treated area (e.g. hoeing between crop rows). Selective methods such as weed harrowing and many herbicides utilise a difference in sensitivity between crop and weed plants and can therefore control intra-row weeds as well. With herbicides, this difference in sensitivity is based on a different deposition, absorbtion, translocation and/or metabolism of the active chemical ingredient in the plant and genetic resistance and tolerance (Harrison & Loux, 1995). Similarly, the selective action of mechanical weeders such as torsion weeders, finger weeders and weed harrows is, amongst others, in some way related to mechanical, morphological and physiological differences between crop and weed plants.

1.2 Agronomic and societal context

In most farming systems, particularly the selective weed control methods fulfil a crucial role. This can be illustrated by the present fact that most organic farmers face problems with the high cost and limited availability of labour for hand weeding, due to a lack of sufficiently selective non-chemical techniques to control intra-row weeds (Schotveld & Kloen, 1996; Geven, 1999; Lokhorst, 2000). Since herbicides were introduced after World War II, formulations have been improved so that the selectivity of herbicides exceeded that of the prevailing mechanical methods. The availability of a wide range of selective herbicides, able to effectively control a wide range of weeds in various crops, has allowed the farmers to rely less on alternative methods. Moreover, herbicides can be applied with high capacity spraying machines. The number of required applications and the weather dependence (regarding effectiveness and timeliness) are generally lower than with mechanical weed control techniques (Wossink *et al*., 1997). Although herbicide efficacy is significantly influenced by weather conditions as well (Collings *et al*., 2001; Green & Strek, 2001; Köcher, 2001; Kudsk, 2001), chemical methods are generally perceived as more convenient, more reliable and cheaper than mechanical methods (U.S. Department of Agriculture, 1990 cited by Olson & Eidman, 1991; Wossink *et al*., 1997; Jensen & Petersen, 2001; but opposed by Bender, 1990). Herbicides have facilitated the development of large, highly mechanised, labour-extensive farms. It is therefore not strange that the potential of alternative methods, their technical implementation and their integration in farming systems have only partly been explored.

Nevertheless, a number of developments in the last decade have increased the pressure on farmers to reduce the use of and dependence on herbicides. Public concern about food safety and soil and water contamination by pesticides has provoked governments to restrict pesticide use, increase the admission requirements for new pesticides and terminate the admission of many persistent and/or environmentally harmful pesticides. Consequently, the pesticide industry considers the introduction of new herbicides profitable only for major crops such as wheat, rice, maize, cotton, tobacco and soyabeans. As a result, the available number of herbicides is decreasing, especially for the minor crops (Chapman, 2001). This increases the risk of a faster buildup of a problematic herbicide-tolerant weed population (Darmency, 1996) and will eventually prohibit the production of some minor crops (Gillott, 2001; in The Netherlands a.o. sown leek, sown onions, carrots and spinach; personal communication J. Hoek, 2001), unless suitable alternative weed control methods are found. Growing herbicide tolerant crops combined with broad-spectrum herbicides has potential advantages but also endorses the risk of building up a herbicide-tolerant weed population and could make farmers more dependant on few multinational companies dominating the seed and pesticides market (Powles *et al*., 1997).

The recently developed cross compliance policy demonstrates the declining willingness of the EU to unconditionally subsidise agricultural production. For example, this policy implies that maize production is only subsidised if at least one mechanical weeding operation is performed and if herbicide use did not exceed 1 kg active ingredient per hectare (Regouin, 2000). Such policies urge farmers to use available non-chemical methods and become less dependent on herbicides (Jensen & Petersen, 2001). Because of these policies, reduced herbicide doses combined with harrowing and hoeing are widely being adopted by Dutch farmers (Huiden, 2000). Nevertheless, herbicide use in the Netherlands has declined by only 33% over the period 1984/88 to 2000 (Nefyto, 2001).

Despite the availability of several non-chemical weed control methods, most arable farmers and vegetable growers in the Netherlands and many regions of the world still rely heavily on herbicides. An increasing group of farmers would like to change their farming practise towards a more ecological and sustainable one, but face considerable problems regarding weed control when herbicides are abandoned. Therefore, alternative selective weed control techniques should be further developed to complement or replace herbicides. These techniques should be integrated in weed management systems that utilise a wider range of preventive and curative methods, tailored to the farm (crops, acreage, mechanisation level, labour availability), natural conditions (climate, soil, weed flora composition) and social-economic conditions (price and availability of farm inputs and products, government policies on herbicide use and land conservation). Because of the large scale and economic problems of arable farms, techniques should be simple, cheap and have a high capacity. In systems that allow frequent shallow soil tillage in the beginning of the cropping season, mechanical weeding can be an important component.

1.3 Mechanical weed control

Mechanical methods control weeds by physical damage, such as cutting leaves and roots, bruising stems and leaves, covering plants by soil or by uprooting them. This damage may kill plants through desiccation, light deprivation, exhaustion of stored reserves or through mechanical resistance of the soil on top of plant sprouts. If the damage is less severe or if soil and weather conditions are less stressful, plants may recover and only have a growth set-back.

As mechanical weed control acts on growing weeds (after weed germination), it is considered a curative method. Both mechanical and thermal weed control methods are often referred to as physical methods. From this point on, the term “mechanical” weed control is restricted to methods implying shallow (0-50 mm) soil tillage, applied after planting or sowing the crop until harvest. Some mechanical methods also have other functions in crop management, such as ridging, improving soil aeration, reducing evaporation and increasing nitrogen mineralisation (Rid, 1964; Bielka & Mügge, 1965; Ascard & Mattsson, 1991; van der Werf *et al*., 1991; Becker & Böhrnsen, 1994).

There is a wide range of implements available to control weeds mechanically (Bowman, 1997; Kurstjens, 1998). Some non-selective implements such as hoes, row cultivators and rotary tillers mainly have a cutting action, whereas horizontal brushes, rolling cultivators and basket weeders primarily uproot plants by loosening the soil. Many of these implements for weed control between crop rows can also control some intra-row weeds by throwing soil into the row. If the working depth of cutting tools is adequately shallow and precisely controlled, they may be operated as close as 20-30 mm from young crop plants (Ascard & Mattsson, 1991; Melander & Hartvig, 1997; Northway & Tullberg, 2000; Home *et al*., 2001). Several tools are able to kill nearly all weeds, even those in more advanced growth stages (Mattsson *et al*., 1990; Pullen & Cowell, 1997; Weber, 1997), so inter-row weed control is generally not a problem if this strip can be tilled.

However, weeds in or close to crop rows, in broadcast-seeded crops and in crops with narrow row spacings are much more difficult to control mechanically, especially in young, sensitive stages of the crop. Various tools have been designed to shallowly till the intra-row strips, such as torsion weeders (Schweizer *et al*., 1992; Ascard & Bellinder, 1996; Hallefält *et al*., 1998), finger weeders and ground-driven brush weeders (Ascard & Bellinder, 1996; Müller *et al*., 1997; Bleeker & van der Weide, 1998; Bleeker *et al*., 2000), powered vertical brush weeders (Naka, 1981; Kouwenhoven, 1997; Melander, 1997; Fogelberg, 1998), and pressurised air jets (Lütkemeyer, 2000)(Fig. 1.1). Spring tine harrows, chain harrows and rotary hoes till both the intra- and inter-row zones and don’t require accurate steering (Fig. 1.2). Although these tools engage the soil in different ways, all are in some degree selective between crop and weed plants by covering and or uprooting them to some degree. Recently developed sensor-controlled intra-row hoes (Bontsema *et al*., 1999; Kielhorn *et al*., 2000) may completely cut and remove the weed in delimited zones between the crop plants, but the working mechanism of the tool itself is not selective. This thesis only considers selective tools for mechanical weed control, especially weed harrows.

1.4 Research developments

1.4.1 Historical overview

Before weed harrows were introduced at the end of the 19^{th} century, weeds in growing crops were controlled mainly by crop rotation, tillage, horse-drawn hoes and manual weeding (Kiesselbach *et al*. (1928) cited by Wicks *et al*., 1995). As harrowing before crop emergence considerably reduced the labour requirement, this became a widely adopted practise in Europe and North America (Hunt (1904) and Campbell (1907) cited by Wicks *et al*., 1995; Exner *et al*., 1996). This was supported by specific and extensive recommendations published in agricultural journals available to farmers (e.g. Kuhn, 1930, 1932; Agena, 1933) and several empirical studies on the effect and method of harrowing, mainly in spring cereals (Bolin, 1924; Korsmo, 1926; Drottij, 1929; Canada Department of Agriculture, 1936 cited by Lafond & Kattler, 1992; Petersen, 1944).

After World War II, Kraus (1948), Habel (1954), Müllverstedt (1961), Kees (1962), Koch (1964a, 1964b) and Meyler & Rühling (1966) performed more detailed fundamental studies. The sensitivity of spring wheat, barley and various weed species to post-emergence harrowing were assessed at different growth stages. The working mechanism (uprooting and covering), the plant reaction to uprooting and

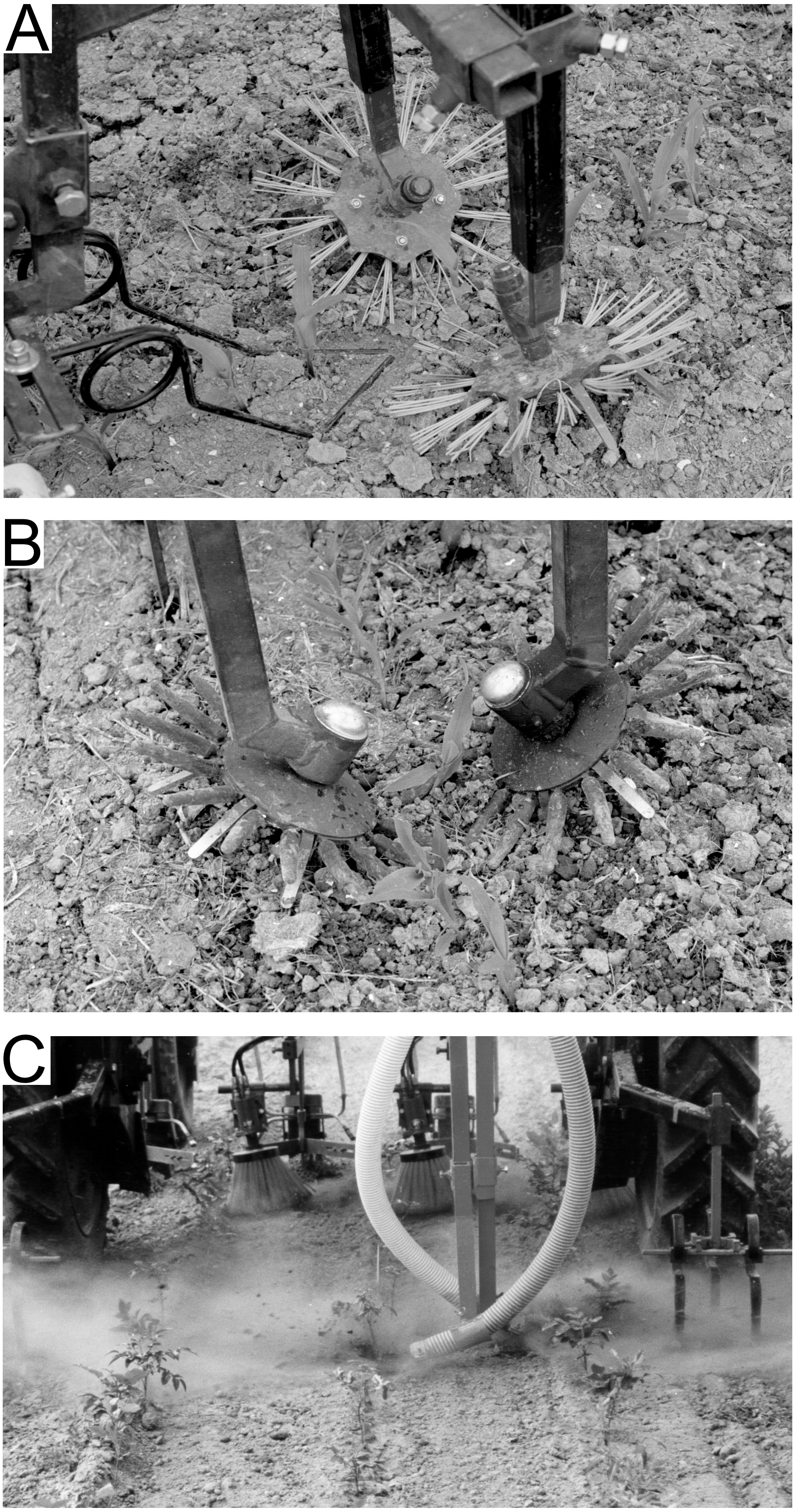

Fig. 1.1 Selective mechanical weeders for intra-row weed control. A: torsion weeders followed by ground-driven rotary brushes, B: finger weeders, C: vertical brush weeders followed by pressurized air jets. Photos courtesy of S.F. van Heulen, IMAG, Wageningen (A, B) and J. K. Kouwenhoven, Wageningen University (C).

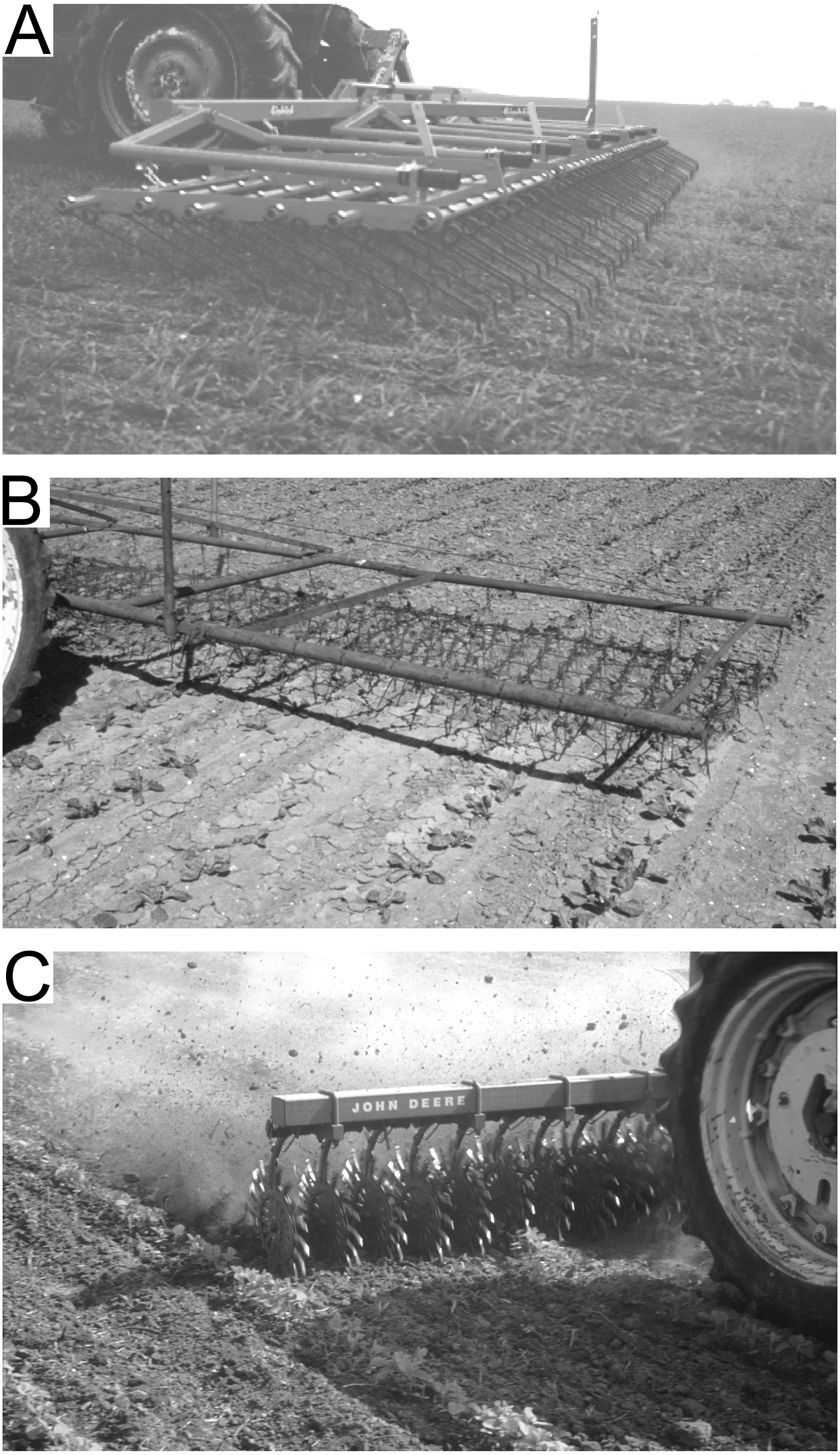

Fig. 1.2 Selective mechanical weeders for full-field weed control. A: spring tine harrow, B: chain harrow, C: rotary hoe. Photos courtesy of PPO Lelystad (A, B) and M. Owen (copyright, www.ent.iastate.edu)(C).

covering and the causes for increased weed emergence after harrowing were studied in field and laboratory experiments. Also the effects of working speed, type of harrow and soil conditions were studied more systematically. In the same period, the effectiveness and timeliness of rotary hoeing was extensively studied in the USA (Lovely *et al.*, 1958; Peters *et al.*, 1959). Meyler & Rühling (1966) attempted to explain the effects of speed and working depth on the covering effect of harrowing by studying the soil movement around single tines in the laboratory. In addition, measured anchorage force and bending resistance of plant sprouts were used to characterise the relative sensitivity of plants to being uprooted and covered by harrowing. They firstly analysed the limitations of selective mechanical weed control by relating the level of weed control to the level of direct crop damage. They concluded that 50% weed control could not be exceeded without causing excessive (>10%) crop damage.

This fundamental research approach on selective mechanical weed control emerged when mechanical techniques were rapidly being replaced by selective herbicides. Habel (1954) ascribed the success of herbicides to the sub-optimal use and effectiveness of mechanical weeding practises, which had until then been developed by empirical trial and error. Nevertheless, research activities on this field diminished in favour of herbicide research, as herbicides could provide better weed control with less crop damage.

Although the increased herbicide use was criticised from the beginning (Habel, 1954; Rid, 1964), its negative environmental impacts and the development of herbicide resistant populations induced a renewed interest in non-chemical weed management only since the mid 1980s. At that time, several field experiments with weed harrowing or rotary hoeing and inter-row cultivation were carried out to compare weed control, yields and costs of mechanical, chemical or integrated weed control strategies in several crops (Böhrnsen & Bräutigam, 1990; Baumann, 1992; Mulder & Doll, 1993; Jobin & Douville, 1994; Eberlein *et al*., 1997; Colquhoun *et al*., 1999). Other research aimed to improve the time of cultivation (crop and weed development stages; e.g. Gunsolus, 1990; Rasmussen, 1992; Cook *et al*., 1993; Jensen *et al*., 1999) and combine mechanical control with low-dose herbicide applications (Buhler *et al*., 1992; Buhler *et al*., 1995; Forcella, 2000). Many studies aimed to optimise the harrowing intensity and maximise the ratio between weed control and crop damage in given situations by changing the harrow adjustment (working depth, driving speed, tine angle; Rasmussen, 1990; van de Zande & Kouwenhoven, 1994; van der Weide & Kurstjens, 1996; Jensen *et al.*, 1999), the number of passes (Rasmussen, 1991a, 1993; Kirkland, 1994) or the direction of harrowing relative to the crop rows (Neururer, 1977), using different implements (Böhrnsen & Bräutigam, 1990; Ascard & Bellinder, 1996; Bleeker & van der Weide, 1998; Bleeker *et al*., 2000), crop row distances and seeding rates (Peters *et al*., 1965; Borm & Wander, 1996; Jensen *et al.*, 1999).

1.4.2 The selectivity concept

Optimising the intensity of a tillage action implies comparison of both weed control and crop damage. Meyler & Rühling (1966) firstly related cereal crop plant loss to weed control to point at the limited potential for selective mechanical weeding in contrast to herbicides. In the early 1990s, this concept was reintroduced and further elaborated by Rasmussen (1990, 1992). He defined selectivity as the ratio between the percentage weed control and the percentage crop soil cover shortly after harrowing (Rasmussen, 1990).

Later, variations in selectivity caused by different intensities of harrowing were defined as quantitative differences (Rasmussen, 1992). If using different implements, adjustments, working speeds or the direction or number of passes would only change selectivity in a quantitative way, then all achieved combinations of weed control and crop damage would compose one single curve. In that case, the issue of optimising the implement design, use and treatment timing could be simplified considerably. However, if changing one factor (e.g. working depth) would result in a different curve than other factors, then selectivity would change in a qualitative way. These qualitative differences are of special interest in improving implements, adjustments and weed control tactics.

The selectivity concept supports two aspects of mechanical weed control decisions. Firstly, it helps to balance crop damage or yield reduction (as a result of damage and competition) and weed control. Secondly, it can be used to detect qualitative differences in selectivity associated to implement design, adjustments and timing of operations. Most experiments with mechanical weed control basically have compared treatments without using any kind of modelling framework. The selectivity concept and modelling approach developed by Rasmussen was an important methodological improvement to analyse experiments and optimise harrowing intensity.

1.4.3 Research problems and challenges

Comparative experiments including various chemical and mechanical weed control strategies, implements and modes of operation provided valuable evidence on the possibilities and limitations of mechanical weed control in various crops. The effectiveness of mechanical weeding operations is generally quite variable and is influenced by many factors, such as the crop–weed situation, the type and use of the implement, soil behaviour and weather conditions after the operation. The causes for different responses of weeds and crops to mechanical weeding are not well understood. Because of the many factors involved, it would not be feasible to find the optimal mechanical weeding treatment or strategy in each situation empirically.

To optimise harrowing intensity with respect to crop yield and final weed seed production, the final response of crop and weeds needs to be related to the direct damage at the day of cultivation. However, only few field studies alow for such relationships to be established (e.g. van der Weide & Kurstjens, 1996; Jensen *et al*., 1999). Rasmussen (1991b) developed a modelling approach to analyse the compensating effects of decreased weed competition and crop damage as induced by harrowing. Nevertheless, more knowledge of the relationship between mechanical damage and plant response is required, especially if combinations of multiple weeding operations should be optimised. To that end, the long-term impact of mechanical weed control efficacy on weed population dynamics should be studied as well (e.g. Christensen *et al*., 1999).

An important complication in mechanical weeding experiments is the lack of comparability of results between sites and times. Even if a weed harrow is operated with the same adjustments and working speed, the tillage intensity may vary with soil conditions (Rydberg, 1993; Elsten, 1994; van der Weide & Kurstjens, 1996; Søgaard, 1998), whereas the damage depends on the growth stage of crop and weeds. Methods to independently quantify tillage intensity and plant sensitivity are only sparsely developed (Meyler & Rühling, 1966; Böhrnsen & Bräutigam, 1990; Fogelberg & Dock Gustavsson, 1998; Peruzzi *et al*., 1998) and rarely used in field experiments.

In addition, the presence of weeds in various growth stages in field plots hinders the assessment of the control effect in relation to weed growth stage and the assessment of growth suppression of surviving weeds. Control of weeds in the white thread stage is difficult to assess, because shallow cultivation also promotes germination of weed seeds and disrupts mechanical resistance (e.g. a crust) for emerging weeds. This is important, as several studies have indicated that weed harrowing and rotary hoeing in these early stages is generally more effective than with weeds in the seedling stage (e.g. Habel, 1954; Peters *et al*., 1959; Kees, 1962; Koch, 1964a; Neururer, 1977; Gunsolus, 1990; Rasmussen, 1996).

These methodological difficulties and knowledge gaps impede further improvement of guidelines for optimising implement adjustment and timing of operations. A more fundamental and detailed type of research could help to alleviate these difficulties through improving field assessments (direct and final damage, plant sensitivity, tillage intensity) and providing insight in how damaging and plant recovery processes and soil, plant and implement factors affect the relationship between crop and weed damage. A better understanding of how soil failure and soil movement around the soil-engaging tools influence the uprooting and covering performance could help to improve selectivity beyond the limits imposed by the actual design of implements. Such basic knowledge could support farmers in optimising their mechanical weeding operations and take maximum advantage of versatile, simple and cheap non-chemical weed control solutions, before introducing more complex, high-tech machines like weeding robots.

1.5 Objectives

Before the laboratory experiments reported in this thesis were conducted, weed harrowing experiments were carried out in the field in co-operation with PAGV Lelystad in 1994. The effects of harrow adjustment, soil type and time of harrowing were studied for six model weed species, by extensive assessment of uprooting, covering and soil surface level upheaval (van der Weide & Kurstjens, 1996). In addition, a laboratory experiment with a single harrow tine was conducted to examine furrow formation and soil movement in relation to patterns of soil-covering and uprooting. Although these experiments were part of the PhD project and helped to define the laboratory research presented in the following chapters, results are not presented here.

Field experiments have raised questions requiring more detailed study, improved research methodology and/or a modelling approach. As such, the work reported in this thesis can be viewed as a follow-up of the fundamental approach initiated in Germany in the early 1950s and the work of Rasmussen and coworkers. This research project was initiated to:

- better understand the damaging mechanism of selective mechanical weeders like weed harrows,
- provide more fundamental insight in factors influencing the relationship between crop and weed damage,
- explore ways to improve the selectivity between weeds and crop plants, and
- help alleviate the methodological difficulties indicated in the previous section.

More specifically, research questions were:

1. How is plant sensitivity to covering and to uprooting related to morphological and mechanical plant characteristics?
2. How can plant sensitivity and tillage intensity be independently quantified?
3. How do covering and uprooting induced by harrowing influence mortality and growth reduction?
4. Can specific strengths of the crop and specific weaknesses of weeds be exploited by using specific harrow adjustments or applying specific kinds of mechanical damage?
5. How do soil failure patterns and soil flow patterns around tines affect the uprooting and covering performance of weed harrows?
6. To which extent can implement handling (working depth, working speed) and soil conditions be used to manipulate the selectivity between weeds and crop plants?
7. How can the relationship between weed control and crop damage be predicted from soil, plant and implement characteristics?
8. How can the final effect of harrowing be predicted from damage assessments directly after harrowing?

1.6 Demarcation and approach

As limited selectivity and risk of crop damage occur mainly in early growth stages of the crop, the laboratory harrowing experiments were conducted on young seedlings and not yet emerged white threads of three model species. These represent a sown crop or seed-propagated weeds. The number of model species, soil types and treatment factors used in this study was limited because the detailed experiments were very time consuming. A sandy soil was used to avoid complications with preparation and to have representative soil failure and flow patterns during tillage.

It was hypothesised that different plant responses to each of the following processes explains the selective performance of mechanical weeding operations such as weed harrowing:

- The uprooting process, which disrupts the root system of the weakest anchored plants from the undisturbed soil below and it within the loosened soil layer.
- The covering process, which buries the plant sprout partially or completely by a layer of soil that blocks photosynthesis and imposes mechanical resistance to sprout re-emergence.
- The recovery process, during which damaged plants attempt to penetrate the soil cover and/or restore the water uptake capability of their root system. This process ends when a plant has resumed normal growth (similar to undamaged plants under stress and competition), or when it has been irreversibly desiccated or when it has depleted its energy reserves entirely.
- The competition process between normally growing plants under environmental stress.

The uprooting and covering processes occur during the pass of the implement, whereas the recovery process may take hours to several days (e.g. Habel, 1954). The outcome of the uprooting and covering process was considered to depend on the balance between the sensitivity of the plant and the damaging capacity of the implement (i.e. plant anchorage force versus tillage-induced forces; plant height and flexibility versus soil level upheaval and downward bending of plants induced by soil forward movement). Although the outcome of the recovery process was considered to depend on several interacting physical and physiological processes, only the effects of different types of mechanical damage were assessed. The competition process and the effects of damage-induced growth retardation on competition were not studied. Also processes that influence the weed population indirectly through alteration of topsoil properties and the enhancement of new weed emergence were not studied.

Although selectivity is a key issue in this thesis, the approach differs from Rasmussen's. It focuses on explaining the selectivity of the uprooting, covering and plant recovery process separately and searching possibilities for manipulation. Furthermore, it was attempted to predict the relationship between weed control and crop damage from plant characteristics and to distinguish the selective potential of the crop–weed situation and the selective ability of mechanical weeders. This extension of the selectivity concept was elaborated only for the uprooting process.

Besides the analysis of processes that explain plant response to mechanical weeding, this approach took account of the heterogeneity of plant sensitivity, implement action and plant response. As these sources of heterogeneity are encountered within the counting plots commonly used in field research, studies were done at the individual plant level. It was hypothesised that both the difference in plant sensitivity between the weed and crop population and variation within populations determine the potential selectivity. This, in combination with the intensity and variability of the uprooting and covering action, determines the level of weed and crop damage caused by harrowing.

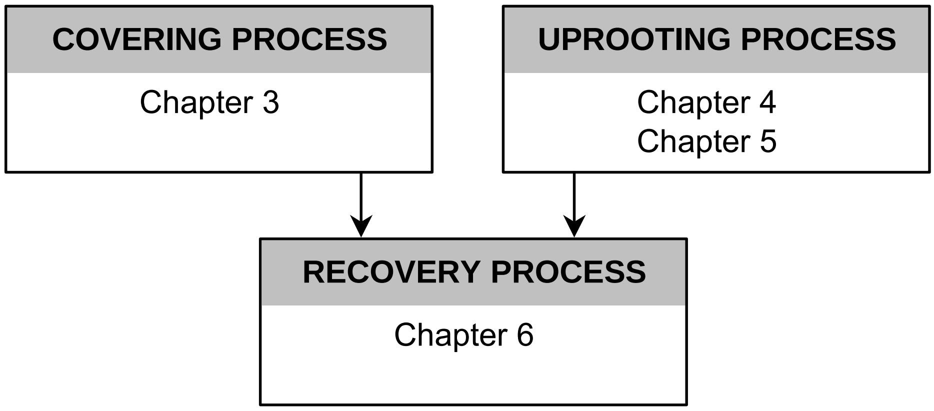

Fig. 1.3 Link between mechanical weed control processes and the chapters in this thesis.

1.7 Thesis outline

The distinction of the three processes that basically determine the effect of selective mechanical weeders is reflected in chapters 3-6 (Fig 1.3). These deal with the research questions listed in section 1.5 and Table 1.1, each with respect to either the uprooting, covering or recovery process. Each of these chapters contains a short materials and methods section, but references are listed at the end of the thesis.

Chapter 2 describes the materials and methods in more detail, to facilitate repetition of experiments and to verify the quality of data from the laboratory experiments on which all chapters are based.

Chapter 3 explores how plants get covered by soil and how a plants' resistance against being covered is related to its height, flexibility and shape of leaves. Spatial patterns of soil surface upheaval and plant bending are analysed and *in-situ* measurements of burial depth are presented. This chapter explores how working depth, working speed and soil moisture influence the relationship between covering of a model weed and a model crop on a sandy soil.

Chapter 4 examines the potential of the uprooting process for selective weed control at early crop growth stages and the effects of working depth, working speed and soil moisture content on uprooting performance. Special attention is paid to the position of the plant relative to the tine paths and the induced soil failure patterns.

Chapter 5 presents a method to predict the relationship between weed control and crop damage due to uprooting by weed harrows from crop and weed anchorage force distributions. A new selectivity parameter is introduced to describe relationships between weed control and crop damage and to discriminate between the selectivity that can be achieved by an idealised harrow in a certain crop–weed situation and the actual selectivity achieved by a real harrow.

Chapter 6 examines the contribution of harrowing-induced uprooting and covering to plant mortality and growth reduction. Field research methods and the predictability of the final harrowing effect based on assessments immediately after harrowing are discussed.

Table 1.1 Link between research questions listed in section 1.5 and the chapters in this thesis. **X** = main subject, x = minor subject.

Research question / issue	Chapter 3	Chapter 4	Chapter 5	Chapter 6
1. Plant sensitivity and morphological and mechanical plant characteristics	**X**	x	**X**	
2. Independent quantification of plant sensitivity and tillage intensity	x	x	**X**	
3. Impact of covering and uprooting on mortality and growth reduction				**X**
4. Exploitability of specific crop strengths and weaknesses of weeds		**X**		
5. Soil failure and soil flow patterns around tines and damaging performance	**X**	**X**		
6. Selectivity manipulation by implement handling and soil conditions	**X**	**X**		**X**
7. Prediction of the relationship between weed control and crop damage	x		**X**	
8. Final effect prediction from damage assessments directly after harrowing				**X**

In the general discussion (chapter 7), the approach and the practical relevance of the achievements of this study are discussed and suggestions for further research and development are given.

2 Materials and methods

2.1 Introduction

This chapter describes the materials, methods and data processing procedure used in laboratory harrowing experiments. It explains why they were chosen and indicates the level of accuracy and reliability of the basic data in this study. The materials and methods sections within chapters 3-6 only describe the essential features that are relevant in that chapter.

As this study aimed to gain insight into the selective damaging mechanisms of weed harrows, a realistic representation of what happens in the field was not a prior concern. The spatial variability of soil conditions, differences between plants within a population, the irregular working depth and harrow tine oscillations are essential to field reality, but make it difficult to study the damaging process in detail. Therefore, it was attempted to either minimise the variability (e.g. of soil conditions, working depth and tine movements of the harrow) or to account for the variability by accurate measurements (e.g. of plant size).

2.2 Materials

2.2.1 Plants

All results presented in this thesis are based on data from laboratory harrowing experiments with three model plant species in successive treatment series. The garden cress (*Lepidium sativum* L.) series was conducted from 19-02-1996 until 20-05-1996, followed by the ryegrass (*Lolium perenne* L.) series from 31-05-1996 until 14-10-1996. These series were harrowed when plants were at an early seedling stage. The quinoa (*Chenopodium quinoa* Willd.) series (from 11-03-1997 until 10-10-1997) was conducted at emergence, using an adapted procedure. The number of species tested was limited to three, because treatments were very time consuming.

The size and characteristics of the test plants used in this study and the detailed growth stage classification are described in chapters 3, 4 and 6 and summarised in Table 2.1. These model plant species were selected for their contrasting mechanical and morphological characteristics rather than their similarity to certain weed or crop species. Additional arguments for selecting the model plant species were a high germination percentage, absence of dormancy and suitability of the seeds for the vacuum sowing technique.

For the purposes of this work it was arbitrary which test plant species (chapters 3, 6) or which growth stage (chapters 4, 5) is regarded as the crop or the weed. As weeds are generally smaller and more damaged than the crop, the most damaged species or growth stage was assumed to represent the weed.

Table 2.1 Classification of detailed growth stages per species, with measured plant dimensions. Average values of all treatments, with standard errors between parentheses.

Species	Detailed growth stage	Classification key	Measured height (mm)*	Cotyledon tip distance (mm)
L. perenne	white thread	invisible at harrowing	-	-
	breaking through	0-25 mm tall	16.8 (6.2)	-
	small	26-35 mm tall	30.4 (2.8)	-
	medium	36-45 mm tall	39.8 (2.8)	-
	large	46-70 mm tall	50.9 (4.6)	-
L. sativum	white thread	invisible at harrowing	-	-
	breaking through	bent hypocotyledon, folded cotyledons	6.0 (3.4)	1.2 (1.1)
	small	upright hypocotyledon, small cotyledons	10.4 (2.1)	7.7 (1.8)
	medium	established cotyledons on small stalks	13.2 (2.4)	10.3 (2.0)
	large	large cotyledons, long wide-angled stalks	15.6 (2.7)	12.8 (2.3)
C. quinoa	white thread	invisible at harrowing	-	-
	small	visible at harrowing	5.3 (4.0)	-

* Leaf length of *L. perenne* and hypocotyledon height of *L. sativum* and *C. quinoa*.

The seeds used in the harrowing experiments were 1 year old (*L. perenne*, *C. quinoa*) or 2 years old (*L. sativum*). To reduce possible variation in recovery ability induced by seed-mass variation within the *L. sativum* population, only the size 1.1 – 1.2 mm was used in experiments. Seeds of *L. perenne* and *C. quinoa* were not sorted. *Lepidium sativum* and *C. quinoa* seeds were pre-treated with LIRO-TMTD powder (80% thiram, dithiocarbaurate) to prevent attack by soil pathogens and fungi.

From 09-04-1999 until 21-05-1999, the anchorage force of *L. perenne* and *L. sativum* plants were measured in a separate series of experiments, using new (1 year old) non-sorted seeds. These measurements are described in chapter 5 and will not be further explained here.

2.2.2 Soil

Fine black sandy soil (Dutch classification zEZ21) was excavated from the ploughed layer of an arable field near Ede, The Netherlands. After drying the soil, it was passed though a 1-mm sieve to remove fine gravel and plant roots. Subsequently, this large batch of approximately 700 kg of soil was thoroughly mixed. As this batch was to be used in all experiments, soil was repeatedly dried and moistened for re-use in multiple treatments. This soil consisted of 73.1% sand >105 µm, 6.5% silt, 3.0% clay and 3.2% organic matter and had a pH value of 5.3.

There were three reasons to choose a sandy soil. Firstly, it can be repeatedly prepared and harrowed at a wide range of soil moisture contents, thanks to the low degree of structure and strength. Secondly, its repetitive and homogeneous preparation is far less complex than that of structured loam and clay soils. Thirdly, regular and small-scale soil failure patterns were preferred because the effects of soil failure and soil movement around the harrow tines were of special interest. With the

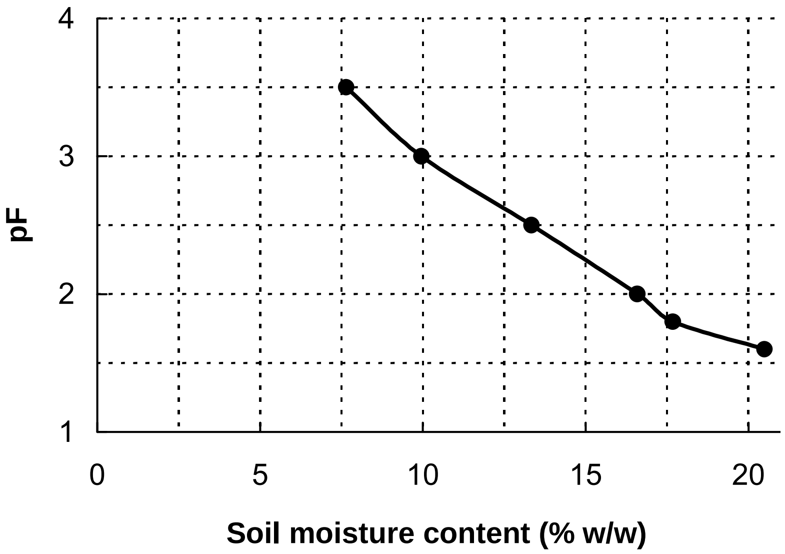

Fig. 2.1 Water retention characteristic of the experimental sandy soil at 0.95 kg/L dry-bulk density. Mean of five samples compacted at 18.5% (w/w) moisture content.

soil preparation method used, the soil failure and flow patterns during harrowing on aggregated soils may not adequately represent topsoil behaviour in the field.

Five soil moisture contents were chosen to create a range of soil strengths and different initial regrowth conditions. The soil moisture content range (8-17 %w/w at preparation) corresponds to pF values ranging from 1.9 to 3.4 (Fig. 2.1). The driest condition represents a very dry, fragile soil, which contains just enough moisture for a reliable germination and for seedling growth in a climate chamber for six days without irrigation. The wettest condition represents a relatively coherent soil that is just workable for harrowing.

In all experiments dry-bulk density before harrowing was 0.95 kg/L, which corresponds to 63.3% pore volume. This value was rather low, as the driest soil was nearly not compacted. The dry-bulk density of loosely deposited soil[1] decreased with increasing soil moisture content and closely resembled the dry-bulk density of the tilled layer directly after harrowing in the laboratory (Fig. 2.2).

2.2.3 Co-ordinate measurement equipment and software

An electro-mechanical three-dimensional co-ordinate measurement device linked to a computer was used to measure the positions of seeds, plants, model harrow tines and reference points on bins and experimental frames. This commercially available device (Fig. 4.2, SpaceArm™, FARO Technologies Inc., Lake Mary, Florida, USA, www.faro.com) measured points within a 740 mm radius with 0.4 mm accuracy[2]. The actual co-ordinates of the hand-held pointer were sent to the computer's serial port

[1] This was determined by filling cylinders (height 100 mm, diameter 100 mm) with sieved homogeneous soil of varying moisture content, without causing compaction.

[2] Standard error provided by the manufacturer.

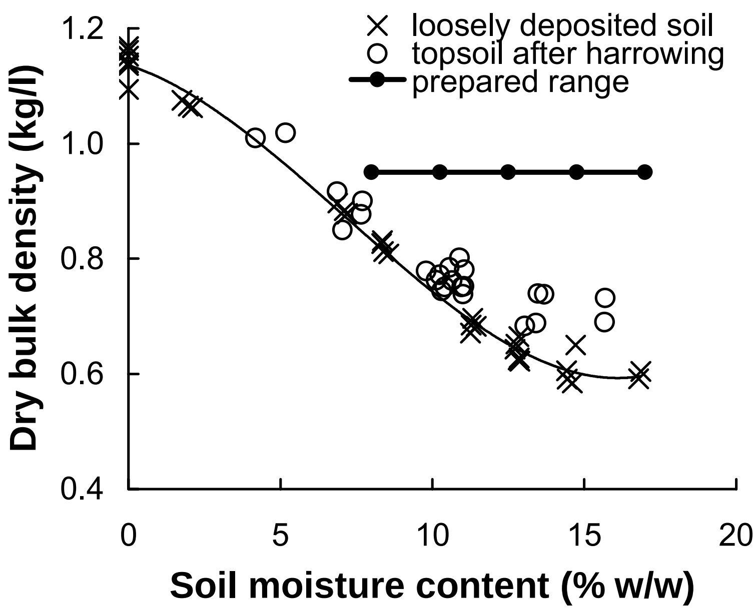

Fig. 2.2 Relationship between soil moisture content and dry-bulk density of loosely deposited soil (in a cylinder of 100 mm diameter and 100 mm height) and of the tilled topsoil immediately after harrowing (based on surface profile measurements).

by touching the foot pedal. The solid base of the SpaceArm was mounted on a frame with three supports, so it could be placed over soil bins at fixed positions on the reference frame.

The standard software (CalipSA for Microsoft Windows) facilitated the alignment of the reference co-ordinate system of the SpaceArm and the acquisition of co-ordinates. As CalipSA offered no convenient way to identify the measured co-ordinates, groups of co-ordinates (objects) or storing extra object information, special software was developed (CalipGRO for Microsoft Windows). The system is easy to operate and allows *L. sativum* plants (four co-ordinates and a classification code) to be measured in 6-10 seconds.

2.2.4 Model harrow and implement testing rail

Harrowing experiments were conducted using a model harrow mounted on a testing rail (Fig. 4.1). The tine configuration (six frame tubes spaced 150 mm with tines spaced 150 mm), tine diameter (6 mm) and the tine path spacing (25 mm) resemble that of conventional spring tine harrows (see Fig. 2.5). The main differences concern the narrower total working width (575 mm, 23 tines), the rigid tines and the stiff harrow frame. The latter two features were required to attain a precise working depth and fixed tine trajectories. Digitised trajectories of the harrow tines were used to determine the position of individual plants relative to the harrow tines and analyse the role of soil failure and soil flow patterns on the uprooting and covering effect of harrowing.

The model harrow was mounted on the arm of a moving carriage, which was adjustable in height and lateral position by spindle wheels. A chain, driven by an electrically powered continuously variable transmission, towed the carriage. Although the speed was set in unloaded condition, the powerful transmission could easily maintain this speed under resistance. The hand-operated clutch and the automatic switch at the end of the 6.5 m long testing rail facilitated an abrupt start and stop of the moving carriage.

The rigid three-point attachment of the harrow to the moving carriage was required to minimise vibrations in the construction. Nevertheless, the chain drive combined with roller bearings pushed tightly to the rails induced some inevitable high-frequency vibrations of very small amplitude.

2.2.5 Soil bins and reference table

One pass of the model harrow tilled a 1.60 m long test area, consisting of four soil bins mounted together on a reference table. Two vertical bars at the head of the reference table fixed the position of the first soil bin. The first and the last bin served as inlet and outlet bin, whereas the second and third bin were sown with either *L. perenne* or *L. sativum* seeds. In *C. quinoa* experiments, one seeded bin was placed between two bins without seeds, resulting in a 1.20 m long test area. The soil bins (inside dimensions: 0.60 x 0.40 x 0.13 m) were made of 3-mm thick aluminium and had two detachable long-side walls. Bins could be mounted together by removing these long-side walls. Both short-side walls each had two conical holes that served as reference points.

A reference table was constructed to provide a stable straight underground for the aluminium soil bins during the harrowing treatment. This frame was placed at a fixed position on the long table below the testing rail that carried the model harrow. Four adjustable supports allowed for horizontal levelling, whereas two adjustable wall supports were used to align the reference table with the testing rail. Six cones and six reference points on the outer left and right bars of the reference table allowed the SpaceArm to be placed in two positions and allowed calibration of the SpaceArm co-ordinate system.

2.2.6 Vacuum sowing mould

A vacuum sowing mould (Fig. 2.3) and a supporting frame (Fig. 2.4) were designed to place seeds in a rectangular grid on top of the levelled and compacted soil in a bin. The sowing mould consisted of nine rows (spaced 20 mm) of 21 hollow medical needles (spaced 22.5 mm) that had their sharp points filed off. With the sowing mould connected to a vacuum pump, each needle could suck a seed against its tip.

Three height adjustment bolts were adjusted so that the seed-filled needles were positioned 2 mm above the soil surface, so that seeds did not roll aside when vacuum was released. After drilling, the distance between seeds and the short side of the bin was 75 mm, whereas the outer rows were spaced 40 mm from the long-side walls. The sowing mould had to be filled and placed on the soil bin twice to sow

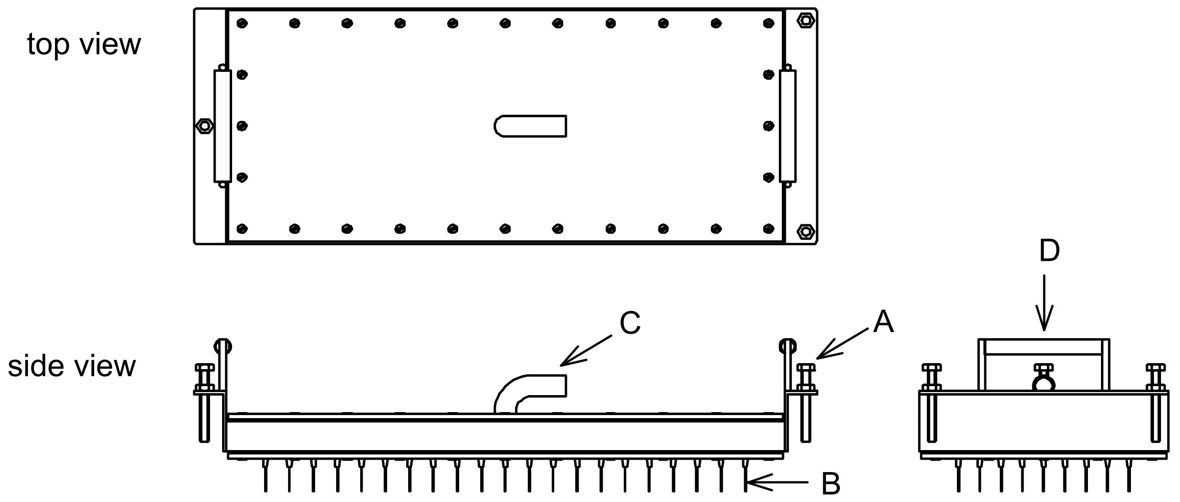

Fig. 2.3 The vacuum sowing mould. A: height adjustment bolt, B: needle, C: air outlet to pump, D: handle.

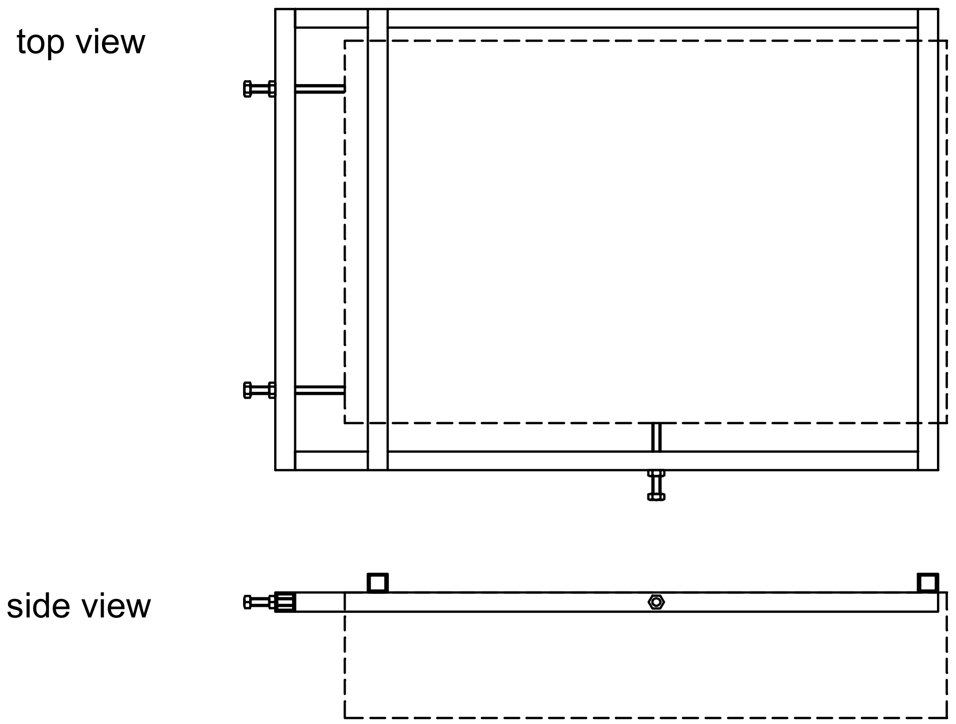

Fig. 2.4 Frame to support the vacuum sowing mould, to be placed on top of a soil bin (dashed).

a bin entirely. A 22.5-mm seed spacing perpendicular to the harrowing direction was chosen to obtain variable distances between plants and paths of the harrow tines, closely resembling a full-field condition with randomly dispersed weeds (Fig. 2.5).

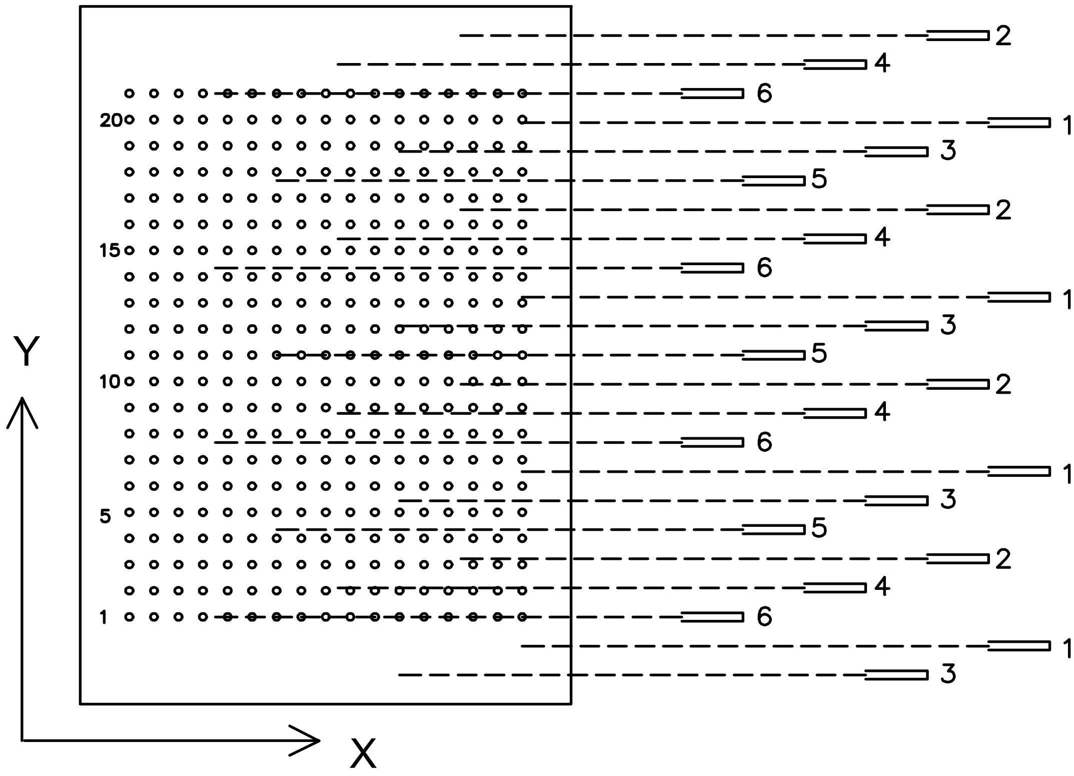

Fig. 2.5 Map of planned seed positions (circles) and harrow tine paths (dashed lines). Harrowing proceeds from the left to the right. The horizontal distance between (numbered) harrow tine rows is not to scale.

It should be noted that the seeds were after all not precisely placed at the target positions. With *C. quinoa*, the standard error perpendicular to the harrowing direction typically ranged from 1 to 1.5 mm (including the SpaceArm measurement error).

2.2.7 Adapted vacuum cleaner

This apparatus was used to remove polystyrene pearls from the surface of sown bins before harrowing and to remove loose soil after harrowing. These materials were collected in a plastic tray with a tightly fitting removable lid. This lid had an air inlet connected to a flexible hose of 17-mm inside diameter, an air outlet connected to the hose of a 1000 W industrial vacuum cleaner and an adjustable false-air hole to adjust the sucking power.

2.3 Methods

2.3.1 Digitisation of harrow tine paths and setting of the harrow

The paths of the four most widely spaced harrow tine tips at each corner of the model harrow were digitised (using the SpaceArm, section 2.2.3) as the harrow was moved stepwise over the reference table. After processing these data, the position of the

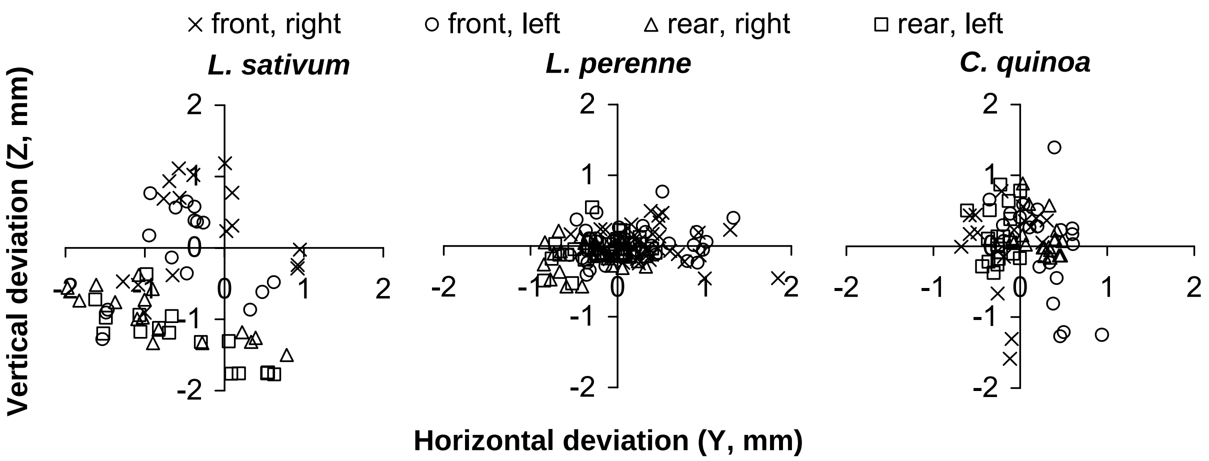

Fig. 2.6 Deviation of digitised tine paths relatively to calculated tine paths within the sown range (*L. perenne* and *L. sativum*: 720 mm long trajectory; *C. quinoa*: 320 mm long trajectory). A positive deviation means that the measured tine positions are left or above the calculated position, seen in the harrowing direction.

reference table was fine-tuned so that its co-ordinate system was closely aligned to the tine trajectories over the second and third soil bin. The reference table was fixed in the same position during the rest of the experiment.

Subsequently, the harrow was precisely adjusted and placed in a reference position to digitise all 23 tine tips. The tine number, tine row number (1-6 in Fig. 2.5) and the average values of the X, Y and Z co-ordinate of each tine were stored in the harrow tine base reference file (HTINEREF).

Then, the trajectories of four tines at the corners of the model harrow were digitised at various harrow positions along the testing rail. The three-dimensional translation of the imaginary midpoint of the harrow relative to the reference position and the rotation around three axes were calculated for each measured position and plotted graphically. For each translation and rotation parameter, a segmented curve was drawn and described by a set of points that were stored in the harrow track file (HTRACK).

After digitising the harrow tine trajectories, no adjustments were made except changing the working depth. Each time after adjusting the working depth, all tines were digitised with the harrow placed at the reference position, resulting in a new harrow reference file (HTINE).

Based on HTRACK, HTINEREF and HTINE, each tine path could be simulated by linear interpolation. Figure 2.6 shows the deviation of the measured tine paths relative to the simulated paths, within bins of *L. perenne* and *L. sativum* (720 mm long trajectory) and within *C. quinoa* bins (320 mm long trajectory). Table 2.2 shows the largest vertical and horizontal shifts of the simulated tine paths over those trajectories.

After all experiments were finished, one aspect of the fixation of the harrow frame to the moving carriage appeared to have been overlooked. Although the

Table 2.2 The range of vertical and horizontal shifts of simulated harrow tine trajectories within sown bins of *L. perenne* and *L. sativum* (720 mm long trajectory) and *C. quinoa* (320 mm long trajectory). A positive shift means that tines go up or to the left as the harrow moves forward.

Species	Horizontal shift (Y, mm)	Vertical shift (Z, mm)
L. perenne	–3.4 - 1.1	–2.2 - 1.2
L. sativum	–3.4 - 1.1	–2.2 - 1.2
C. quinoa	1.2 - 2.0	–0.3 - 1.3

vertical positions of the harrow main frame relative to the moving carriage were registered, the horizontal positions were not. In about one-third of the *C. quinoa* treatments, the harrow frame was slightly rotated around its vertical axis. In these cases, the trajectories of the first tine row were up to 6 mm too far right and the trajectories of the last tine row were up to 6 mm too far left, so the tine path distance varied between 20 and 32 mm. This phenomenon caused an irregular distribution of *C. quinoa* seed-tine distances (Fig. 2.7C) but did not affect the results presented in chapters 3-6. *Lolium perenne* and *L. sativum* plants were distributed quite uniformly (Fig. 2.7A, B).

2.3.2 Soil bin preparation and sowing

For each soil bin, a portion of soil was mixed, sampled for moisture content and stored in a sealed plastic tray. After bringing the soil to the desired moisture content, it was left to homogenise for two or three days. After mixing, the soil was left to homogenise for another day and sieved before filling the aluminium bins.

Each sown bin consisted of two soil layers of equal dry-bulk density (0.95 kg/L), with seeds placed in between. The total thickness of the two layers after compaction was 90 mm, with the thickness of each layer depending on sowing depth (*L. perenne* and *L. sativum*: 10 mm; *C. quinoa*: 5, 10 or 30 mm). The bottom layer was filled in using a mould with six equal compartments that were filled with measured weights of moistened soil. Each compartment was levelled using a fork, without causing compaction. After removing the mould, the surface was levelled again without moving soil from one compartment to another.

After compacting this layer to a fixed height using a hydraulic ram, seeds were placed using the vacuum sowing mould (section 2.2.6) and its supporting frame. Then, seeds were manually placed at eventual empty spots and pressed into the soil surface without causing additional compaction. In *C. quinoa* experiments, seed positions and the four reference points on the sidewalls of the bin were digitised, using the SpaceArm and the CalipGRO software. Finally, the topsoil layer was filled in and compacted in a similar way, using a mould with 18 compartments. These compartments were small enough (0.10 x 0.13 m) to spread a small amount of soil to a thin layer of equal height.

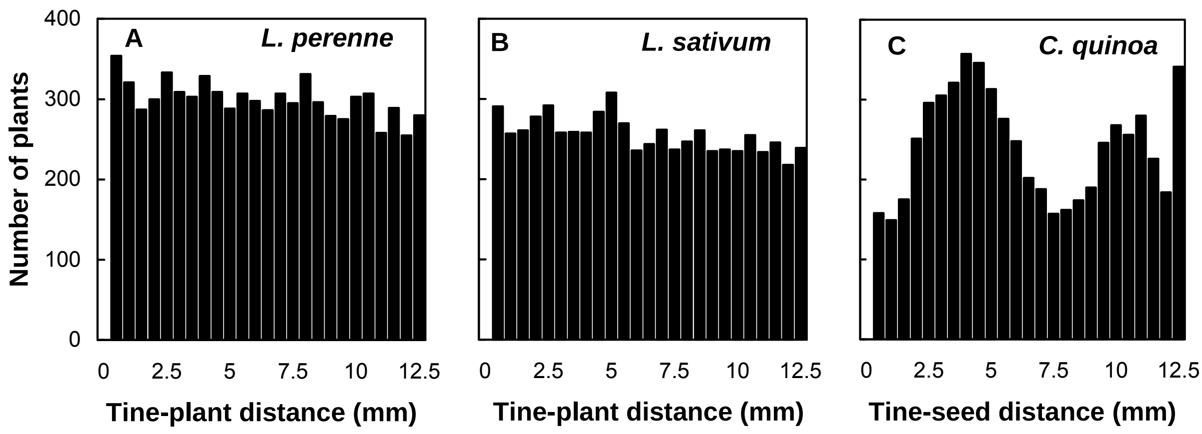

Fig. 2.7 The spatial distribution of emerged *L. perenne* (A) and *L. sativum* (B) plants and *C. quinoa* seeds (C) in relation to the path of the nearest passing harrow tine. Plant numbers of all treatments per species together.

For each harrow pass, two extra bins (without seeds) were prepared to serve as inlet and outlet bins ahead and behind the two sown bins at harrowing. These bins were prepared at the same day and had the same density and soil moisture content as the sown bins. Unlike the sown bins, the entire 90-mm soil layer was filled in altogether. All bins were taped up and sealed by wooden plates with foam rubber strips, to prevent evaporation during preparation and storage.

2.3.3 Plant establishment and regrowth in climate chambers

After applying a 5-mm thick layer of polystyrene pearls on top of the soil surface, sown bins were sealed by glass plates with foam rubber strips, placed in the climate chamber and kept in the dark until emergence. After emergence, bins were illuminated at a light intensity of 143 μE m^{-2} s^{-1}. Temperature and air humidity were equal for the 16-hour day and 8-hour night period, but differed per species: *L. perenne*: 12 °C, 85% r.h.; *L. sativum*: 17 °C, 85% r.h. and *C. quinoa*: 17 °C, 55% r.h. The lower temperature with *L. perenne* was chosen to restrain leaf growth. With *C. quinoa*, lower air humidity was chosen because preceding *L. perenne* and *L. sativum* experiments had shown little mortality.

Glass plates and polystyrene pearls reduced evaporation and preserved homogeneity within a bin during plant establishment. However, the air below the glass plate was nearly saturated and approximately 5 °C warmer than the air in the climate chamber (due to irradiation during the day period). The temperature gradient induced condensation on the bin walls, which in turn moistened the adjacent 10-15 mm of soil. These phenomena could be partially suppressed by clamping 40-mm wide strips of thick filter paper to the bin walls above the soil surface. As the filter paper absorbed much condense, less water drained into the soil.

Despite all evaporation reducing measures, the moisture content of the tilled layer immediately after harrowing was lower than at preparation (Table 2.3). The

Table 2.3 Experimental layout and measured soil moisture contents in the tilled topsoil and the undisturbed subsoil, at harrowing and six days later.

Treatment	Working depth (mm)	Working speed (m/s)	Sowing depth (mm)	Prepared moisture content (%w/w)	Measured soil moisture content (%w/w)									
					at harrowing				six days after harrowing					
					topsoil		subsoil		topsoil			subsoil		
					L. perenne	*L. sativum*	*L. perenne*	*L. sativum*	*L. perenne*	*L. sativum*	*C. quinoa*	*L. perenne*	*L. sativum*	*C. quinoa*
Standard	20	1.8	10	12.5	11.0	10.3	12.3	12.2	2.2	2.2	1.7	10.8	6.4	8.5
Shallow seed	20	1.8	5	12.5	-	-	-	-	-	-	1.9	-	-	8.7
Deep seed	20	1.8	30	12.5	-	-	-	-	-	-	2.3	-	-	9.3
Shallow till	10	1.8	10	12.5	10.1	10.4	12.0	12.3	2.4	2.0	1.4	9.7	7.1	7.6
Deep till	30	1.8	10	12.5	10.9	11.1	12.5	12.6	4.3	3.3	2.7	12.0	8.4	9.7
Slow	20	1.2	10	12.5	10.8	10.6	12.7	12.4	2.7	2.3	1.9	10.6	7.7	8.8
Fast	20	2.4	10	12.5	11.0	9.8	12.4	12.2	2.5	2.5	1.9	10.8	7.9	8.9
Dry	20	1.8	10	8	4.2	5.2	8.2	8.1	1.4	1.5	1.3	6.4	5.0	5.3
Moist	20	1.8	10	17	15.7	15.7	16.5	16.4	6.3	4.0	3.0	14.0	9.6	11.0
Shallow*dry*fast	15	2.1	10	10.3	6.9	7.0	10.2	10.2	2.2	1.7	-	8.7	5.6	-
Shallow*wet*slow	15	1.5	10	14.8	13.4	13.0	14.3	14.5	3.8	3.0	-	12.3	9.6	-
Deep*dry*slow	25	1.5	10	10.3	7.7	7.7	10.4	10.2	2.1	2.1	-	9.1	7.3	-
Deep*wet*fast	25	2.1	10	14.8	13.7	13.5	14.4	14.6	5.3	3.9	-	13.0	10.6	-

largest part of this moisture was probably lost during measurements before harrowing, although air humidity in the laboratory was kept as high as possible (70-80%, also to prevent plant shock). The high air humidity required to reduce moisture loss from the topsoil may have influenced plant development after emergence. In field conditions, plants would be more damped off.

As soil moisture content affected the emergence rate, sown bins were put in a climate chamber for periods of varying length, to obtain similar growth stages within a species. For all soil moisture contents except 8%, *L. perenne*, *L. sativum* and *C. quinoa* stayed in the climate chamber for 11, 4 and 3 days, respectively. With 8% soil moisture content, this period was extended by two days for all species. *Chenopodium quinoa* sown at 30 mm depth was harrowed four days after sowing.

After harrowing, one bin per treatment with *L. perenne* and *L. sativum* and both bins with *C. quinoa* were returned to the climate chamber for six days, to assess plant recovery. The climate chamber settings were the same as during plant establishment, but the glass plates were not used. This resulted in gradual soil desiccation (Fig. 6.2). Six days after harrowing, the topsoil was almost air dry, whereas the desiccation of the undisturbed subsoil depended on species (Table 2.3).

2.3.4 Preparations and measurements before harrowing

One bin sown with *C. quinoa* or two bins sown with *L. perenne* or *L. sativum* were placed on the reference table, between two bins without seeds. After removing the filter paper, the polystyrene pearls on the soil surface were hovered up. The bins were mounted together and aligned to have the harrow tines at the planned paths relative to the plants. Subsequently, the SpaceArm co-ordinate system was aligned to the reference points on the reference table and emerged plants were measured row by row using the CalipGRO software. For each *L. perenne* and *C. quinoa* plant, the emergence point at the soil surface and the leaf tip or hypocotyledon tip were digitised. With *L. sativum*, the emergence point was digitised and the detailed growth stage classification code (Table 2.1) was entered at the keyboard (in both bins), whereas in the second bin the hypocotyledon tip and both leaf tips were digitised as well. The four reference points at the sidewalls of the third bin were digitised, so that the position of plants measured six days after harrowing could be transformed to the co-ordinate system of the reference table.

2.3.5 Measurements after harrowing

The emerging point at the loose soil surface and the leaf tip or hypocotyledon tip of all visible plants in the last seeded bin were digitised in a non-disturbing way. Their individual degree of covering (in steps of 10%) and uprooting status (roots visible at the soil surface or not) and growth stage information (white thread or emerged plant) were classified by a two-digit code entered at the keyboard. Emerged plants and white threads that were dragged beyond the last seeded bin were collected and counted. Subsequently, this bin was returned to the climate chamber.

Immediately after harrowing, two soil moisture sample cylinders of 40 mm diameter and 100 mm height were placed in the first seeded bin of *L. perenne* and *L. sativum* treatments, sealed by plastic lids on top. Ten points at the rim of each soil moisture sample cylinder and at least 1000 points across the tilled soil surface were digitised to reconstruct the soil profile and the positions of the sample cylinders. Subsequently, all plants were digitised in a disturbing way, first the visible plants and then the completely covered plants. After digitising the leaf or hypocotyledon tip and the emerging point at the loose soil surface, plants were gently pulled upright (without pulling out the non-uprooted plants) to digitise their root location. The tilled soil was carefully sucked up so that leaf or hypocotyledon tips of covered plants could be digitised in their original position. The same two-digit code was used, but the uprooting status was classified differently (either “not uprooted”, “uprooted with roots buried”, “uprooted with roots visible at the soil surface”, or “probably uprooted with roots in vertical position in the soil”). Uprooted plants were collected, adhering soil was washed off and plants were oven-dried 24 hours at 65 °C. The anchorage forces of the remaining non-uprooted plants in the second bin were measured row by row (see chapter 5).

After finishing all plant-related measurements, the soil in the sample cylinders was strongly compressed by a tightly fitting ram to prevent soil from falling out of the cylinders as they were taken out. Each soil moisture sample was divided into five equal layers (subsamples). These subsamples were weighed, oven-dried 24 hours at 105 °C and then weighed once again. The soil moisture profile of each sample cylinder was reconstructed from the dry weights and moisture contents of the five subsamples, assuming that harrowing did not change the amount of soil in the cylinder.

2.3.6 Plant recovery assessment

Six days after harrowing, bins were taken from the climate chamber and put on a table in the laboratory at 70-80% relative air humidity. After digitising the four reference points at the sidewalls of the bin, the living non-desiccated visible plants were digitised and pulled out row by row. Measurements were similar to those in the second bin directly after harrowing, but anchorage status was classified as “loosened”, “firmly anchored” or “weakly anchored/re-anchored”. Sprouts were cut at a distance above the seed equal to the sowing depth[3] and fresh weighed individually. Plants were collected per anchorage force status and oven-dried 24 hours at 65 °C to determine their average dry weight.

After all visible plants had been removed and all visible desiccated plants had been collected and counted, three soil moisture sample cylinders were placed in the bin. The tilled topsoil was carefully removed so all plants that remained buried could then be digitised as well. Their sprouts were not weighed because these plants were considered to have been killed by harrowing. After the desiccated plants were collected, the soil samples were taken and processed as described in section 2.3.5.

2.4 Data processing

This section explains how the original data were processed to obtain a table containing all attributes of individual plants before harrowing, directly after harrowing and six days later. Figure 2.8 represents the files and programs involved in this procedure. The procedure consist of four steps: (1) creation of suitable data files, (2) calculation of surface profiles, (3) matching plants measured at several times and (4) creation of tables for further analysis.

2.4.1 Creation of suitable data files

As a first step, the program DATDIV.BAS read the measurement data files created by CalipGRO (GRB) for a particular treatment and created separate data files for points on the soil surface profile, plants, and other measurements, with formats suitable for further processing. Each object in the created files was identified by a five-digit number (ID) corresponding to line numbers in the GRB file. GR# files contain points at the soil surface of a particular bin at a particular time, whereas PL# files contain positions, sprout coordinates and classification codes of seeds or plants

[3] This was done to make plant mass of harrowed bins independent of sowing depth and comparable to plant mass of undisturbed bins, in which plants were cut at the soil surface.

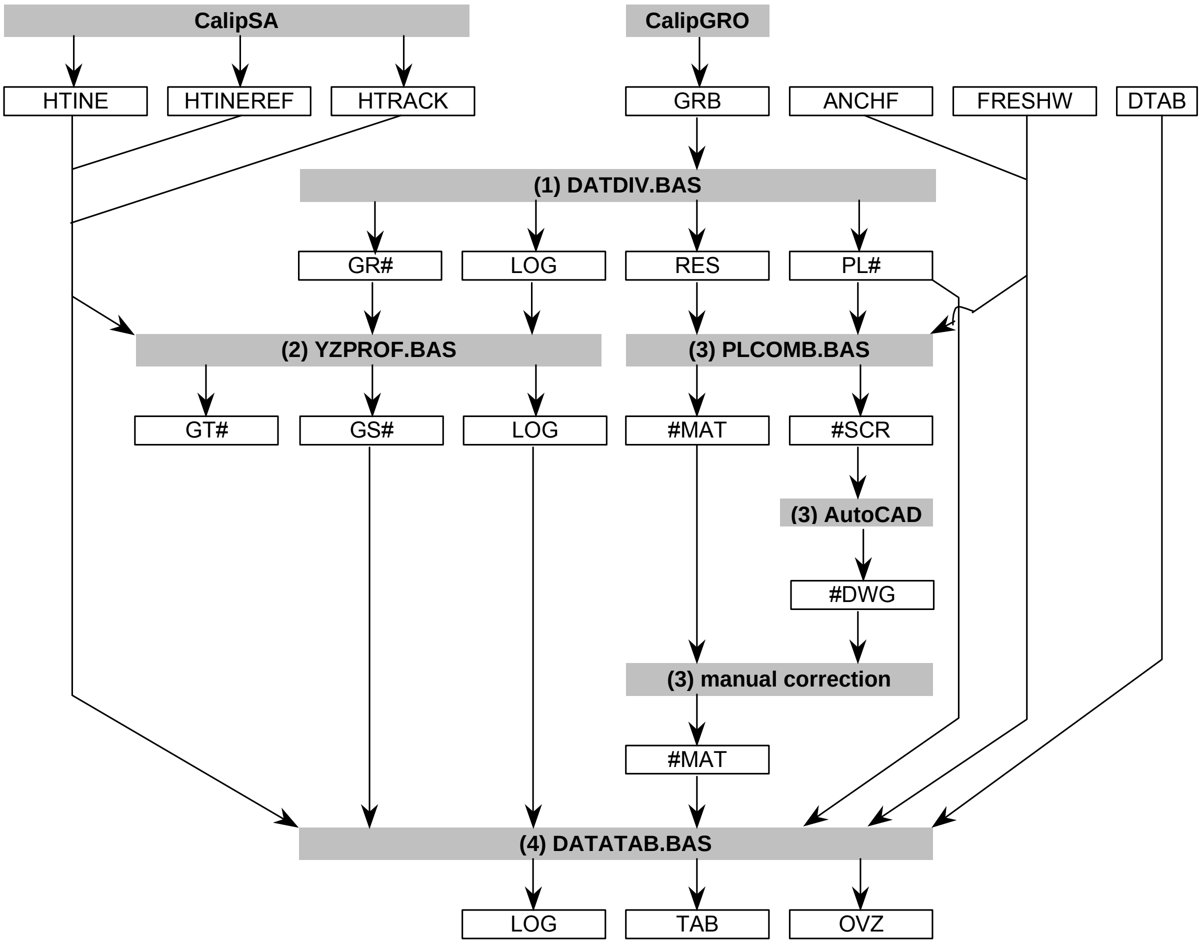

Fig. 2.8 Diagram of the four-step data processing procedure. White boxes represent files, grey boxes represent programs or a manual procedure. For abbreviations see sections 2.3.1 and 2.4.1 to 2.4.4.

in a particular bin at a particular time (# represents a number). The RES file contains reference points, the used co-ordinate systems, remarks entered at the keyboard during measurement and the calculated centre points of sample cylinders. The LOG file provides an overview of the number of objects measured in each GRB file and states the calculated translations and rotations needed to transfer co-ordinates in a “free co-ordinate system” (used when digitising *C. quinoa* seeds or plants six days after harrowing) to the co-ordinate system of the reference table. The measured accuracy of reference points at the sidewalls of the bins and the accuracy of the iterative calculations to transfer the free co-ordinate system are provided as well.

2.4.2 Calculation of soil surface profiles

The second step in the data processing procedure is the calculation of soil surface profiles after harrowing, using GR# files and the YZPROF.BAS program. This program calculates two kinds of profiles perpendicular to the harrowing direction: from one (short) side of the bin to the other (GS#) and between two tines in the last

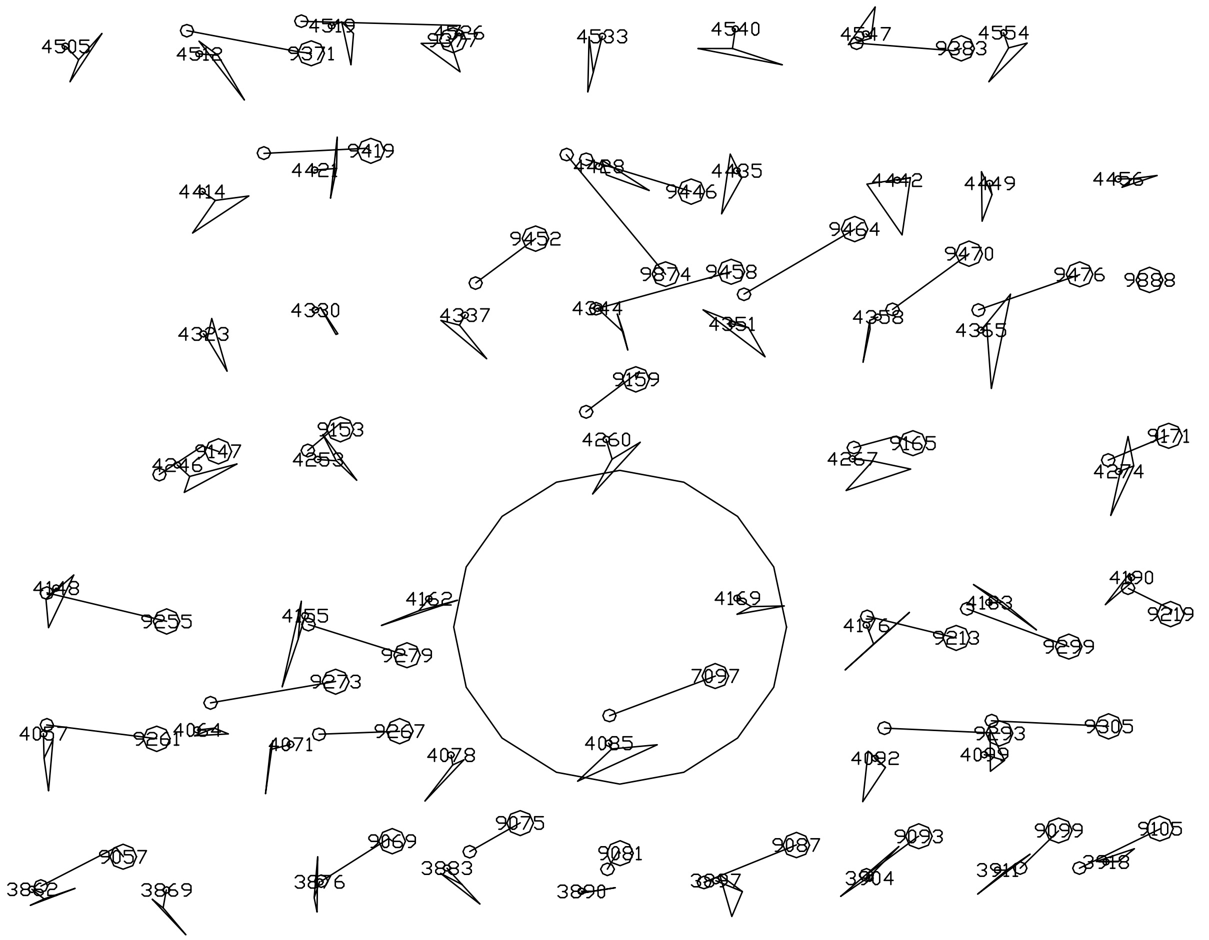

Fig. 2.9 Example drawing of a part of a bin with *L. sativum* before harrowing (line with a small circle at emergence location and a triangle representing the leaf tips and the hypocotyledon tip, ID 3862-4554) and after harrowing (line with a small circle at the rooting point and a big circle at the hypocotyledon tip, ID 7097-9888) and a soil sampling cylinder.

tine row of the model harrow (GT#, see Fig. 2.5). To correct for sideward shifts of the tine paths, YZPROF.BAS used the measured tine positions (HTINE and HTINEREF, see section 2.3.1) and the three-dimensional translations and rotations of the harrow frame at various positions along the testing rail (HTRACK).

Profiles were calculated for specific bins and had a 1-mm grid. The height at each profile point was calculated as the average of measured points within a 4-mm wide band (over the whole bin length, perpendicular to the harrowing direction) around the profile grid point.

2.4.3 Matching plants measured at several times

The third step in the data processing procedure was to identify plants and seeds from the same bin measured at different times. The program PLCOMB.BAS read two PL# files and produced a list of potential combinations of plants from both files

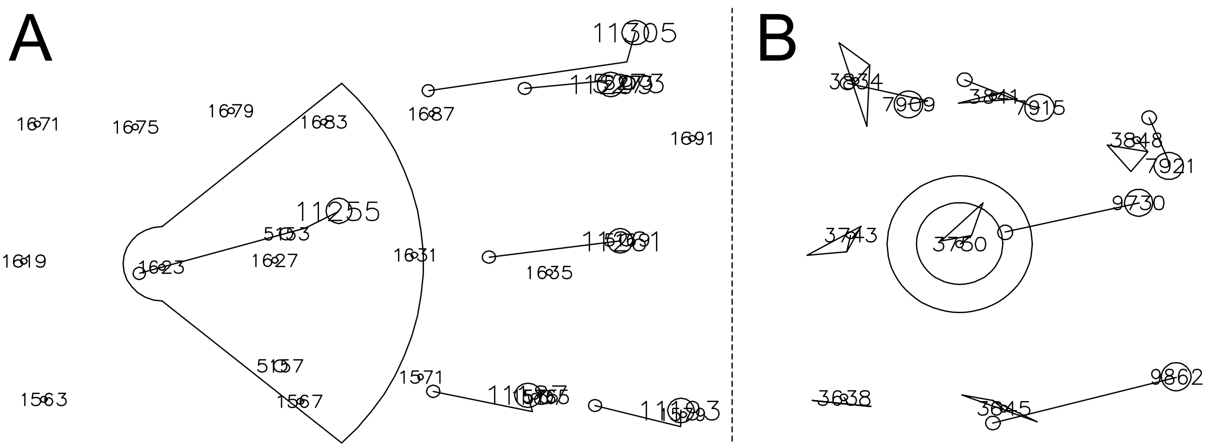

Fig. 2.10 Example of the search area used when matching plants from non-destructive measurements (A, ID's 1563-1693: plant emergence locations before harrowing, ID's 5153-5273: plant emergence point at the tilled soil surface after harrowing. ID's 11187-11305: surviving plants six days after harrowing) and the search area used when matching plants with digitised emergence and rooting locations (B, inner circle: certain match, outer circle: potential match).

(#MAT). PLCOMB.BAS also produced a drawing command script file (#SCR) by which AutoCAD® automatically produced a three-dimensional colour drawing of plants in both PL# files (Fig. 2.9). All plants from both PL# files were drawn including their ID. The sample cylinders were drawn as well, so that plants caught in the sample cylinder could easily be identified and discarded.

The matching procedure and the matching list depend on the PL# file combination.

In the first case, rooting locations are not available (e.g. with data from non-destructive measurements directly after harrowing). PLCOMB.BAS then finds emergence points at the loose soil surface that are within the area displayed in Fig. 2.10A. The radius of the small circle around the seed or emerged plant before harrowing was set to 6 mm. The radius of the big crescent at the right was calculated from the plant height before harrowing and increased by an uncertainty range of 3 mm. It was assumed that plants bent at an imaginary bending point at a certain depth below the soil surface, 0-10 mm less than the working depth of the harrow. In addition, it was assumed that the sideward bending angle would be restricted to about –40 to +40 degrees relative to the harrowing direction.

In the second case, if both files contained data on emergence point or rooting locations (Fig. 2.10B), the matching process proceeded in two steps. First, "firmly anchored" or "non-uprooted" plants were matched, using seed co-ordinates, emergence point locations before harrowing and root locations after harrowing. All plants in the second PL# file that were rooted within 10 mm from a plant or seed in the first PL# file were candidate. A unique match was considered certain if the rooting location of a non-uprooted plant lay within 6 mm from the seed or emergence position before harrowing. Second, plants from the first PL# file that were not matched, not uniquely matched or not certainly matched in the first step were matched with plants classified as “probably uprooted” or “weakly anchored/re-anchored”. These plants were matched only if their root position was not further than 6 mm away from the original seed or plant position. In that case, they were classified as “not uprooted”. Uprooted plants were not matched. Although moved plants could have rooted again at another plant’s site, the combination of plant position and anchorage force provided a reliable identification method. In addition, PLCOMB.BAS checked whether the number of non-uprooted plants in a row was equal to the number of measured anchorage forces of that row in the ANCHF file. If the second PL# file contained measurements six days after harrowing, the number of fresh weights in the FRESHW file was checked similarly.

2.4.4 Creation of tables for further analysis

After the #MAT files were manually edited to correct the suggested matches, a table of various plant attributes reflecting the life history of each plant was produced, using the DATATAB.BAS program and previously produced data files. This table (TAB in Fig. 2.8) was the basis for further data analyses. It states the treatment number, with the associated species, working depth, working speed, sowing depth and soil moisture content, identifications for bins and plants, information on the position of the seeds or the emerged plants before harrowing relative to the harrow tine paths, plant height at harrowing and six days later, the detailed growth stage classification, the leaf top distance and leaf angle of *L. sativum* at harrowing and the measured fresh weight or anchorage force, the uprooting status and the degree of covering immediately after harrowing and six days later, the sideward and downward bending angle, the leaf tip lowering and the covering depth directly after harrowing.

The materials and methods sections of chapters 3-6 explain how these parameters were calculated. After all data per bin were processed, the TAB files of all bins were merged in Microsoft Excel. Based on the final germination percentages in untreated bins, records were added to account for killed white threads of *L. perenne* and *L. sativum* in the last seeded bin, which could not be detected at harrowing. Similarly, some records of unmatched *C. quinoa* seeds were randomly removed to account for partial germination.

Table 2.4 presents the number of plants per detailed growth stage per treatment per species and Table 2.5 presents the average height of emerged plants at the time of harrowing. These tables show that plant size differences between treatments of a species could not be avoided. However, these differences have been partially accounted for by the statistical analysis of chapters 3-6.

2.5 Experimental design and statistical analysis

As the experimental procedure was quite laborious, the experimental design should be very efficient to be practical. Therefore, a reduced central composite design was used to examine the effects of working depth, working speed and soil moisture content in *L. perenne* and *L. sativum* experiments (Table 2.3; Fig. 2.11). A full central

Table 2.4 Number of plants per species, detailed growth stage and harrowing treatment.

	L. perenne					*L. sativum*					*C. quinoa*	
Treatment	white thread	breaking through	small	medium	large	white thread	breaking through	small	medium	large	white thread	small
Standard	45	275	262	84	2	32	26	65	344	143	563	23
Shallow seed	-	-	-	-	-	-	-	-	-	-	546	43
Deep seed	-	-	-	-	-	-	-	-	-	-	569	3
Shallow till	33	91	189	246	107	33	38	148	353	62	581	1
Deep till	31	93	178	248	118	53	38	92	306	129	448	164
Slow	51	162	326	512	279	41	33	154	339	45	581	1
Fast	43	170	238	183	35	55	48	194	413	136	579	4
Dry	8	98	105	185	184	31	14	56	265	172	68	275
Moist	34	27	51	162	411	88	31	71	329	111	466	167
Shallow*dry*fast	14	145	218	226	32	19	51	131	358	64	-	-
Shallow*wet*slow	13	97	187	285	64	64	57	101	268	109	-	-
Deep*dry*slow	22	418	151	37	1	22	80	167	332	14	-	-
Deep*wet*fast	18	99	162	179	177	86	45	120	297	54	-	-
Total	312	1675	2067	2347	1410	524	461	1299	3604	1039	4401	681

composite design of three experimental factors would have had eight instead of four interaction treatments and five instead of one repetition of the “centre” or “standard” treatment. Nevertheless, it was possible to estimate the main effects and first order interactions based on only 11 treatments in the reduced central composite design. A full factorial design with three levels per factor would have required 3 x 3 x 3 = 27 treatments.

Chenopodium quinoa experiments had seed depth as additional experimental factor. As a reduced central composite design would have required 17 treatments (1 centre, 8 extremes, 8 interactions), it was decided to give up the analysis of interaction effects and skip the 8 interaction treatments.

A bin was the experimental unit for the treatment factors species, working depth, working speed, soil moisture content and seed depth. Within a bin, individual plants were the experimental units for the factors growth stage and tine–plant distance. In analyses of plant recovery (chapter 6), also the degree of covering and the uprooting status induced by harrowing were treatment factors at the plant level. Therefore, the experiment was analysed as an unbalanced split-plot design, using generalised linear mixed models with two error strata (bins and plants).

Table 2.5 Measured leaf length of emerged *L. perenne* plants (mm) and hypocotyledon height of emerged *L. sativum* and *C. quinoa* plants at harrowing (mm). Means of all detailed growth stages except white threads. Standard errors between parentheses.

Treatment	*L. perenne*	*L. sativum*	*C. quinoa*
Standard	25.5 (8.8)	14.4 (3.2)	2.7 (1.4)
Shallow seed	-	-	2.3 (1.9)
Deep seed	-	-	7.9 (4.4)
Shallow till	35.6 (10.5)	11.6 (2.5)	2.8 (-)
Deep till	35.9 (10.6)	15.0 (3.6)	2.6 (1.5)
Slow	36.8 (10.4)	10.6 (2.7)	2.7 (-)
Fast	30.4 (10.3)	10.9 (2.7)	2.6 (1.8)
Dry	37.9 (13.0)	15.0 (2.8)	8.8 (3.7)
Moist	46.5 (10.6)	13.0 (3.2)	3.4 (2.2)
Shallow*dry*fast	31.5 (10.0)	12.0 (2.9)	-
Shallow*wet*slow	34.1 (10.0)	12.7 (3.1)	-
Deep*dry*slow	20.8 (9.0)	11.4 (3.1)	-
Deep*wet*fast	37.4 (12.8)	11.7 (3.8)	-
Average	34.2 (12.3)	12.5 (3.4)	5.3 (4.0)

Principally, each treatment was replicated in two bins that were harrowed in two separate passes (*C. quinoa*) or in one pass (*L. perenne* and *L. sativum*). Some treatments were partly repeated an extra time because of data loss or a defective SpaceArm. It was considered that less replicates would be required than in field experiments (generally 3 - 5), because the laboratory techniques were expected to considerably reduce variations in working depth, working speed, plant characteristics and soil properties. It was conceived that, with reduced experimental error, less residual degrees of freedom would allow accurate estimation of treatment effects.

It can be disputed whether the two bins per treatment can be considered as true replications, because both bins were harrowed at the same pass (*L. perenne* and *L. sativum*) and the same day instead of randomised over time. Furthermore, destructive assessment of uprooting directly after harrowing might yield different results than uprooting assessments six days later (method bias). Although this phenomenon occurred at some treatments (Table 2.6), no systematic differences could be detected in our experiments.

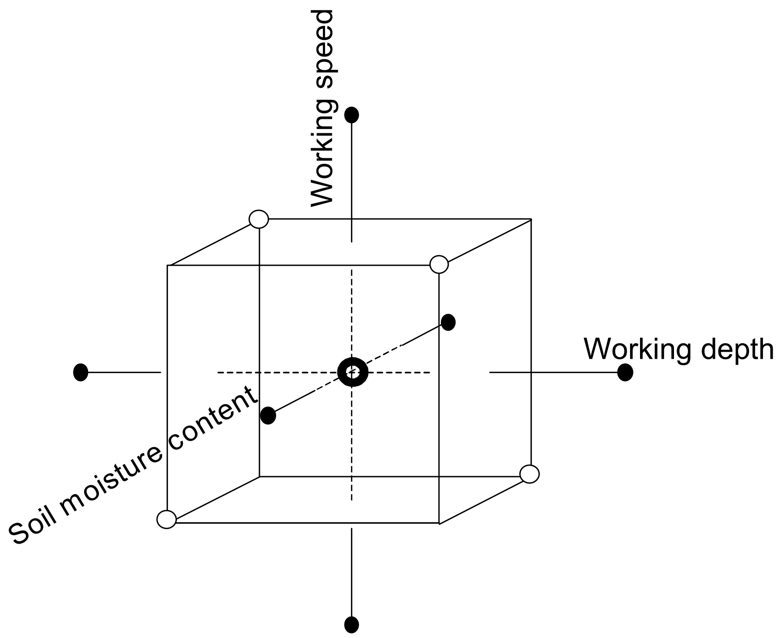

Fig. 2.11 Reduced central composite design with one “centre” or “standard” treatment (donut), two axis endpoints for each factor (solid dots) and four interaction treatments (open dots).

2.6 Closing remarks

Besides the high time requirement and the reduced similarity between laboratory and field conditions, this experimental set-up had two noticeable drawbacks. Firstly, treatments within a series could not be conducted simultaneously. Although experiments were performed under controlled conditions, time-dependent conditions may have introduced additional sources of error. Secondly, different species did not occur in the same experimental units (bins). Therefore it was principally not possible to address the significance of differences in damaging selectivity between species in a statistically sound way.

Both drawbacks become of smaller practical importance when experimental conditions can be better controlled. For our objective, these drawbacks were outweighed by the possibilities offered by the experimental method used:

- Accurate assessment of small-scale spatial effects related to soil–tool–plant interactions.
- Effects of variations within plant populations.
- *In situ* measurement of burial depth.
- The analysis of effects of sequential events and processes (relation between immediate and final effects on individual plants) through reconstruction of the life history, because individual plants could be traced (except uprooted ones).
- The assessment of immediate and final effects of harrowing at the white thread stage if the germination probability is known.

Table 2.6 Differences in uprooting percentages between bins of a treatment. With *L. perenne* and *L. sativum*, a positive number means that more plants were found uprooted in the bin returned to the climate chamber than in the bin assessed destructively directly after harrowing. Only differences > 7% are displayed. Significance was tested by *t*-tests using binomial distributions.

	L. perenne		*L. sativum*		*C. quinoa*	
Treatment	emerging plants	seedlings	emerging plants	seedlings	emerging plants	seedlings
Standard		9	16		15 **	
Shallow seed	-	-	-	-		8
Deep seed	-	-	-	-		
Shallow till			–17		–12 *	
Deep till			–10			
Slow						
Fast	–7		30 **		–9	
Dry	–29 *		31			
Moist		12 **	–31 **		8	
Shallow*dry*fast	–24 *				-	-
Shallow*wet*slow	–12		–19	8	-	-
Deep*dry*slow	–33 ***				-	-
Deep*wet*fast	20	10			-	-

* = significant at the *P* <0.05 level.
** = significant at the *P* <0.01 level.
*** = significant at the *P* <0.001 level.

To the knowledge of the author, a method providing all these possibilities has not been developed before. These possibilities may be significant for future research on mechanical weed control.

3 The selective soil covering mechanism of weed harrows on sandy soil

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Summary

Improvement of intra-row mechanical weed control is important to reduce the reliance on herbicides in arable crops and vegetables. Covering weeds by soil is an important weed control mechanism of weed harrows. A shallow post-emergence harrow cultivation controls weeds but also damages the crop to some extent. This paper explores how plants get covered by soil and how a plant's resistance against being covered is related to its height, flexibility and shape of leaves.

Seedlings of two contrasting species were sown in bins filled with a sandy soil and harrowed by a small model harrow in the laboratory. Covering selectivity (percentage covered ryegrass / percentage covered garden cress) could be influenced by soil moisture content, working depth and working speed. Differences in covering were related to spatial patterns of plant downward bending and soil surface level upheaval. These patterns are associated with soil failure patterns near tines and soil flow patterns, connected with different effects of plant height and plant flexibility.

This study indicates that relationships between weed control and crop covering may not only depend on weed and crop characteristics but also on soil conditions and implement settings. As less than 10% of the covered plants were buried deeper than 15 mm, covering would mainly cause growth reduction and little killing. Limited burial depth may be an important cause for limited weed control effectiveness of harrowing.

Keywords: *weed harrowing, mechanical weed control, selectivity, biomechanics.*

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3.1 Introduction

Field experiments have shown that weed harrowing before and after crop emergence can considerably reduce the reliance on herbicides for weed control in arable crops and vegetables (van der Weide *et al.*, 1993). To enhance a broader acceptance of weed harrowing and other mechanical weed control methods in agricultural practice, the required number of cultivations (up to 8 passes according to Rasmussen, 1991a; Baumann, 1992) and dependence on favourable weather conditions (concerning workability and effectiveness) should be reduced.

The weather dependence and required harrowing frequency are generally high because harrowing predominantly kills or suppresses small weeds in early growth stages. Since Habel (1954), Kees (1962) and Koch (1964a) found that harrowing uproots only a small proportion (1-24%) of the weeds, covering by a loose soil layer is generally perceived as the primary mode of control. As plants grow older, they become taller and less flexible and therefore become more resistant to being covered by soil (Meyler & Rühling, 1966). In addition, larger plants are more able to break through a covering soil layer (Habel, 1954; Kees, 1962; Koch, 1964b). As spring tine harrows and other implements for intra-row mechanical weeding affect both crop and weeds, differences in resistance against covering and recovery capability between crop and weeds must be exploited to give the crop a relative advantage over the weeds.

Meyler & Rühling (1966) measured the bending resistance of shoots of barley, wheat and five weed species. They found that the more rigid species were less covered in the weed harrowing experiments performed by Habel (1954) and Koch (1964a). The difference in bending resistance between cereals and weeds also increased in the course of time, meaning that harrowing at the 5-leaf stage of the cereal could be more selective between crop and weeds than at the 2-3 leaf stage. In those later growth stages, however, the attainable harrowing intensity may not be sufficient to control weeds that have become more established meanwhile. Nevertheless, Rasmussen (1991a) found 69-95% weed control without crop damage after five passes on two dates with a heavy spring tine harrow, whose tines were pushed sideward by the 0.2-0.25 m tall winter wheat. Instead of aggressive harrowing on bigger weeds in late crop stages, Baumann (1992) achieved 90% and 86% weed control without crop damage in maize and horse beans by repeated (2-8 times) weed harrowing at a low driving speed and low tine pressure when weeds were in the cotyledon stage.

Covering of crop and weeds is not only governed by their resistance against being covered, but also by the intensity (or aggressiveness) of harrowing. Increased working speed (Neururer, 1977; Rydberg, 1993; Pullen & Cowell, 1997), an increased number of consecutive passes (Rasmussen, 1991a; Wilson *et al.*, 1993; Rasmussen & Svenningsen, 1995), increased working depth (Rydberg, 1995; Søgaard, 1998) and friable topsoil (Habel, 1954; Koch, 1964a; Rydberg, 1993; Wilson *et al.*, 1993) generally improve weed control. However, in comparable crop–weed situations, increased weed control generally goes together with a more than proportional increase of crop covering (Rasmussen, 1990; Rasmussen & Svenningsen, 1995).

To balance the negative effect of crop damage and the positive effect of reduced weed competition on crop yield, Rasmussen (1991b, 1993) developed a modelling approach for optimising the harrowing intensity, based on empirical relationships between (1) weed control and crop damage, (2) weed density and crop yield and (3) crop damage and crop yield. Especially relationships (1) and (3) still lack predictive ability, as they may depend on weed and crop species, their growth stages (Rasmussen, 1993) and soil conditions. Therefore, fundamental research into the underlying mechanisms of mechanical weed control is needed to understand how and why (differences in) plant characteristics, soil conditions and implement handling change these relationships. Such basic research would support the further development of quantitative methods for optimising the timing and intensity of harrowing in different crop growth stages.

The presented research attempts to provide a fundamental understanding of the selective covering ability of weed harrows. This chapter quantifies the effects of working depth, working speed and soil moisture content of sandy soil on the percentage covered plants and burial depth for two contrasting species that represent weeds or crops in an early growth stage. These effects will be related to the spatial pattern of soil surface upheaval and leaftip lowering. Based on detailed observations from harrowing experiments in the laboratory, we clarify the role of plant height, plant flexibility and leaf morphology for a plants' resistance against being covered. Finally we explore possibilities to manipulate covering selectivity and discuss the implications for the relationship between weed control and crop covering in the optimisation of harrowing intensity.

3.2 Materials and methods

3.2.1 Plants

Two species were selected to represent weed or crop seedlings in early growth stages that have contrasting seedling flexibility, shape and height. Ryegrass (*Lolium perenne* L.) and garden cress (*Lepidium sativum* L.) were harrowed 3-4 days after emergence. Ryegrass had one thin, 1-70 mm (average 34 mm) long leaf, which is more flexible than the relatively thick and short hypocotyledon of garden cress in the cotyledon stage. Garden cress seedlings are relatively small (0-25 mm, average 12.5 mm), but the well-established cotyledons of the bigger seedlings (11 mm average distance between cotyledon tips) might be captured more easily by moving soil. Smaller garden cress seedlings had folded or small cotyledons, with tips spaced 6 mm.

3.2.2 Experimental design

For each species, the effects of working depth, working speed and soil moisture content were analysed in two separate experiments, each having a reduced central

Table 3.1 Levels of experimental factors per treatment. Soil moisture contents (g water per 100 g dry soil) are measured averages from the tilled layer directly after harrowing.

Treatment	Working depth (mm)	Working speed (m/s)	Soil moisture content (% w/w)
Standard	20	1.8	10.7
Shallow till	10	1.8	10.3
Deep till	30	1.8	11.0
Slow	20	1.2	10.7
Fast	20	2.4	10.4
Dry	20	1.8	4.7
Moist	20	1.8	15.7
Shallow*dry*fast	15	2.1	7.0
Shallow*wet*slow	15	1.5	13.2
Deep*dry*slow	25	1.5	7.7
Deep*wet*fast	25	2.1	13.6

composite design of 11 treatments, centred around the standard treatment (Table 3.1). The experimental design is an unbalanced split-plot, with bins as main-plots and individual plants regarded as subplots. The effects of species, working depth, soil moisture content and speed were analysed on the main-plot level, whereas effects of plant height and plant position (relative to the harrow tine pattern) were analysed on the subplot level. Each treatment was replicated in at least two seeded bins per species. Each bin was seeded with 357 seeds of which 167-303 emerged. The natural variation in emergence rate between seeds was used to study effects of plant height.

3.2.3 Bin preparation

To avoid the complexity associated with aggregated soils (spatially inhomogeneous and hardly repetitive topsoil conditions, irregular soil failure patterns), harrowing was performed on fine black sand with moderate organic matter content (3.2% organic matter content, 3.0% clay, 6.5% silt, Dutch classification zEZ21). Predetermined weights of sieved soil were filled into aluminium bins (l x w x d = 0.60 x 0.40 x 0.13 m), carefully levelled and compacted by a hydraulic ram to a homogeneous dry-bulk density of 0.95 Mg/m^3. On this compacted layer, a hand-operated vacuum sowing mould placed seeds of one species in a rectangular grid of 21 rows of 17 seeds parallel to the harrowing direction. Subsequently, the top soil layer was carefully filled in and compacted, giving a seed depth of 10 mm for both species. Seeded bins were covered by a 5-mm layer of polystyrene pearls and sealed by a glass plate to prevent

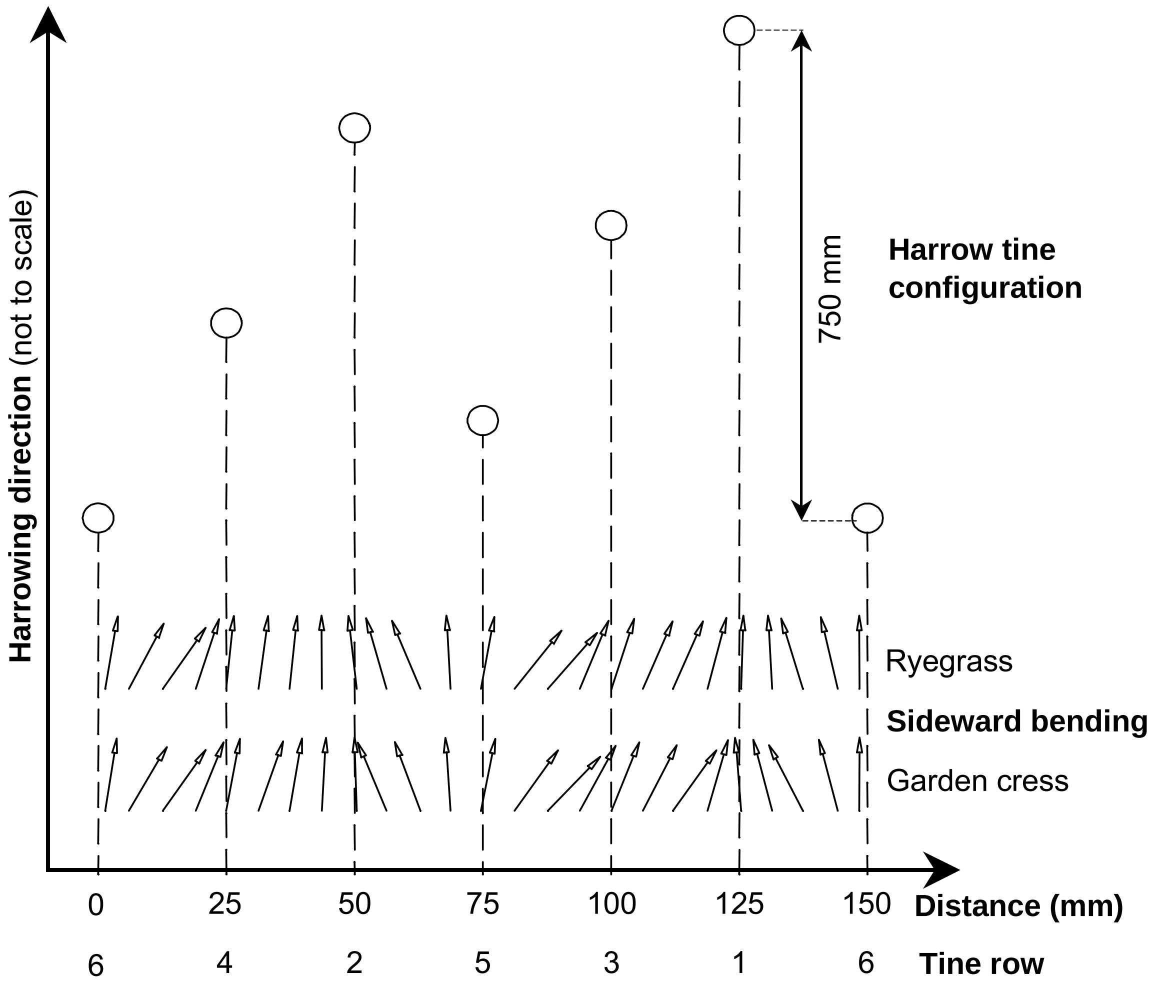

Fig. 3.1 Tine configuration (circles = tines; dashed lines = tine paths) and sideward bending angle per distance class of ryegrass leaves and garden cress hypocotyledons (arrows) after harrowing (top view). Angles are medians of all digitised seedlings from all treatments. The model harrow consists of four of these tine configuration patterns side by side.

evaporation. The bins remained in a climate chamber for periods of varying duration, to obtain similar development stages for all treatments of a species.

3.2.4 Model harrow

The model harrow had six rows of tines, with 23 rigid vertical tines of 6 mm diameter. Tine paths were spaced 25 mm apart, with a tine configuration like that of conventional spring tine harrows (Fig. 3.1). The rigid tines follow fixed paths as the model harrow was mounted on a rail carriage, so the soil in the bins was tilled at a pre-set working speed and accurate working depth. The combination of 23 tine paths spaced 25 mm and 21 seed rows spaced 22.5 mm yields a uniform distribution of tine–plant distances. Therefore, a bin approximates a full-field situation with randomly distributed weeds.

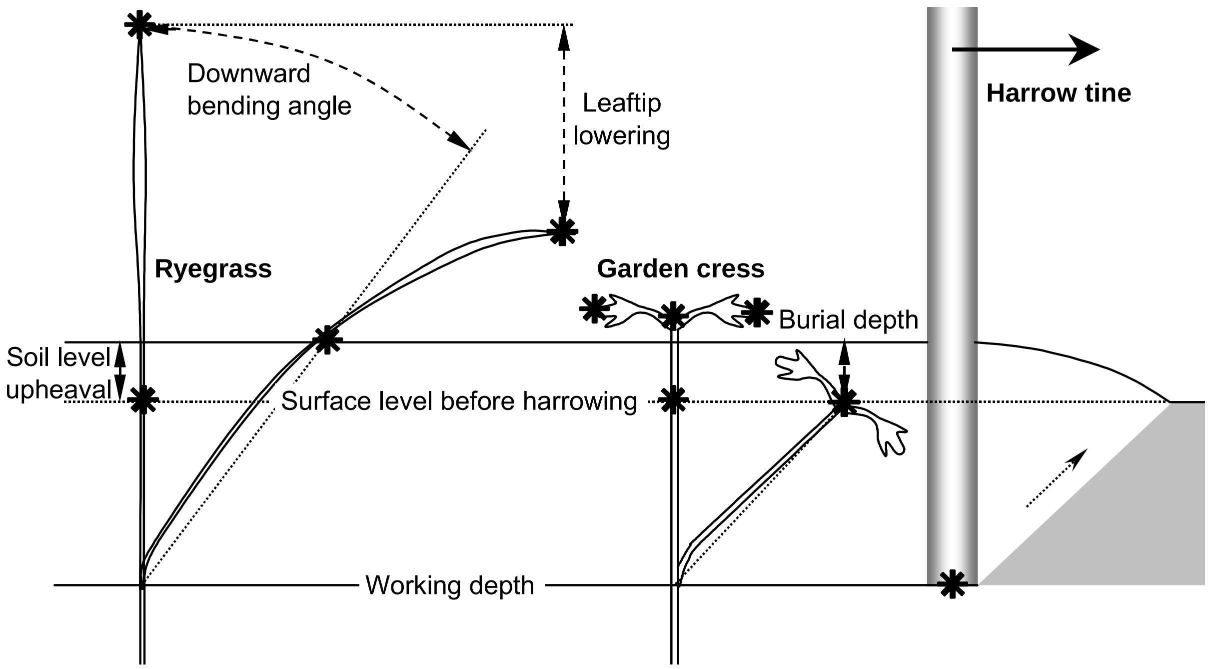

Fig. 3.2 Digitised coordinates (marked *) of a harrow tine and a ryegrass and garden cress seedling before and after harrowing, with illustration of derived parameters (side view).

3.2.5 Harrowing procedure and plant measurements

Just before harrowing, the polystyrene pearls and the long-side walls of the bins were removed. Two seeded bins were screwed together on a reference frame, between two non-seeded soil bins. To take account of natural size variation between plants within a bin, the height and position of each emerged plant were measured using an electromechanical computer-linked 3D digitising device (SpaceArm™, FARO Technologies, 125 Technology Park, Lake Mary, FL 32746-6204, USA). In addition, the size and development of garden cress cotyledons was assessed visually. Directly after harrowing, all visible plant co-ordinates were digitised again (Fig. 3.2), while assessing their uprooting status and their individual degree of covering (the estimated percentage covered leaf area in steps of 10%). Completely covered plants in the first seeded bin were digitised after carefully excavating part of the tilled soil using an adapted vacuum cleaner, so leaf- or hypocotyledon tips could be digitised before disturbing their position. The second seeded bin was left undisturbed after harrowing, so covered plants were not digitised.

3.2.6 Data processing, calculation of sideward and downward bending angle and burial depth

Co-ordinate transformation and plant matching software identified plants before and after harrowing and linked information on each plant's degree of covering, height and position relative to the tine paths. The sideward and downward bending angle of the subsurface part of the plant were calculated from the locations where the hypocotyledon or leaf emerged through the soil surface before and after harrowing, with the assumption that plants remain straight while bending at the working depth level (Fig. 3.2). The bending angles of covered plants were calculated from the leaftip location and the original point of emergence. The sideward bending angle is the projected angle on the horizontal plane, whereas the downward bending angle is measured in the vertical plane parallel to the bending direction. Plant bending angles were only calculated for non-uprooted emerged plants, if the above mentioned points are sufficiently spaced to give accuracy better than 10°, associated with the SpaceArm™ measurement accuracy of 1 mm.

The burial depth of completely covered emerged plants was calculated as the vertical distance between the buried tip of leaf or hypocotyledon and the soil surface. This distance was calculated from a surface profile perpendicular to the harrowing direction with a 1-mm grid, derived from at least 1000 digitised soil surface points.

3.2.7 Statistical analysis

To account for tine pattern-induced variations within a bin, non-uprooted plants were divided into 25 distance classes (DC) according to their position relative to the tine pattern (Fig. 3.1). The fraction completely covered plants (covering, $C = c / n$, with c = number of completely buried plants and n = total number of plants) was analysed by generalised linear mixed models with two variance components (bins and plants), a logit link [logit (C) = ${}^{e}\log(c / \{n - c\})$] and a binomial variance function allowing for overdispersion. The IRREML directive of the CBW Genstat procedure library 4.1 (Goedhart & Thissen, 1998) and the GENSTAT 5.4.1 statistical package (Genstat 5 Committee, 1993, 1997) were used to estimate effects of species (P), plant height (H), working depth (WD), working speed (S) and soil moisture content (MC) on covering by model (1):

$$\text{logit}(C) = \text{DC} + P + P{\cdot}H + P{\cdot}\text{WD} + P{\cdot}\text{S} + P{\cdot}\text{MC} \qquad (1)$$

To examine whether working depth, speed and soil moisture would change the effects of plant height on covering, this model was extended to model (2):

$$\text{logit}(C) = \text{DC} + P + P{\cdot}H + P{\cdot}\text{WD} + P{\cdot}\text{S} + P{\cdot}\text{MC} + P{\cdot}H{\cdot}\text{WD} + P{\cdot}H{\cdot}\text{S} + P{\cdot}H{\cdot}\text{MC} \qquad (2)$$

To examine interactions between effects of working depth, working speed and soil moisture content, model (1) was extended to model (3):

$$\text{logit}(C) = \text{DC} + P + P{\cdot}H + P{\cdot}\text{WD} + P{\cdot}\text{S} + P{\cdot}\text{MC} + P{\cdot}\text{WD}{\cdot}\text{MC} + P{\cdot}\text{WD}{\cdot}\text{S} + P{\cdot}\text{S}{\cdot}\text{MC} \qquad (3)$$

Significance of the terms and differences between parameter values were evaluated by t-tests.

The downward bending angle was analysed in a similar way, assuming a normal error distribution. For the downward displacement of the leaftip or hypocotyledon tips

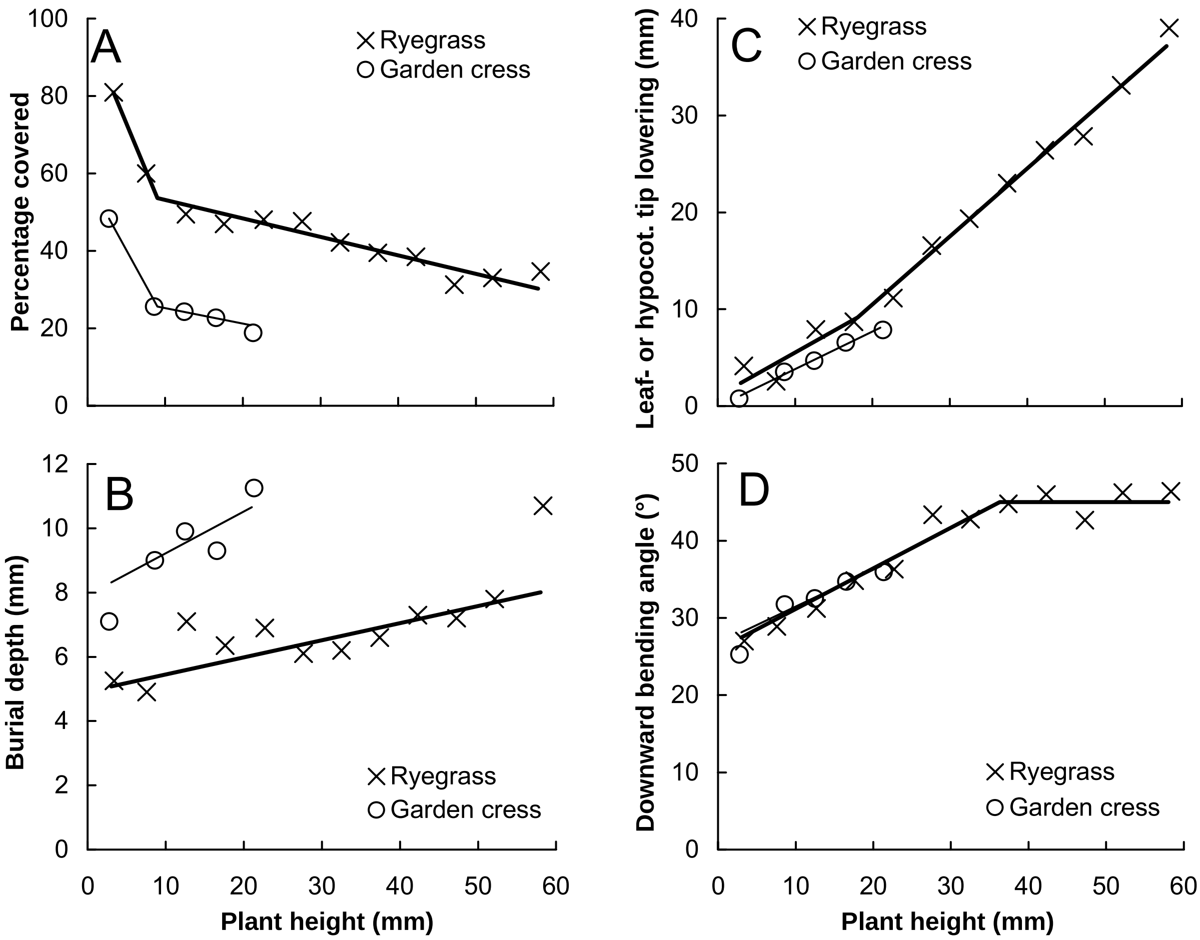

Fig. 3.3 Effect of plant height on the percentage covered plants (A), their burial depth (B), leaftip and hypocotyledon tip lowering (C) and downward bending angle (D). Averages (A,D) or medians (B,C) from all treatments.

(hereafter termed leaftip lowering) and the burial depth, analysis on a log-scale (with a proportional model) appeared more appropriate.

As the position and height of uprooted seedlings is not known, covering of uprooted plants (which have a loose root and are displaced further than 6 mm from the original position) is compared to covering of non-uprooted plants by a separate analysis using the plant counts per bin instead of data from individual plants.

3.3 Results

3.3.1 Effects of species, plant size and uprooting

Although ryegrass was nearly three times taller than garden cress, harrowing covered a greater proportion of the ryegrass seedlings (Fig. 3.3A, $P < 0.001$, on average 41% and 31%, respectively, of the non-uprooted plants). Uprooted plants were 12% more covered than non-uprooted plants of the same species (not shown,

$P < 0.01$, ryegrass: 53%, garden cress: 43%). Covered garden cress was buried deeper than covered ryegrass (Fig. 3.3B, $P < 0.001$, medians 9.6 mm and 6.7 mm respectively). The relationship between covering and the vertical distance between leaf- or hypocotyledon tips and the soil surface (not shown) indicates that garden cress must be bent further downwards to achieve the same degree of covering. This extra distance (6 mm) corresponds to half the distance between cotyledon tips.

Taller plants of the same species were less covered (Fig. 3.3A, $P < 0.001$), but those covered taller plants were buried deeper (Fig. 3.3B, ryegrass: $P < 0.001$, garden cress: $P < 0.05$). For plants taller than 9 mm, the absolute proportion of covered plants decreased linearly with plant height, with an equal slope for both species (Fig. 3.3A). The steepest decline in covering occurred in the plant height range between 0 and 9 mm. Although ryegrass leaves were lowered further than garden cress hypocotyledons (Fig. 3.3C), the relationship between plant height and downward bending angle (Fig. 3.3D) was essentially the same for both species.

3.3.2 Spatial variability

The harrow tines cause forward and sideward soil movement, which causes plants to bend sideward (Fig. 3.1) and downward (Fig. 3.2), while leaving soil ridges between tine paths of the fifth and sixth tine row (Fig. 3.4). This process caused the proportion of covered plants to vary in the direction perpendicular to the harrowing direction (Fig. 3.5). Less than 30% of all plants standing in trenches between the soil ridges were covered, whereas the ridge covered about 40-80%. With ryegrass, short and tall plants were only covered to a different degree when plants stood in the soil ridge. The spatial pattern of garden cress burial depth (not shown) was similar to Fig. 3.5, whereas ryegrass burial depth was not spatially variable (not shown).

Plants near tine paths bent downward further than plants between the tine paths (Fig. 3.4). This bent position was preserved where subsequent tines immediately put soil on top of the pushed-over plants, whereas plants in trenches (between soil ridges) appeared to flex back upward again. The working depth effect on the spatial pattern of covering (Fig. 3.5A) and leaftip lowering of ryegrass (Fig. 3.4A) not only illustrates this preserving role of loose soil, but also marks the effect of the soil failure pattern around a tine. At shallow harrowing depth, soil between tine paths hardly got loosened and displaced forward, whereas deep harrowing intensely disturbed the entire topsoil.

3.3.3 Effects of working depth

Increased working depth promoted covering of both species (Fig. 3.6, ryegrass: $P < 0.05$, garden cress: $P < 0.001$), but the effect on garden cress was more than three times stronger than on ryegrass ($P < 0.05$). Deeper tillage increased the ryegrass leaftip lowering (Fig. 3.8, $P < 0.01$) but did not significantly increase burial depth of both species (Fig. 3.7). With garden cress, deeper harrowing yielded a much steeper relationship between plant height and downward bending angle (not shown, $P < 0.01$) and hypocotyledon tip lowering (not shown, $P < 0.05$). Nevertheless, working depth

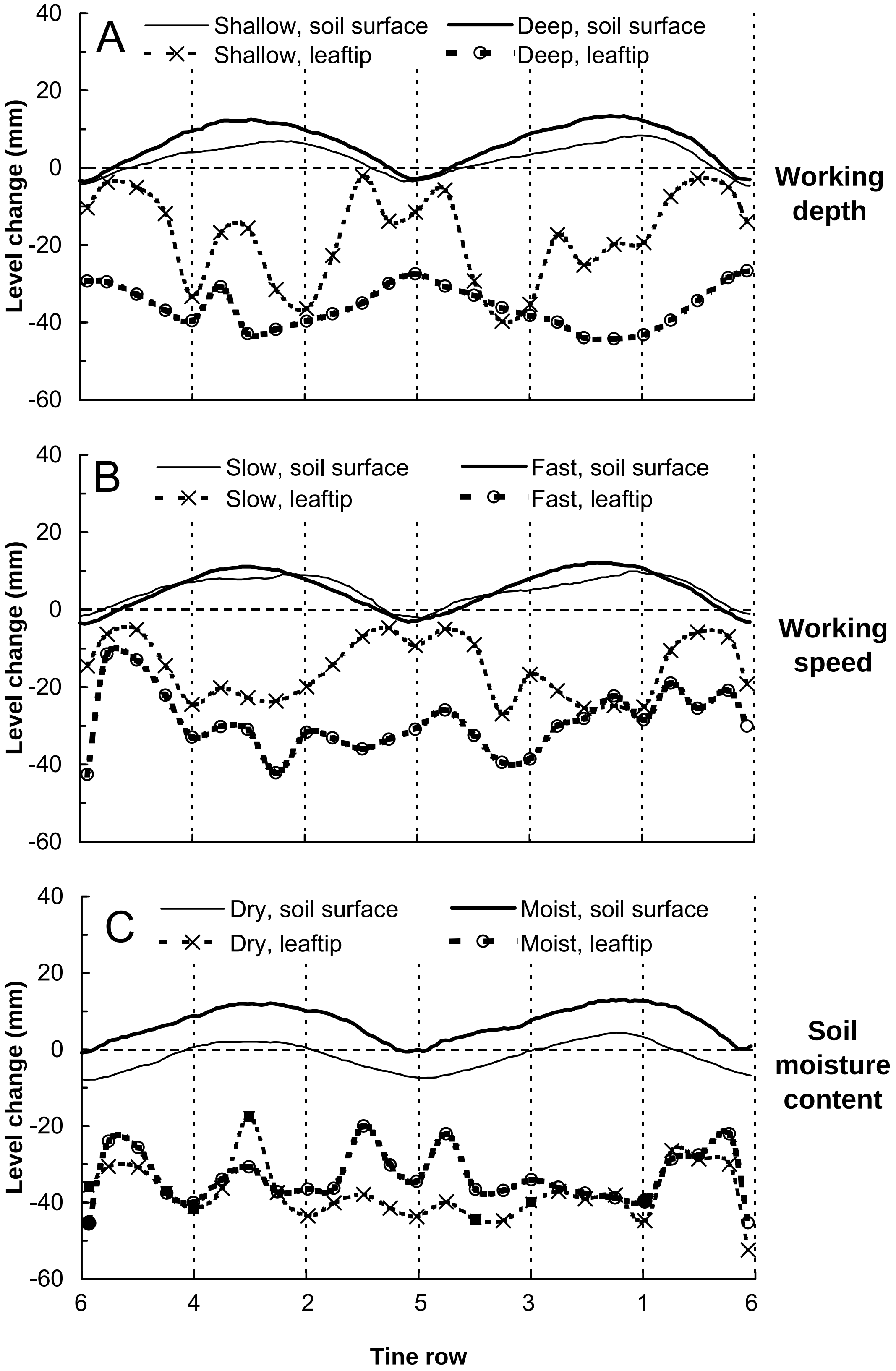

Fig. 3.4 Average soil surface upheaval and median ryegrass leaftip lowering as related to plant and tine path positions (see Fig. 3.1). Effects of working depth (A), working speed (B) and soil moisture content (C). Bold points represent less than 10 measured plants.

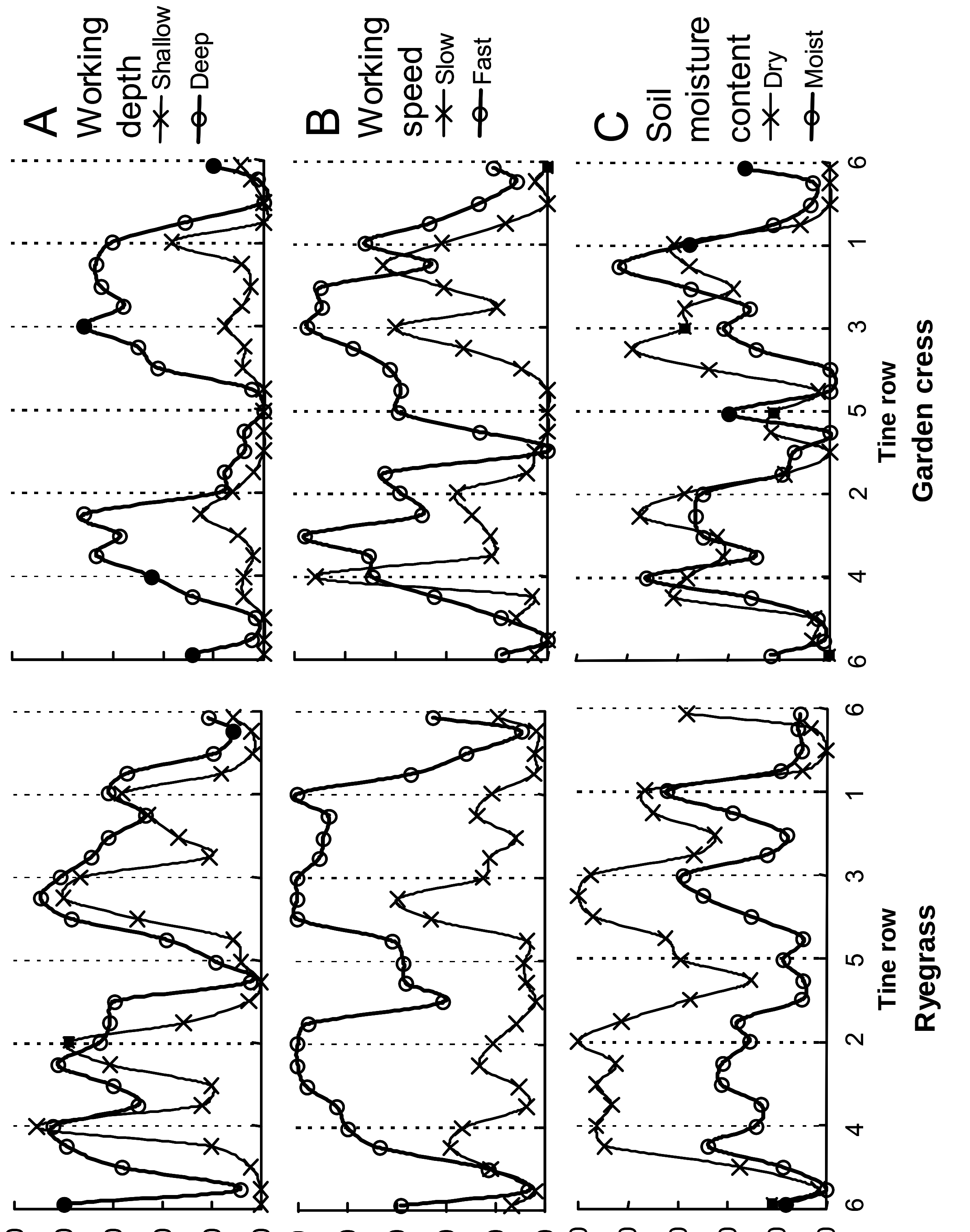

Fig. 3.5 Covering of ryegrass (left) and garden cress (right) as related to plant and tine positions (see Fig. 3.1). Effects of working depth (A), working speed (B) and soil moisture content (C). Bold points represent less than 10 seedlings.

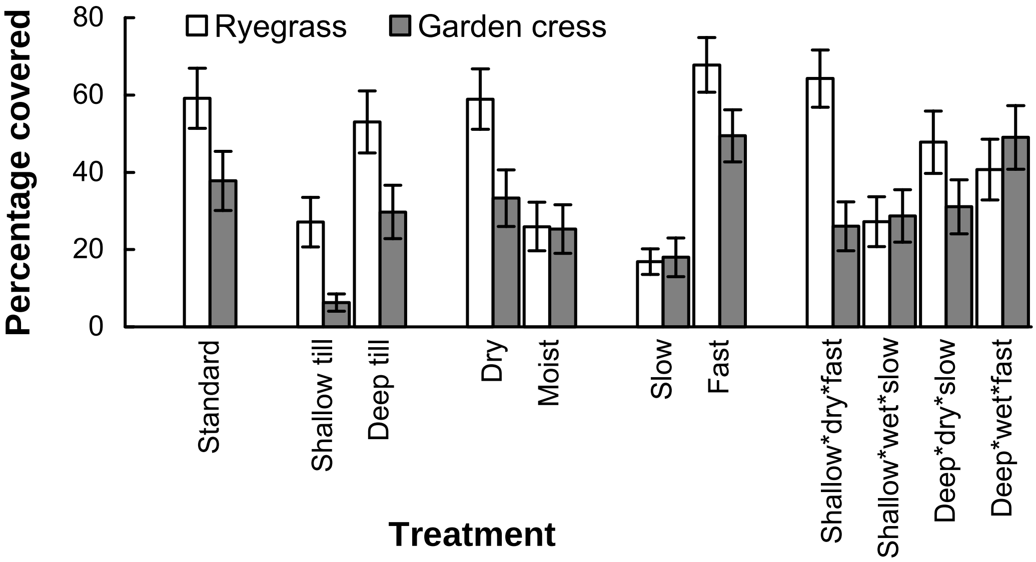

Fig. 3.6 Mean percentage covered seedlings per treatment and species, with bars representing mean standard errors.

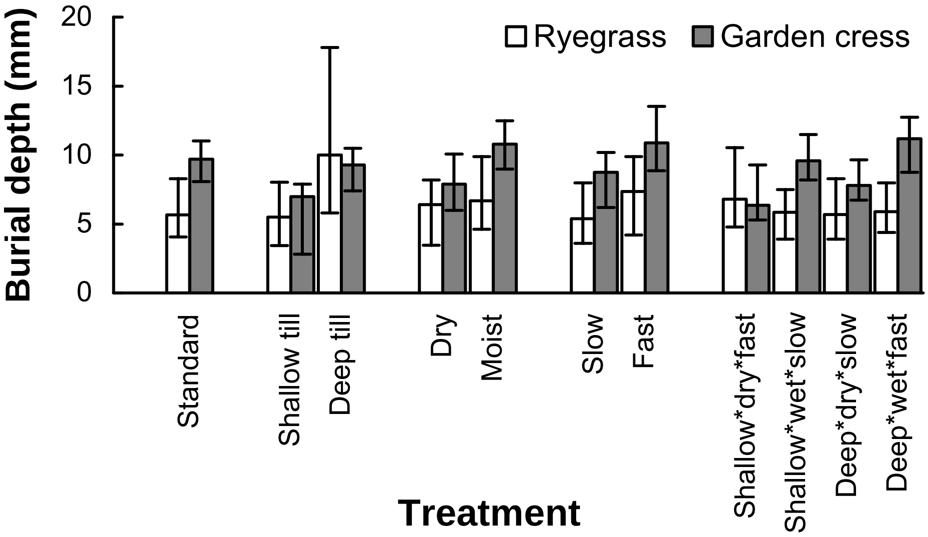

Fig. 3.7 Median burial depth of covered seedlings per treatment and species, with bars representing quartiles.

had no significant effect on the relationship between plant height and covering.
The increased surface level upheaval at increased working depth (+ 6 mm) caused a relatively important contribution to the covering capacity of harrowing capacity of garden cress (Fig. 3.8). However, with ryegrass, increased leaftip lowering (+ 14 mm) largely exceeded the contribution of soil level upheaval (+ 3 mm).

Figure 3.5A clarifies the different backgrounds of the working depth effect: increased covering of garden cress solely occurs in the soil ridges (because of soil

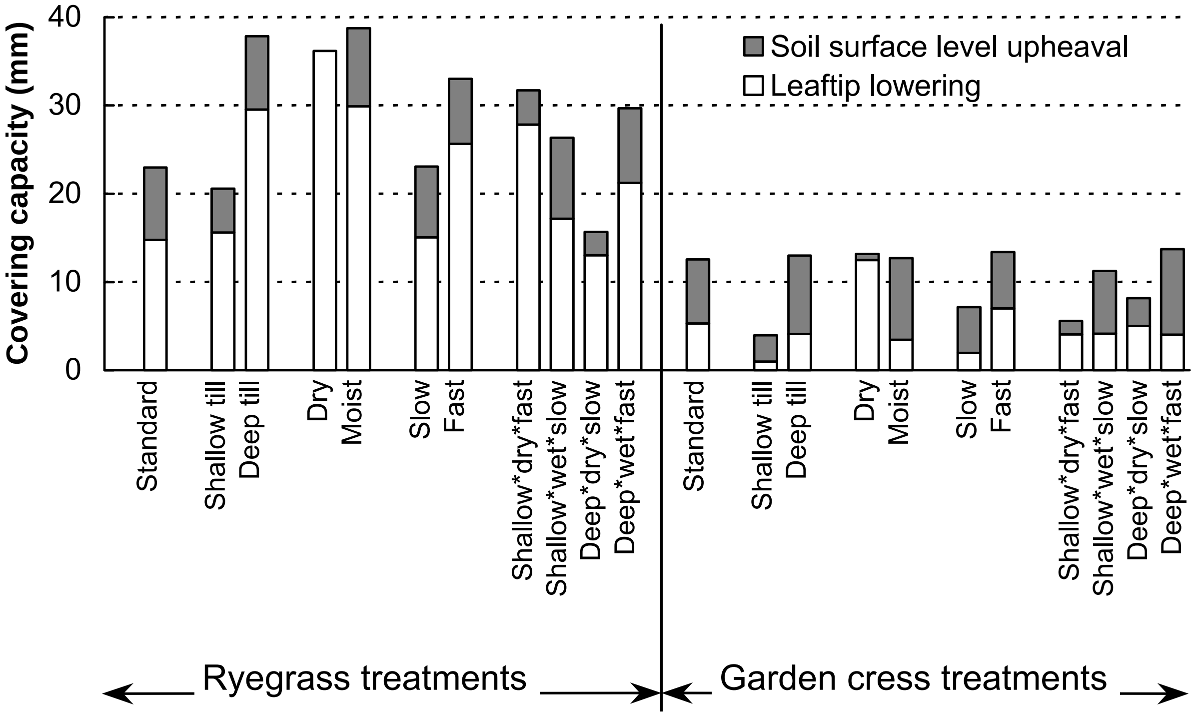

Fig. 3.8 Contributions of soil surface level upheaval and leaftip lowering to the covering capacity (sum of level change) per treatment and species.

level upheaval), whereas widened “covering peaks” near tine paths (because of downward bending) mostly contribute to increased covering of ryegrass at increased harrowing depth.

3.3.4 Effects of working speed

Increased working speed resulted in more covering of ryegrass (Fig. 3.6, $P < 0.001$) and garden cress ($P < 0.01$), but did not increase burial depth significantly (Fig. 3.7). The effect of working speed on covering increases considerably when plants are taller, especially with ryegrass (not shown, ryegrass: $P < 0.001$, garden cress: $P < 0.01$). This made harrowing at low speed more selective (Table 3.2).

Faster harrowing increased the downward bending angle and leaftip lowering (Fig. 3.8, ryegrass: $P < 0.001$, garden cress: $P < 0.05$), especially of the taller plants (not shown, ryegrass: $P < 0.001$, garden cress: $P \approx 0.11$). As working speed hardly influenced surface level upheaval (Fig. 3.8), the working speed effect on covering is mainly due to increased lowering of hypocotyledons or leaves. Particularly near the trench created by the fifth tine row, seedlings bent further downward (Fig. 3.4B) and about 50% remained covered at high speed (Fig. 3.5B), probably because the tines from the sixth tine row threw soil into the trench created by fifth tine row. Deeper harrowing enhances the speed effect on covering (Table 3.3, $P \approx 0.15$).

Table 3.2 Predicted effect of plant height and working speed on the percentage covered plants at 20 mm harrowing depth and 10.7% soil moisture content, using regression model 2.

Species	Plant height (mm)	Working speed (m/s)	
		1.2	2.4
Ryegrass	10	34	62
	40	18	70
Garden cress	10	14	39
	20	4	43

Table 3.3 Predicted effect of working depth and working speed on the percentage covered plants at 10.7% soil moisture content, using regression model 3.

Species	Working depth (mm)	Working speed (m/s)	
		1.5	2.1
Ryegrass	15	11	15
	25	36	64
Garden cress	15	11	19
	25	19	51

Table 3.4 Predicted effect of soil moisture, working depth and working speed on the percentage covered ryegrass, using regression model 3.

Working depth (mm)	Working speed (m/s)	Soil moisture content (%w/w)	
		7.5	13.5
15	1.8	36	35
25	1.8	66	35
20	1.5	29	28
20	2.1	73	43

3.3.5 Effects of soil moisture content

A drier soil solely enhanced covering of ryegrass (Fig. 3.6, $P < 0.001$) and decreased burial depth solely for garden cress (Fig. 3.7, $P < 0.05$). In addition, dry soil considerably magnified the effects of working depth ($P < 0.05$) and working speed ($P \approx 0.067$) on covering of ryegrass (Table 3.4). Harrowing caused the fragile structure of the dry soil to collapse, whereas the more coherent moist soil formed chunks.

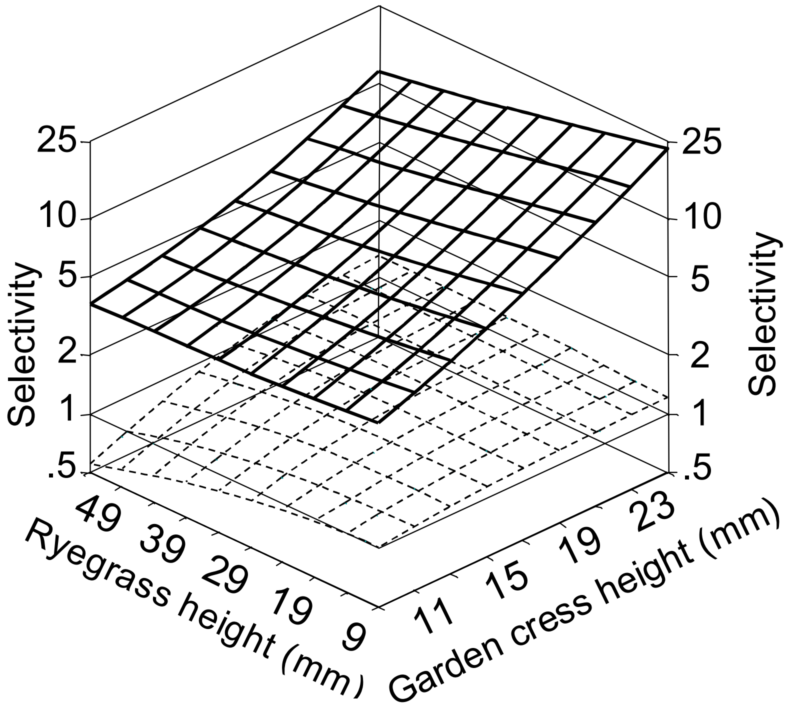

Fig. 3.9 Predicted maximum (bold) and minimum (dashed) covering selectivity (log scale, percentage covered ryegrass / percentage covered garden cress) as related to plant height of the ryegrass "weed" and the garden cress "crop". Based on simulations using parameters from regression model (2), with values for working depth, working speed and soil moisture content lying within the reduced central composite design "sphere" around the standard treatment (no extrapolation).

Although the soil surface level after harrowing on dry soil was 9 mm lower than on moist soil (Fig. 3.4C), increased leaftip lowering at dry soil (Fig. 3.8, ryegrass: $P < 0.001$, garden cress: $P < 0.05$) compensated for the lower surface level. Drier soil also levelled out the plant height effect on covering of ryegrass (not shown, $P < 0.05$).

3.3.6 Covering selectivity

Regression model (2) was used to search combinations of working depth, working speed and soil moisture content for maximum and minimum covering selectivity for all plant height combinations, when controlling ryegrass-like weeds in a garden cress-like crop (Fig. 3.9). The vertical distance between the two surfaces in Fig. 3.9 indicates that these factors have a considerable effect on the selective action of the harrow. For example, with 54 mm tall ryegrass and 9 mm tall garden cress, shallow fast harrowing in dry soil (11 mm, 1.95 m/s, 8.6%) would mostly cover the flexible ryegrass seedlings (45%, at 12% covering of garden cress, selectivity = 3.8), whereas relatively deep and slow harrowing in moist soil (25 mm, 1.4 m/s, 14%) would mostly cover short garden cress plants (28% at 16% covering of ryegrass, selectivity = 0.56). Plant height of both species hardly influences the optimal working

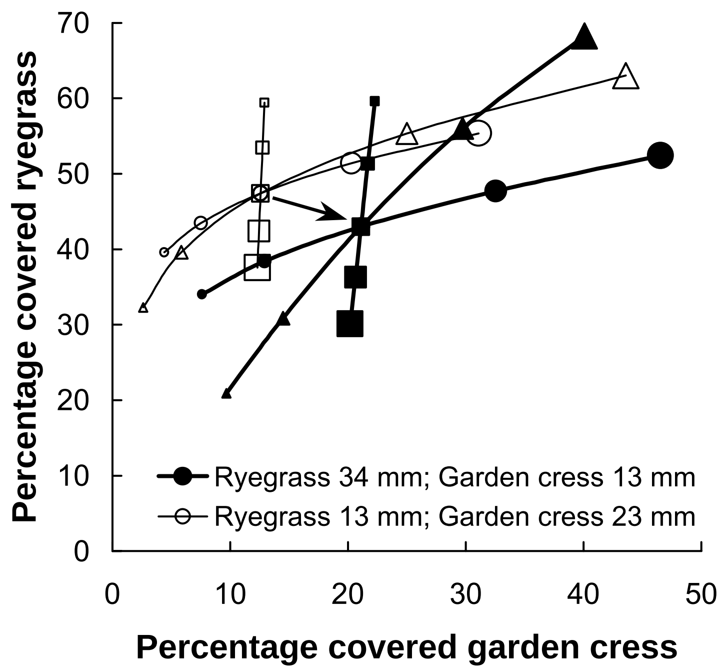

Fig. 3.10 Predicted effects of increasing working depth (circles of increasing size), increasing working speed (triangles of increasing size) and increasing soil moisture content (squares of increasing size) on covering curves for two combinations of ryegrass and garden cress plant heights, using regression model (2).

depth and soil moisture content (simulations, not shown), whereas the optimal working speed is lower with shorter ryegrass and taller garden cress. The maximum achievable covering selectivity depends much more on garden cress plant height than on ryegrass plant height (Fig. 3.9).

Figure 3.10 shows that working depth and working speed affect the predicted relationship between covering of ryegrass and garden cress (covering curves) in a similar way with short (13 mm) ryegrass "weeds" in a tall (23 mm) garden cress "crop" (thin lines). In taller (34 mm) ryegrass and shorter (13 mm) garden cress (bold lines), the curves for working depth (circles) and soil moisture (squares) would mainly shift sideward and downward. Variation of working speed would yield a steeper curve (triangles), which means that taller ryegrass is relatively more sensitive to speed increase. The different slopes of the curves reflect that ryegrass and garden cress respond differently to changes in working depth, working speed and soil moisture content.

3.4 Discussion

3.4.1 The covering mechanism

From a biomechanical viewpoint, effects of plant characteristics on their resistance against being covered seem consistent and understandable (Fig. 3.2). Covering arises from raising the soil surface level and/or lowering the plant sprout. Taller plants and plants having widespread leaves need to be bent further downward to cover them completely with soil. When shorter plants are pushed over, a similar bending angle would cause less leaftip lowering. Moreover, shorter plants were pushed over less far, probably because the force applied by moving soil and the resulting bending momentum depend on the size of the “soil capture surface” and its distance to an imaginary bending point. Therefore, upheaval of the soil surface is relatively more important when plants are shorter. Downward bending becomes more important when taller plants should be covered.

During the pass of the harrow tines, plants may be pushed over by (1) friction between near- and sub-surface plant parts and the soil stream in the failure zone near a tine, and by (2) inertial force of fast-moving soil particles being thrown out of the furrow, colliding with higher plant parts. These types of force transfer are related to vertical gradients of forward soil movement distance (as observed by Kouwenhoven & Terpstra, 1970) and soil speed. Although these gradients have not been measured in our experiment, spatial patterns of plant downward bending and covering suggest that working depth, working speed and soil moisture content affect these gradients and associated forces in different ways. These gradients are probably steeper at higher working speeds and drier soil, so taller plants experience more force. The working depth- and soil moisture-dependent failure zone shape near tines also determine the extent of disturbance of plant anchorage. The increased momentum of moving soil would explain the increased downward bending of less flexible, taller garden cress at increased working depth. This effect would be less with flexible sub-surface plant parts that offer little resistance to moving soil. In our experiments, the effect of different plant flexibility might have been compensated by a different soil capture surface area, for both species have an identical relationship between downward bending angle and plant height.

Finally, flexible above-surface parts of pushed-over plants may also bend further downward through gravitation force (Fig. 3.2). This may explain the continued increase of leaftip lowering of ryegrass >40 mm, whereas the downward bending angle of the subsurface plant remains at a maximum of 45°. This angle corresponds to the maximum angle of soil aggregate displacement during soil failure in front of a tine (Kouwenhoven & Terpstra, 1970).

We think these biomechanical phenomena and their small-scale spatial aspects determine the shape of the covering curves in specific situations of the weed, the crop and the soil. Although the above representation of the soil–tool and soil–plant interactions in the covering process is rather qualitative, quantitative modelling of the mechanics and three-dimensional geometry of plant and soil displacement could be a next step in analysing the role of several plant and tillage-process characteristics for covering selectivity.

3.4.2 The role of spatial variability

Knowledge of the spatial pattern of soil level upheaval (ridges) and leaftip lowering near the harrow tine paths is essential in understanding the covering mechanism and the effects of working depth, working speed and soil moisture content. Poor covering in trenches formed by the last two rows of harrow tines may restrict the attainable degree of covering. Spatial effects may also explain the high selectivity in 0.2-0.25 m tall winter wheat found by Rasmussen (1991a), where harrow tines were forced sideward into the inter-row spaces. In such situations, selectivity is based on different plant heights, for the wheat is not pushed over, while high ridges can be created in the crop row to cover weeds. The same principle could be used with other implements for mechanical intra-row weed control, such as torsion weeders, spring hoes or hoe ridgers.

From the viewpoint of variability, increasing the selectivity and decreasing the number of cultivations means that the least covered weeds should be suppressed more severely, while saving the most vulnerable crop plants within the present populations.

3.4.3 Manipulation and prediction of covering selectivity

The above description of the covering mechanism suggests that the rather broad notion of “harrowing intensity” has two separate aspects: plant bending and soil level upheaval. These aspects can be manipulated semi-independently, so that leaf flexibility and plant height are of different importance for a plant’s resistance against being covered. In other words, the selective principle of harrowing can be manipulated. This would have two implications for modelling approaches to optimise timing and intensity of harrowing.

Firstly, empirical relationships between weed control and crop covering (covering curves) would not solely be governed by crop and weed characteristics, but also by soil cohesion and the handling of the harrow (e.g. working depth and working speed). Rasmussen (1992) found that the type of weed harrow did not affect the relationship between weed control and covering of cereal crops, when varying the number of harrow passes. Our results suggest that different working depths would not greatly affect this relationship, whereas different working speeds and soil conditions would only change the relationship if crop and weed have a clearly different height and flexibility.

Secondly, crop covering as a measure for harrowing intensity may not correctly reflect the ability to cover weeds that have different characteristics. Rydberg (1993) and Rasmussen (1993) advocated crop covering as a measure of harrowing intensity as an alternative for technical characterisations (such as working speed, tine angle, type of harrow) because yield loss was better related to crop covering than to working speed (Rydberg, 1993), and because modelling studies to optimise harrowing intensity need a suitable quantification of harrowing intensity. To optimise harrowing intensity at different growth stages, the time-dependent resistance against covering of both weed and crop should principally be related to plant-independent harrowing intensity parameters, instead of relating weed resistance to a variable crop resistance. However, defining measurable plant-independent parameters for harrowing intensity is not easy, because the covering ability of a tillage operation comprises both soil level upheaval and bending of plants.

3.4.4 Comparison to harrowing in the field

Despite the above-mentioned fundamental problems, measurement of plant height, working depth, soil level upheaval and soil cohesion, supplemented by indicators for forward soil movement could have additional value for field experiments with harrows or tools for intra-row mechanical weed control. After all, field experiments allow little control of factors like working depth, soil conditions and growth stages of crop and weeds. In some cases, increased speed tends to reduce working depth on soils with high mechanical resistance (Elsten, 1994; van der Weide & Kurstjens, 1996). The magnitude of the working speed effect may depend on tine angle (van der Weide & Kurstjens, 1996), soil conditions (Rydberg, 1993) and the weeds and crops present (van der Weide & Kurstjens, 1996). Several workers noted that the effects of harrow type and harrow weight (Kees, 1962; Meyler & Rühling, 1966; Böhrnsen & Bräutigam, 1990), tine angle (Elsten, 1994; Søgaard, 1998), working speed and soil type (Elsten, 1994; van der Weide & Kurstjens, 1996) and time-specific soil conditions (Habel, 1954; Rydberg, 1993; Wilson *et al.*, 1993; Elsten, 1994; Søgaard, 1998) were related to working depth. Such interactions between factors complicate comparisons between experiments and make the effects of separate factors difficult to analyse and understand.

3.4.5 Burial depth and weed suppression

Although burial depth is decisive for the level of growth suppression and mortality, the actual burial depth of weeds after harrowing has never been measured *in situ* before. Artificial covering experiments of Habel (1954), Kees (1962) and Koch (1964b) showed that, for the majority of the weed species, a burial depth of 10-15 mm is needed to kill 90% of the weeds in the 1-2 leaf stage. Some large-seeded species required 20 mm or more. In experiments of Terpstra & Kouwenhoven (1981), 15 mm soil surface level upheaval beside the path of a hoe-ridger was sufficient to kill 25-30 mm tall garden cress plants.

In this experiment, 24% of the covered ryegrass and 44% of the covered garden cress plants were buried deeper than 10 mm, whereas only 9% and 7% were buried deeper than 15 mm. Therefore, it is likely that covering will mainly cause growth retardation, without killing many covered weeds. Searching ways to increase covering depth is therefore an important issue, especially when bigger seedling weeds should be controlled. Also the contribution of uprooting to the weed control effect of harrowing should be studied in more detail.

3.5 Conclusions

The role of plant height, leaf flexibility and leaf geometry in plant resistance against being covered, is related to three aspects of the covering ability of a cultivation: (1) the ability to push the subsurface parts of the plants forward and downward in the soil failure zone near the tines, (2) the ability to consolidate this bent orientation by deposition of sufficient soil on top of the leaves, and (3) the ability to raise the soil surface level to cover plants that do not bend downward substantially.

Harrowing depth, working speed and soil moisture content can influence the covering of different plant groups to a different extent, so that the covering selectivity of harrowing can be manipulated.

If, like in this experiment, different plant groups are not equally sensitive to changes in working depth, working speed or soil moisture content, empirical relationships between weed control and crop damage (by covering) would be situation-specific. This would limit the applicability of such relationships in the optimisation of harrowing intensity.

The burial depth measured in this experiment seems insufficient for effective weed control and may be a major cause for the limited harrowing efficacy.

4 Selective uprooting by weed harrowing on sandy soils

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Summary

Uprooting by weed harrowing and the potential of the uprooting process for selective weed control at early crop growth stages was studied. Effects of working depth, seed depth, soil moisture content and working speed on uprooting of Lolium perenne *L.,* Lepidium sativum *L. and* Chenopodium quinoa *Willd. were investigated in laboratory harrowing experiments on a sandy soil.*

Harrowing uprooted on average 51% of the emerging plants and 21% of the plants in the seedling stage. Seventy percent of all uprooted plants were completely covered by soil. An increase in working depth from 10 mm to 30 mm doubled the average fraction of uprooted plants. Uprooting was also promoted by higher soil moisture contents and higher working speeds. Average uprooting selectivity (= fraction of uprooted emerging plants / fraction of uprooted seedlings of the same species) varied between 2.0 (deep tillage and high speed) and 5.6 (dry soil). If tines could keep a distance of more than 3 mm from the crop and weed plants, the average selectivity of all treatments would improve from 2.4 to 5.5 and the average fraction of uprooted seedlings would decrease from 21% to 8%.

This study indicates that uprooting may be a more important weed control mechanism than commonly believed. If working depth and the path of the harrow tines in relation to crop rows could be accurately controlled, uprooting could be a relatively selective weed control mechanism at early crop growth stages.

Keywords: *mechanical weed control, selectivity, working depth, working speed, soil moisture.*

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4.1 Introduction

Pre- and post-emergence harrowing are important in non-chemical or integrated weed control strategies, as harrowing is relatively cheap, suitable for many crops and has a high capacity (Baumann, 1992). Another advantage is that the tines control both intra-row and interrow weeds. However, the intra-row action not only controls small weeds, but can also damage crop plants.

Rasmussen (1990) defined selectivity as the ratio of percent weed control and per cent covered crop plants and found that high weed control levels are generally associated with lower selectivity. The risk of crop damage thus restricts the level of weed control that can be attained, especially at early growth stages when crops are more sensitive. Baumann (1992) achieved high selectivity when harrowing at early growth stages in several row crops. However, harrowing at these sensitive growth stages often results in severe crop damage (Rydberg, 1993; de Visser & Hoekstra, 1995; Wevers, 1995; Ascard & Bellinder, 1996) and low selectivity (Rasmussen, 1992). At later growth stages, crops allow a more aggressive harrowing, and consequently weed control can be more successful (Rasmussen, 1991a).

Many researchers have attempted to find the optimum timing, number of passes and harrow adjustment in various crops under different conditions (Rasmussen, 1990, 1992; Peruzzi *et al*., 1993; Rydberg, 1993; Wevers *et al*., 1993; Wilson *et al*., 1993; van de Zande & Kouwenhoven, 1994; Rasmussen & Svenningsen, 1995; van der Weide & Kurstjens, 1996). The selectivity concept and empirical models describing the relationship between weed control, crop damage and crop yield (Rasmussen, 1991b) provide a method to select treatments with improved weed control and to optimise harrowing intensity. Still, a better understanding is needed of the uprooting and soil covering process during cultivation and the effect of covering and uprooting on the subsequent growth process of damaged plants.

As such basic studies are scarce, many workers refer to the detailed harrowing experiments of Habel (1954), Kees (1962) and Koch (1964a). They found that soil covering is the primary mode of action, as only about 6% of the weeds in the seedling stage were visibly uprooted (Habel: 3-24%, Kees: 1-13%, Koch: 1-11%). When carefully examining the loose soil layer of some sampling plots, Habel (1954) found but a few covered uprooted plants. Accordingly, most research has focussed on the soil covering effect, not discerning uprooted plants.

For several reasons however, the focus on the covering effect of harrowing may not be legitimate. First, the few studies showing that the uprooting effect of harrowing is of minor importance (Habel, 1954; Kees, 1962; Koch, 1964a) did not consider germinated weeds not yet emerged. These weakly anchored “white threads” might be more susceptible to uprooting than weed seedlings. Second, uprooting is probably underestimated if part of the uprooted weed seedlings and white threads are covered by soil or die within a very short time after harrowing. Third, even if uprooting is less important than covering, it might still cause a significant crop stand reduction at early growth stages in sensitive row crops like sugarbeet, carrots and onions. Although weed response to artificial covering and uprooting has been studied in glasshouse experiments (Habel, 1954; Kees, 1962; Koch, 1964b; Jones *et al*., 1995, 1996), it is not clear how many buried and/or uprooted weeds and crop plants will eventually recover after harrowing in the field. Studies examining the contribution of uprooting and covering to crop plant loss and weed control are scarce (van der Weide & Kurstjens, 1996; Fogelberg & Dock Gustavsson, 1999). Moreover, methods to count uprooted plants (Habel, 1954; van der Weide & Kurstjens, 1996; Fogelberg & Dock Gustavsson, 1999) may be unreliable at early growth stages.

This study aimed to verify whether separate assessment of the uprooting and covering performance of harrows is necessary and whether the uprooting process can be used to achieve selective weed control in early crop growth stages. Therefore, the study examined the extent of the uprooting effect of weed harrows on a fragile sandy soil at early growth stages of three plant species, as influenced by working depth, soil moisture content, working speed, and seed depth. The spatial uprooting pattern around a tine was studied to understand how these factors affect the uprooting process.

4.2 Materials and methods

4.2.1 Plant species and growth stages

Three species with contrasting growth habit were used to represent both weed and crop plants with different resistance against uprooting. *Lepidium sativum* L. (garden cress) has a thick hypocotyledon and tap root, which provide a high bending resistance and strong anchorage. *Lolium perenne* L. (ryegrass) has a long flexible leaf and a thinner, more weakly anchored root. Because of its secondary roots within the topsoil layer, *L. perenne* might experience higher forces during harrowing and thus be more susceptible. However, secondary roots were not clearly developed at the time of harrowing (11 days after sowing). *Chenopodium quinoa* Willd. (quinoa) is a more delicate broad-leaved plant with a thin tap root, resembling the common weed *Chenopodium album* L.

Lepidium sativum and *L. perenne* were harrowed 3-4 days after emergence and *C. quinoa* was harrowed on the day of emergence. Seedlings were classified into four growth stages according to their size. *L. sativum* seedlings were visually classified as either large (15.6 mm average height, large cotyledons on long wide-angled stalks), medium (13.2 mm average height, established cotyledons on small stalks), small (10.4 mm average height, upright, small cotyledons) or breaking through (6.0 mm average height, bent hypocotyledon with folded cotyledons). *Lolium perenne* plants were classified using measured leaf lengths (large: 45-70 mm, medium: 35-45 mm, small: 25-35 mm, breaking through: 0-25 mm). All emerged *C. quinoa* plants were classified as small (5.3 mm average height). The fifth growth stage, “white threads”, are germinated seeds that had not emerged at the time of harrowing. The number of white threads was corrected for non-germinated seeds, based on the number of visible plants at the time of harrowing and the final emergence percentage of untreated bins. In most analyses, small, medium and large plants were clustered as “seedlings”, while white threads and plants breaking through the soil surface were clustered as “emerging plants”.

Table 4.1 Levels of experimental factors per treatment.

Treatment		Seed depth (mm)	Working depth (mm)	Working speed (m/s)	Soil moisture content (% of dry mass) Prepared	At harrowing
Standard	a,b	10	20	1.8	12.50	10.7
Shallow seed	b	5	20	1.8	12.50	-
Deep seed	b	30	20	1.8	12.50	-
Shallow till	a,b	10	10	1.8	12.50	10.3
Deep till	a,b	10	30	1.8	12.50	11.0
Slow	a,b	10	20	1.2	12.50	10.7
Fast	a,b	10	20	2.4	12.50	10.4
Dry	a,b	10	20	1.8	8.00	4.7
Moist	a,b	10	20	1.8	17.00	15.7
Shallow*dry*fast	a	10	15	2.1	10.25	7.0
Shallow*wet*slow	a	10	15	1.5	14.75	13.2
Deep*dry*slow	a	10	25	1.5	10.25	7.7
Deep*wet*fast	a	10	25	2.1	14.75	13.6

a Treatments in *L. sativum* and *L. perenne* experiments.
b Treatments in the *C. quinoa* experiment.

4.2.2 Experimental design

Each species was separately subjected to a number of treatments with different combinations of seed depth (only *C. quinoa*), working depth, soil moisture content and working speed (Table 4.1). *Lepidium sativum* and *L. perenne* experiments had a reduced central composite design of 11 treatments, centred around the standard treatment. The same experimental factors and levels were used with *C. quinoa*, but the four interaction treatments from the reduced central composite design (shallow*dry*fast, etc. in Table 4.1) were replaced by two seed depth treatments.

The experimental design was an unbalanced split-plot, with bins as main-plots and individual plants as sub-plots. The effects of species, seed depth, working depth, soil moisture content and speed were analysed on the main-plot level, whereas effects of plant growth stage and tine–plant distance were analysed on the sub-plot level. Each treatment was replicated with at least two bins, each containing 357 seeds of one species. The natural variation in emergence rate between seeds yielded a variable number of replicates per growth stage within bins.

4.2.3 Bin preparation

Fine black sand with moderate organic matter content (Dutch classification zEZ21) was dried, passed through a 1-mm sieve and moistened to the desired moisture

Fig. 4.1 The model harrow in action on bins with *L. sativum*.

content (Table 4.1). After repeated mixing, predetermined weights of soil were filled into aluminium bins (0.60 m x 0.40 m x 0.13 m), carefully levelled and then compacted by a hydraulic ram to a homogeneous dry-bulk density of 0.95 t/m^3. On this compacted layer, seeds were placed in a rectangular grid of 21 rows parallel to the harrowing direction, each containing 17 seeds. Subsequently, the topsoil layer was carefully filled in and compacted. Seeded bins were covered by a 5-mm layer of polystyrene pearls and sealed by a glass plate to prevent evaporation. The bins remained in a climate chamber for periods of varying lengths, to obtain similar development stages for all treatments of a species.

4.2.4 Model harrow

The model harrow (Fig. 4.1) had 23 rigid vertical tines of 6-mm diameter, with tine paths spaced 25 mm and a tine configuration like conventional spring tine harrows. As seed rows were spaced 22.5 mm apart, a bin approximated a full field situation with a uniform distribution of tine–plant distances. The model harrow tilled the bins at a pre-set working speed and accurate working depth, with tines following a fixed path.

4.2.5 Harrowing procedure and plant measurements

On the day of harrowing, the long-side walls of the bins were removed and two seeded bins were screwed together on a reference frame. Soil bins without seeds were mounted on either side of the seeded bins, giving a total experimental area of 1.6 m x 0.6 m. To prevent evaporation during treatment and a sudden change in

Fig. 4.2 Plant positions after harrowing are digitized using the SpaceArm™.

plant environment, relative air humidity in the laboratory was kept at about 80%. Nevertheless, the moisture content of the tilled layer measured directly after harrowing was a little lower than at preparation (Table 4.1). After removing the polystyrene pearls, the position and size of each emerged plant was digitised using an electromechanical 3D co-ordinate measurement device (SpaceArm™, FARO Technologies Inc., Lake Mary, Florida, USA) linked to a computer.

Plants were digitised again directly after harrowing, while assessing soil cover (= 100 − percentage visible leaf area) and root exposure (only for visibly uprooted plants) (Fig. 4.2). Plants in the first bin of the *L. sativum* and *L. perenne* treatments were gently pulled by hand to qualitatively classify the anchorage force (loosened, anchored or uncertain). Their rooting location was digitised simultaneously. Tilled soil was carefully removed from the first bin by an adapted vacuum cleaner and covered plants were digitised before disturbing their position. Before returning the second bin of the *L. sativum* and *L. perenne* treatments and both *C. quinoa* bins to the climate chamber, visible plants were digitised in a non-disturbing way. After six days, plants of these undisturbed bins were pulled up and digitised in a similar way to the first bins.

4.2.6 Data processing

Each plant's uprooting status was classified using co-ordinate transformation and plant matching software, which identifies plants before and after harrowing by combining information on positions, size, root exposure and the qualitative anchorage force. *Chenopodium quinoa* seed positions were digitised before filling in the top soil layer, so the displacement of "white threads" could be calculated as well. A plant was classified as uprooted if it was classified as "loosened", or if classification as "uncertain" coincided with more than 6 mm distance between the original plant (or seed) position and the rooting point position after harrowing. Six days after harrowing, most uprooted plants could be recognised by their weak anchorage, but for rerooted plants and "white threads", plant co-ordinates or seed positions were required for reliable classification.

4.2.7 Statistical analysis

Uprooting (U = u / n, with u = number of uprooted plants and n = total number of plants) was analysed by generalised linear mixed models using a logit link [logit(U) = ^{e}log(u / {n − u})] and a binomial variance function allowing for overdispersion. The GENSTAT 5.3.2 statistical package (Genstat 5 Committee, 1993) and the GLW-DLO Genstat procedure library (Goedhart & Thissen, 1998) were used to estimate model parameters. Effects of working depth, measured soil moisture content of the tilled layer after harrowing, working speed and seed depth relative to the standard values (20 mm working depth, 10.7% soil moisture content, 1.8 m/s working speed and 10 mm seed depth) were analysed by main effect models. Significance of the terms in these models was calculated by non-hierarchical Wald tests (Buist *et al.*, 1998). Mean standard errors were back-transformed from the logit scale (Z) using the approximation described by Engel (1997):

$$\mathrm{var}(U) = \frac{\exp(2Z)}{(1+\exp(Z))^4} \cdot \mathrm{var}(Z)$$

In this study, uprooting selectivity between species could not be analysed because different species did not occur in the same experimental units (bins). Instead, we analysed selectivity arising from the natural variability in emergence time, considering "emerging" plants as weeds to be controlled in a crop of the same plant type in the "seedling" stage. Uprooting selectivity is calculated as the ratio of the fraction of uprooted emerging plants and the fraction of uprooted seedlings ($U_{emerging}$ / $U_{seedling}$) of the same species.

The effects of working depth, working speed, soil moisture content and seed depth on uprooting selectivity were analysed by loglinear regression of counts (y) of uprooted and non-uprooted emerging plants and seedlings, as described by McCullagh & Nelder (1989). Variance was assumed proportional to the expected value of y. Treatment effects were proportional to the natural logarithm of the total number of plants per growth stage within a bin (n). For each species, the following model with two growth stages (GS), two uprooting statuses (U), working depth (WD) and other treatment factors (not shown) was fitted (model (1)):

$${}^{e}\log(y) = c + {}^{e}\log(n) + GS + U + GS{\cdot}U + \alpha_{GS}{\cdot}(WD-20) + \alpha_{U}{\cdot}(WD-20) + \alpha_{GS{\cdot}U}{\cdot}(WD-20) + \ldots \quad (1)$$

Coefficients with suffix GS estimate treatment effects on LWC (log of weighted counts) for emerging plants and seedlings. Similarly, each coefficient with suffix U represents a vector of two estimates for a treatment factor effect on LWC of uprooted and non-uprooted plants. Coefficients with suffix GS·U estimate treatment factor effects on differences in uprooting between growth stages. Significance of the latter coefficients was determined by *t*-tests. As model (1) does not yield standard errors for selectivity directly, coefficients of variation for selectivity were calculated from approximated variances of the percentage uprooted emerging plants (U_0) and seedlings (U_1) and their approximated covariance (Stuart & Ord, 1987):

$$\mathrm{var}\left(\frac{U_0}{U_1}\right)=\left(\frac{U_0}{U_1}\right)^2\cdot\left(\frac{\mathrm{var}(U_0)}{U_0^{\,2}}+\frac{\mathrm{var}(U_1)}{U_1^{\,2}}-\frac{2\cdot\mathrm{cov}(U_0,U_1)}{U_0\cdot U_1}\right)$$

Covariances were back-transformed from the logit-scale by an approximation similar to the approximation for variances:

$$\mathrm{cov}(U_0,U_1)=\frac{\exp(Z_0)}{\left(1+\exp(Z_0)\right)^2}\cdot\frac{\exp(Z_1)}{\left(1+\exp(Z_1)\right)^2}\cdot\mathrm{cov}(Z_0,Z_1)$$

4.3 Results

4.3.1 Amount of uprooting – effect of species and growth stage

Even in homogeneous bins with uniform seed depth, the natural variation in time of emergence of plants within a bin caused differences in growth stage and considerable differences in uprooting (Fig. 4.3). White threads, plants breaking through the soil surface, small and medium size seedlings all had different sensitivity to uprooting (P < 0.001). The sensitivity to uprooting decreased most rapidly at the stage when plants break through the soil surface, especially for *L. perenne*. On average, *L. perenne* seedlings were less sensitive to uprooting than *L. sativum* seedlings and *C. quinoa* seedlings (P < 0.05, Table 4.2). *Chenopodium quinoa* white threads were less uprooted than emerging *L. perenne* and emerging *L. sativum* plants (P < 0.01).

4.3.2 Uprooting, soil-covering and their interrelationship

A significant part of the uprooted plants was covered by soil (93% of the uprooted emerging plants and 48% of the uprooted seedlings). Stated differently, 22% of the covered seedlings and 54% of the covered emerging plants were also uprooted. If only visible uprooted plants were counted, uprooting would be seriously underestimated (11% instead of 21% uprooting of seedlings and 4% instead of 51% uprooting of emerging plants).

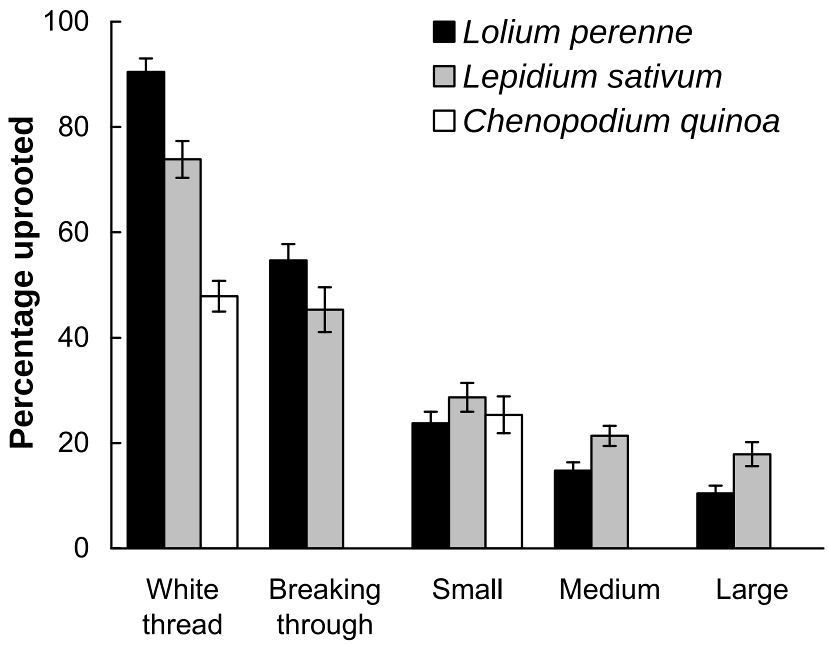

Fig. 4.3 Percentage uprooted plants per species and growth stage. Averages of all treatments with mean standard errors.

Uprooting and soil-covering of emerging plants showed no correlation (Fig. 4.4). For seedlings, covering and uprooting showed a weak positive correlation ($R^2 = 0.43$, $P < 0.001$), but the standard error (14%) appears rather large to predict uprooting from covering assessments. There was also no correlation between uprooting of emerging plants and covering of seedlings of the same species (not shown).

4.3.3 Amount of uprooting – effect of working depth, soil moisture content, working speed and seed depth

Table 4.2 shows the different responses of emerging plants and seedlings of the three species to the treatments. Increasing working depth from 10 mm to 30 mm doubled the average fraction uprooted plants from 21% to 44% ($P < 0.01$), with the largest increase between 10 mm (shallow treatment) and 20 mm (standard treatment). Increased speed ($P < 0.01$) and soil moisture content ($P < 0.001$) enhanced uprooting of *L. perenne* and *L. sativum*, but these trends were not significant for *C. quinoa*. Increased seed depth resulted in less uprooting of *C. quinoa* ($P < 0.05$). In the *L. perenne* and *L. sativum* experiments, the effects of soil moisture content and speed tended to be more pronounced at greater working depth, but differences were not significant. The effect of speed tended to be most pronounced on dry soil (NS).

Table 4.2 Percentage uprooted emerging plants and seedlings per treatment and species.

	Lolium perenne		*Lepidium sativum*		*Chenopodium quinoa*		
Treatment	Emerging plants	Seedlings	Emerging plants	Seedlings	White threads	Seedlings	Average
Standard	53.8 (5.4)	18.8 (3.8)	79.1 (8.7)	25.5 (3.8)	54.1 (4.4)	45.6 (16.8)	40.6 (6.3)
Shallow seed	-	-	-	-	56.2 (4.4)	49.3 (12.5)	55.7 (10.6)
Deep seed	-	-	-	-	35.9 (4.1)	33.2 (42.9)	35.9 (10.3)
Shallow till	43.9 (12.2)	6.8 (1.9)	35.4 (9.4)	9.9 (2.3)	38.5 (4.2)	-	21.4 (5.3)
Deep till	69.4 (7.1)	29.2 (4.0)	65.9 (8.3)	32.5 (4.3)	60.2 (4.5)	44.5 (6.9)	44.0 (6.4)
Slow	68.1 (5.5)	14.4 (2.0)	53.1 (9.7)	23.4 (3.7)	35.0 (4.0)	-	27.2 (4.9)
Fast	58.9 (6.2)	21.9 (3.8)	72.0 (7.3)	27.0 (3.3)	44.2 (4.3)	52.3 (39.5)	36.7 (5.8)
Dry	69.7 (7.5)	9.7 (2.4)	71.1 (11.0)	16.8 (3.2)	81.7 (7.2)	13.1 (3.8)	22.9 (6.3)
Moist	93.8 (4.8)	20.8 (3.3)	72.3 (6.9)	20.5 (3.5)	56.5 (4.6)	33.8 (6.5)	36.7 (6.1)
Shallow*dry*fast	46.7 (7.0)	14.7 (3.0)	38.5 (9.7)	17.9 (3.2)	-	-	21.5 (6.6)
Shallow*wet*slow	59.1 (8.0)	14.9 (2.9)	53.3 (7.9)	18.3 (3.4)	-	-	23.9 (6.9)
Deep*dry*slow	46.9 (5.0)	17.4 (4.6)	46.1 (8.4)	23.4 (3.7)	-	-	32.4 (7.6)
Deep*wet*fast	64.4 (7.6)	32.7 (4.3)	74.0 (6.5)	34.8 (4.5)	-	-	40.9 (8.0)
Average	59.1 (3.2)	17.3 (1.5)	60.3 (3.9)	22.6 (1.8)	47.8 (2.7)	26.4 (4.3)	

Figures in parentheses are approximated mean standard errors.
Treatments are described in Table 4.1.

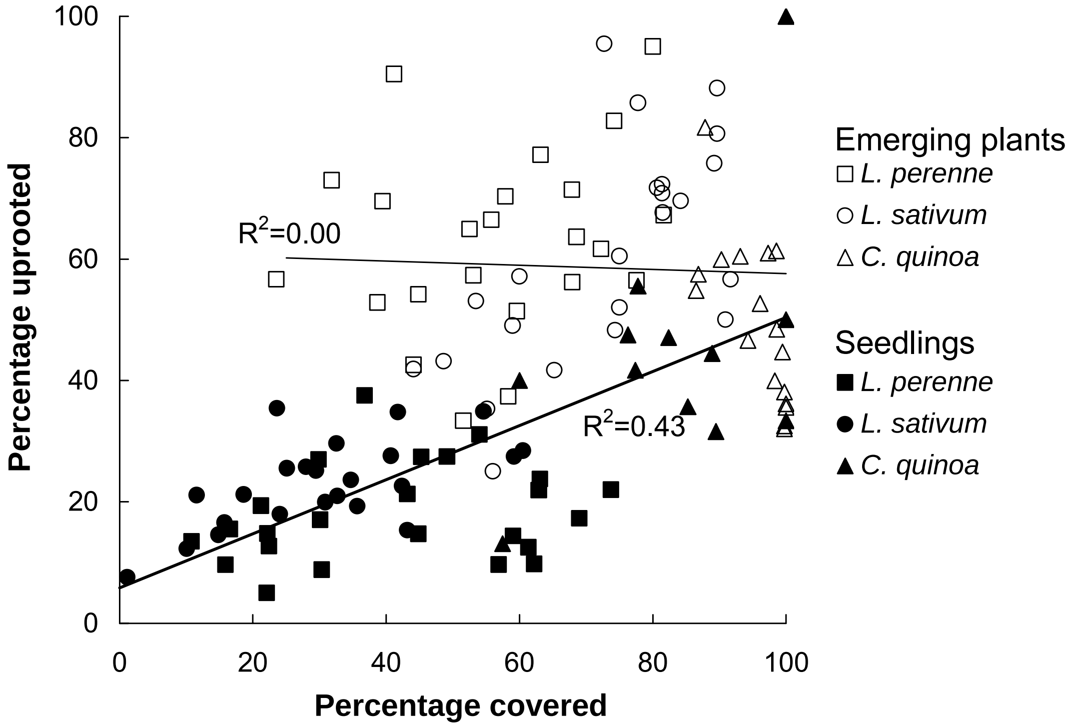

Fig. 4.4 Correlations between covering and uprooting of plants of the same species and growth stage.

4.3.4 Uprooting selectivity – effect of relative time of emergence

In this study, selectivity is caused by the natural variation in time of emergence within a bin, so emerging plants were regarded as weeds in a crop of the same plant type in the seedling stage. With *L. perenne* and *L. sativum,* the difference in emergence time was about three days. The difference in emergence time of *C. quinoa* was only about one day, resulting in a considerably lower average uprooting selectivity (Table 4.3). Differences in working depth, soil moisture content and working speed caused considerable variations in uprooting selectivity, especially for *L. perenne* and *C. quinoa*.

4.3.5 Uprooting selectivity – effect of working depth, soil moisture content, working speed, and seed depth

Selectivity generally improved at lower soil moisture content and decreasing working depth (Table 4.3). Increased working depth hardly affected *L. sativum* and *C. quinoa* selectivity but decreased selectivity of *L. perenne* (P < 0.01). *Lolium perenne* showed the most pronounced trend, as its seedlings were more sensitive to a working depth increase than its emerging plants (P < 0.05, Table 4.2). Increased soil moisture content resulted in much more uprooting of *L. perenne* and *C. quinoa* seedlings (P < 0.05) and lower uprooting selectivity of *C. quinoa* (P < 0.05). Moreover, increased speed weakly tended to improve selectivity for *L. sativum* (NS), but *L. perenne*

Table 4.3 Uprooting selectivity (percentage uprooted emerging plants / percentage uprooted seedlings) per treatment and species.

	All plants			Tine-plant distance > 6 mm		
Treatment	*L. perenne*	*L. sativum*	*C. quinoa*	*L. perenne*	*L. sativum*	*C. quinoa*
Standard	2.87 (0.20)	3.10 (0.17)	1.19 (0.37)	8.10 (0.50)	9.21 (0.44)	3.57 (1.26)
Shallow seed	-	-	1.14 (0.25)	-	-	1.06 (0.36)
Deep seed	-	-	1.08 (1.29)	-	-	-
Shallow till	6.43 (0.37)	3.56 (0.32)	-	4.13 (0.67)	6.56 (0.77)	-
Deep till	2.37 (0.15)	2.03 (0.16)	1.35 (0.15)	2.74 (0.33)	3.09 (0.45)	1.61 (0.22)
Slow	4.74 (0.15)	2.27 (0.22)	-	10.95 (0.31)	5.04 (0.69)	-
Fast	2.69 (0.17)	2.67 (0.14)	0.85 (0.76)	5.05 (0.43)	5.16 (0.44)	0.87 (0.98)
Dry	7.18 (0.25)	4.23 (0.23)	6.24 (0.29)	13.07 (0.49)	6.33 (1.40)	16.50 (0.66)
Moist	4.50 (0.16)	3.52 (0.18)	1.67 (0.19)	9.50 (0.39)	7.48 (0.51)	2.34 (0.33)
Shallow*dry*fast	3.18 (0.22)	2.15 (0.28)	-	7.52 (0.47)	31.72 (1.06)	-
Shallow*wet*slow	3.96 (0.21)	2.92 (0.21)	-	9.58 (0.43)	5.52 (0.52)	-
Deep*dry*slow	2.70 (0.26)	1.97 (0.21)	-	4.23 (0.47)	5.02 (0.37)	-
Deep*wet*fast	1.97 (0.15)	2.13 (0.14)	-	2.83 (0.32)	1.91 (0.76)	-
Average	3.42 (0.08)	2.67 (0.08)	1.81 (0.16)	5.64 (0.14)	5.37 (0.20)	2.44 (0.22)

Figures in parentheses are approximated variation coefficients.
Treatments are described in Table 4.1.

showed an opposite trend ($P \approx 0.07$). Deeper sowing did not change selectivity for *C. quinoa*.

As selectivity declined with increased uprooting of seedlings (Fig. 4.5A), the way treatment factors influenced the uprooting action of the harrowing did not appear to be essentially different. However, the dry treatment had a relatively high selectivity, whereas deep seeding resulted in a relatively low selectivity. Although the corresponding relationship between the percentage uprooted emerging plants and the percentage uprooted seedlings (Fig. 4.5B) showed larger variations, it had the same logistic shape as the relationship between weed control and crop covering reported by Rasmussen (1991b) and Rasmussen & Svenningsen (1995).

4.3.6 The spatially heterogeneous uprooting pattern

The relationship between the fraction of uprooted plants and the distance between a plant and the nearest tine path (TPD) was analysed using individual plant position data and the digitised trajectories of the rigid harrow tines. White threads of *L. sativum* and *L. perenne* were excluded from the analysis because their seed positions were not digitised.

Uprooting decreased with increasing tine–plant distance (Fig. 4.6). Of the seedlings that were touched by a tine (TPD ≤ 3 mm) 34-56% were uprooted, while seedlings well between two tines (9 ≤ TPD ≤ 12 mm) were only scarcely uprooted (*L.*

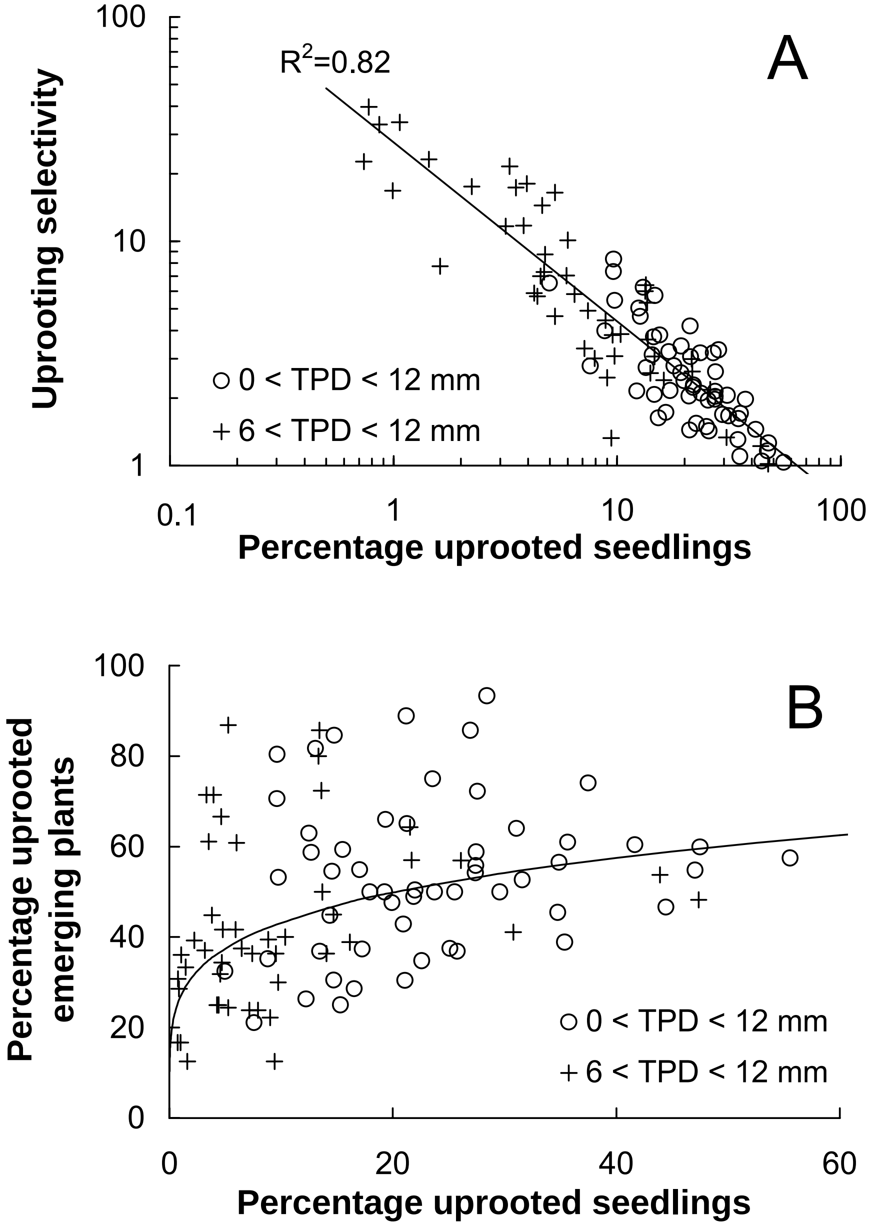

Fig. 4.5 Uprooting selectivity (A) and percentage uprooted emerging plants (B) in relation to the percentage uprooted seedlings. Data and regression lines in (A) and (B) correspond.

perenne: 5%, *L. sativum*: 4%, *C. quinoa*: 16%). The effect of TPD was much less with white threads and plants breaking through the soil surface ($P < 0.001$). Therefore, uprooting selectivity between tines was much higher than on the tine path ($P < 0.001$). If flexible tines would avoid crop and weed plants closer than 3 mm to the tine (TPD > 6 mm), average selectivity would improve considerably (Table 4.3) with much less uprooting of a crop in the seedling stage (Fig. 4.5B).

Treatment effects on selectivity primarily arose between the tine paths, whereas selectivity on the tine path was less affected (Fig. 4.7). Nevertheless, these small

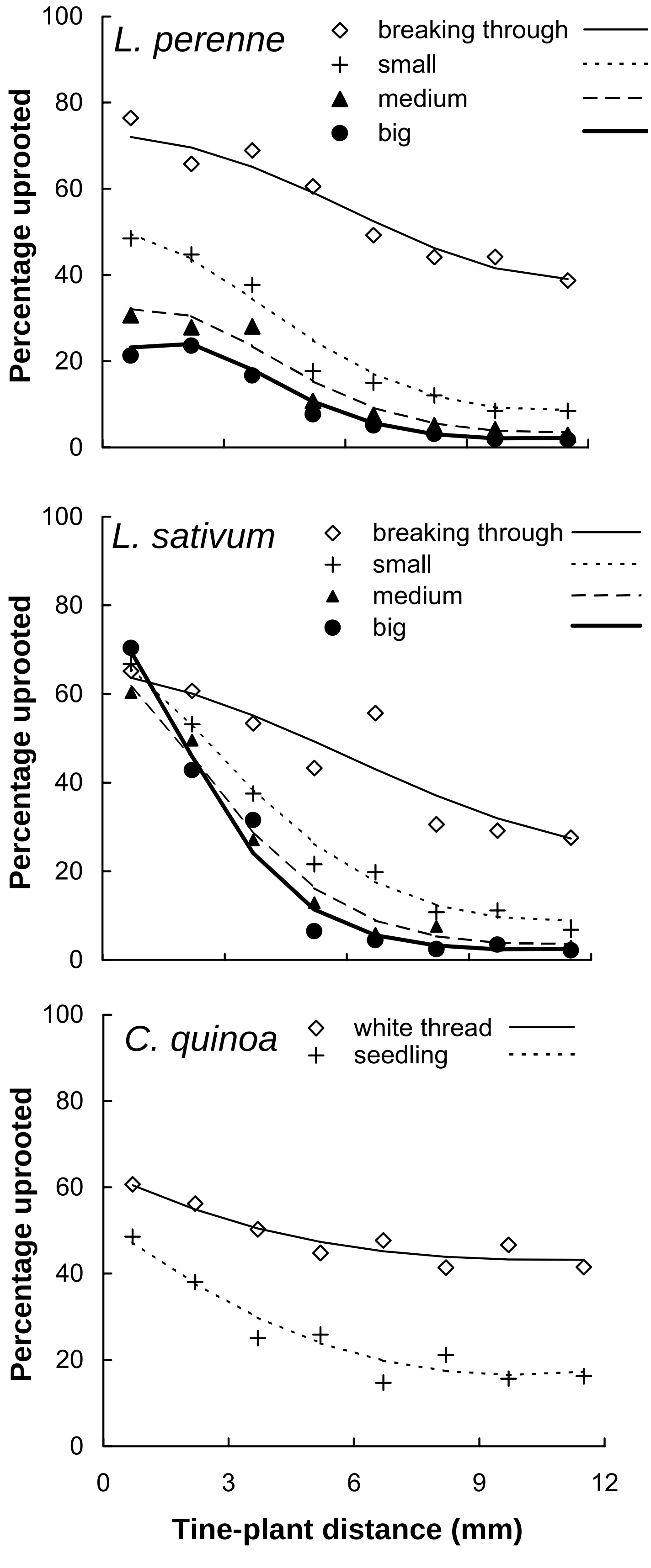

Fig. 4.6 Relationship between uprooting and tine–plant distance for each species and growth stage. Data points represent means for 1.5 mm distance increments.

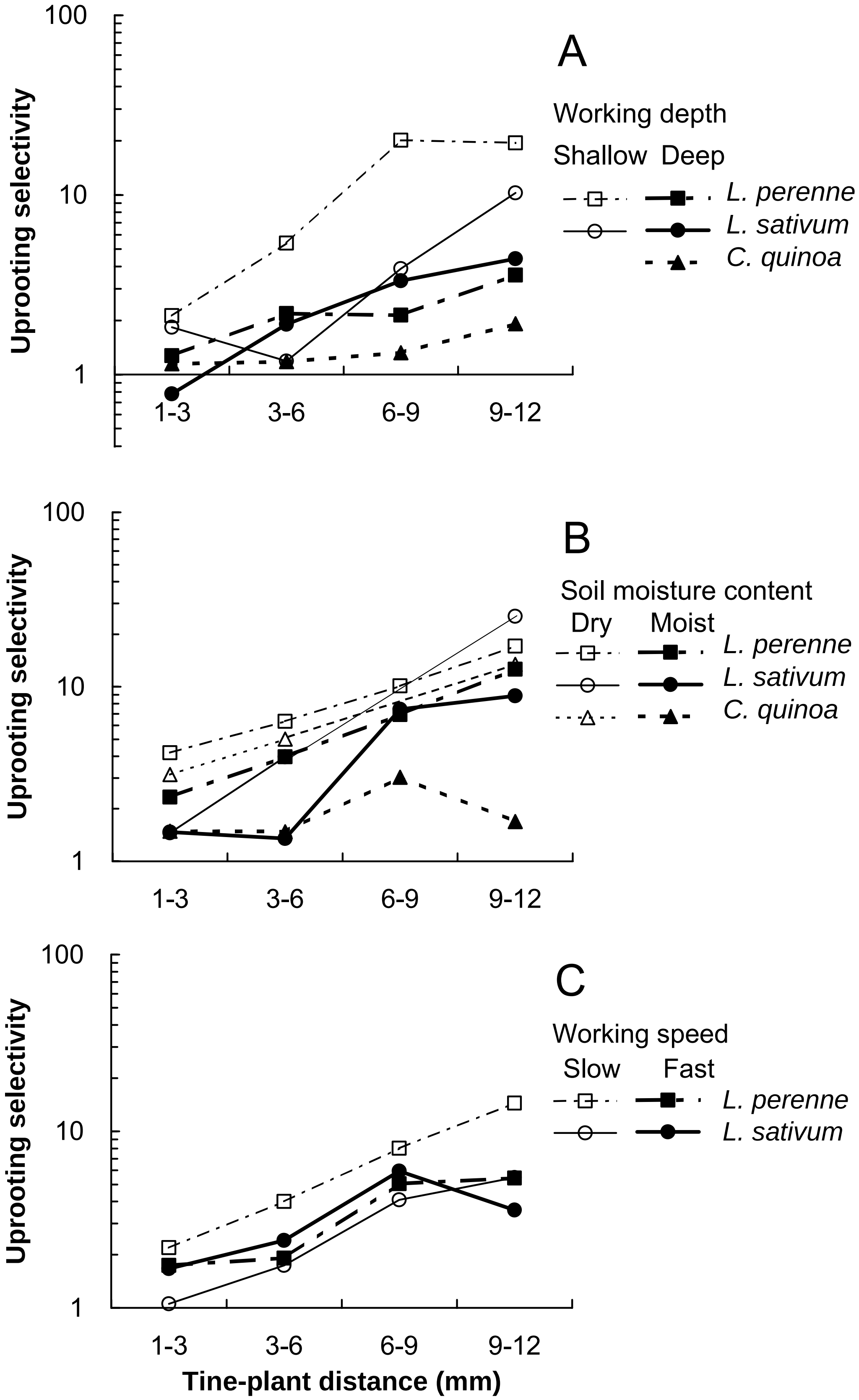

Fig. 4.7 Effect of working depth (A), soil moisture content (B) and working speed (C) on uprooting selectivity at different tine–plant distances. White threads of *L. perenne* and *L. sativum* are omitted.

selectivity differences were important because 56% of the uprooted seedlings were uprooted within the TPD ≤ 3 mm zone. Uprooting on the tine path was only selective (i.e. selectivity > 1) with *L. perenne* ($P < 0.001$). Only with *L. sativum*, higher working speed improved selectivity for plants on the tine trajectories ($P < 0.05$).

4.4 Discussion

4.4.1 Importance of uprooting and separate covering and uprooting assessment

In this study, harrowing caused much more uprooting than in the field experiments of Habel (1954), Kees (1962) and Koch (1964a), mainly because these researchers disregarded uprooted plants that were also covered. As 70% of the uprooted plants in our study were also covered, the common practice of counting visible plants before and after harrowing would not correctly reflect the damage associated with uprooting, particularly for emerging weeds. This is a problem because uprooting and covering were not well correlated, especially for the emerging weeds, which were uprooted to the largest extent.

Not counting the uprooted covered plants can also cause confusing results. For example, Habel (1954), Kees (1962) and Koch (1964a) observed more visible uprooting at later weed growth stages. This may be caused by better recognition of larger plants, or by the sorting effect of harrow tines (Kouwenhoven & Terpstra, 1979), increasing the proportion of the uprooted plants being visible. Similarly, the smaller amount of uprooting on loose soil observed by Habel (1954) and Kees (1962) could be due to the improved covering effect.

Rydberg (1995) found that the average selectivity (based on covering) increased from 1.3 to 2.4, when harrowing cereals at the three and six leaves-growth stage respectively. Rasmussen (1992) also concluded that later harrowing resulted in higher selectivity. However, our results indicate that the uprooting process can already achieve high uprooting selectivity a few days after crop emergence.

The above-mentioned considerations imply that separate assessment of the covering and uprooting effect should be considered in future mechanical weed control research. Furthermore, the high levels of uprooting in this study indicate that the common focus on the covering effect of weed harrowing may not be legitimate. Nevertheless, the contribution of uprooting to the final weed control effect will depend on the rerooting capacity of weeds, which depends on species, growth stage and the weather conditions after harrowing (Habel, 1954; Jones *et al.*, 1995, 1996). Besides the fraction uprooted plants, the amount of soil attached to uprooted plants and the root position within the loosened soil layer may be important aspects of uprooting performance. Especially if the length of the dry period after harrowing is limited, covering will probably be relatively more important. The killing and growth impeding effects of artificial mechanical plant damage have been studied in glasshouse experiments (Habel, 1954; Kees, 1962; Koch, 1964b; Jones *et al.*, 1995, 1996). However, the relative contribution of uprooting and covering to mechanical weed control efficacy needs to be studied with damage as created by harrows or other implements in the field.

4.4.2 Reference parameters for harrowing intensity

Rasmussen (1990, 1991b) and Rydberg (1993) suggested crop covering as a reference parameter for harrowing intensity, because it was well correlated with weed control and crop yield. Using crop damage (i.e. uprooting and covering) as a reference parameter is also preferable because effects of harrow adjustment and speed are variable and depend on soil conditions (Habel, 1954; Rasmussen, 1990; Rydberg, 1993; Wilson *et al*., 1993; Søgaard, 1998). However, as harrowing selectivity decreases with increasing crop covering (Rasmussen, 1990) and uprooting of seedlings (Fig. 5A), selectivity should be compared using a standardised level of damage to a standard crop at a standard growth stage. Also Rydberg (1995) recognised that comparison of selectivity ratios from treatments in which crops and weeds have different growth stages, may not be correct.

The uprooting performance of harrowing results from both the uprooting capacity of the harrow and the plants' resistance to uprooting. Working depth and soil properties may affect both parameters. The vertical gradients of root anchorage strength, soil strength and tensile strength of the root tissue also play an important role. Increased working depth increases the soil volume that can transfer force on plant parts anchored in the tilled layer, and this force is exerted on deeper, weaker root parts (Ennos, 1991), which will contribute to an increased uprooting probability. The effect of soil type and conditions is more complex, as higher soil strength increases both the forces exerted on the soil and the root anchorage strength (Ennos, 1990; Fogelberg & Dock Gustavsson, 1998). In addition, soil conditions influence root development and the type and spatial pattern of soil disturbance (Koolen & Kuipers, 1983), which may affect the dynamic force transmission on plant parts anchored in tilled soil.

Independent assessment of plant resistance to uprooting and the uprooting capacity of harrowing could provide better understanding of the role of soil, plant, and cultivation characteristics on the uprooting performance and improve comparability of results from different experiments. Meyler & Rühling (1966) and Fogelberg & Dock Gustavsson (1998) measured anchorage strength of crop plants and weeds to explore possibilities for selective weed control. The uprooting capacity of harrowing is likely to be related to both the volume of the disturbed soil (working depth) and the "disturbance intensity" of this layer. Although "disturbance intensity" needs to be properly defined, the specific soil resistance (N/m^2) might be a suitable parameter which is easy to quantify by measuring drawbar pull, working depth and working speed (Böhrnsen & Bräutigam, 1990; Peruzzi *et al*., 1998).

4.4.3 Validity of laboratory experiments

When comparing the results with other experiments, the role of soil coherence in relation to soil moisture is likely to be most critical. The fact that uprooting decreased rapidly after emergence is probably due to the relatively loose, fragile soil in our experiments. Higher soil moisture content caused more uprooting of seedlings, indicating that plants experience larger forces. As larger plants are generally better anchored, the steepest decline in uprooting would probably occur at later growth stages. In addition to harrow adjustments, manipulation of soil coherence by seedbed preparation and sowing techniques might offer possibilities to regulate harrowing intensity, plant resistance to harrowing and the optimum time for cultivation.

The loose, sieved soil with a perfectly flat surface, the rigid harrow tines with millimetre-precision depth control and the damp growth environment used in these experiments are not representative of field conditions. Nevertheless, the effects of working depth and speed in this study are in line with results from field experiments concerning the covering or final weed control effect (Rasmussen, 1990; Baumann, 1992; Rydberg, 1993, 1995; Peruzzi *et al*., 1998; Søgaard, 1998). Also Rasmussen (1990) and Rydberg (1993) found a decrease of (covering) selectivity at higher speeds. However, results are sometimes not comparable as harrowing depth in the field may vary with speed (e.g. Elsten, 1994).

The seed density used in our experiments (2222 seeds/m^2) is very high as compared with common field conditions (50-400 weeds/m^2). Rasmussen (1994) found that in 10 out of 15 experiments weed control did not depend on initial weed density. In contrast, Peruzzi *et al*. (1993) observed less weed control at higher weed densities. Less weed control at higher density is likely if weed and crop densities in field plots are correlated with factors influencing harrow intensity (soil structure influences working depth, coarse aggregates have less covering ability), plant sensitivity (more and larger weeds in plots with a less competitive crop) or a spatially heterogeneous harrowing effect (irregular working depth). These disturbing influences were absent in our experiments. Furthermore, it seems unlikely that neighbouring plants could have protected each other from being uprooted.

4.4.4 The role of tine flexibility and tine spacing

In late growth stages in cereals (Rasmussen, 1992; Rasmussen & Svenningsen, 1995) or in wider spaced crop rows (Rasmussen & Svenningsen, 1995; Borm & Wander, 1996), harrowing can be more selective because the crop forces tines into interrow spaces, and because crop plants protect each other from being pushed over and covered by soil. This study shows that very selective uprooting would be possible even at early growth stages, if contact between tines and crop plants could be avoided (e.g. 34% uprooted emerging “weeds” and only 2% uprooted “crop” seedlings, Fig. 4.5B).

As the model harrow has rigid tines, this experiment only clarifies a geometric aspect of tine flexibility. Beside a varying tine distance, tine vibrations may cause a variable speed of the tine tip in the soil (e.g. 0.6 m/s more or less at 20 Hz and 5 mm amplitude). To the knowledge of the authors, the flexing and vibrating behaviour of harrow tines in the presence of plants has not been studied.

Rasmussen (1990, 1992) did not find a different relationship between selectivity and crop covering using a rigid seedbed harrow, flexible chain harrow or spring tine harrow. However, harrows with larger tine spacing probably have a lower uprooting capacity, as the fraction uprooting decreases with increasing tine–plant distance. Habel (1954) used a rigid seedbed harrow with fixed tines spaced 50-60 mm apart, working 60-80 mm deep at speeds ranging from 0.8 to 1.2 m/s. Modern harrows have flexible tines spaced 25-40 mm apart and are operated at higher speeds (1-3 m/s) and shallower working depths (20-40 mm), so uprooting intensities may not be comparable.

4.5 Conclusions

This study indicates that the uprooting effect of harrowing could be more important for weed control than commonly assumed, especially for controlling weeds in the white thread stage. On loose sandy soil, plant sensitivity to uprooting decreases rapidly after plant emergence. If the crop emerges earlier than the weeds, selective uprooting of emerging weeds should be possible at early crop stages, when selective covering is difficult to achieve. To exploit uprooting selectivity, working depth should be shallow, spatially homogeneous and precisely controlled.

As the uprooting process is most selective beside the tine paths, contact with crop plants should be avoided while keeping the tine tip as close as possible to the crop row. This requires steering precision of about 10 mm, or flexible tines being able to follow a sharp spatial gradient in soil compactness close to the crop row, created by an adapted sowing or seedbed preparation technique.

Separate assessment of covering and uprooting, including covered uprooted plants, is necessary for a better understanding of the performance of selective mechanical weeders under different soil and weather conditions. Current methods for separate assessment are time consuming and prone to undesired uprooting of white threads and sensitive plants during excavation of the tilled layer. Simple practical methods for field experiments should be developed that also allow for standardisation of environmental conditions after cultivation.

5 Predicting selective uprooting by mechanical weeders from plant anchorage forces

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Manuscript

Summary

This paper presents a method to predict the relationship between the immediate weed and crop uprooting by mechanical weeding after crop emergence from anchorage force data. Uprooting and anchorage force of young Lolium perenne *L. and* Lepidium sativum *L. plants were measured in laboratory harrowing experiments on sandy soil. Although the fraction of uprooted plants was negatively correlated to mean anchorage force, such empirical relationships depend on harrowing intensity.*

A non-linear equation was introduced to describe the relationship between weed uprooting and crop uprooting. The parameters representing the selective potential of the crop–weed situation (K_{pot}) and implement selective ability (K_{till}) did not depend on crop uprooting. The relationship between potential weed uprooting and crop uprooting that could theoretically be obtained by a perfectly selective implement (i.e. pulling each plant with equal force) was calculated from plant anchorage force distributions measured before harrowing. This reflects the selective potential of a crop–weed situation and could serve as a reference to assess qualitative differences in harrowing selectivity.

As expected, the observed uprooting percentages achieved by harrowing were lower than the potential uprooting percentages. With K_{till} accounting for imperfect weeder selective ability, prediction accuracy was satisfactory. Field validation should confirm whether this method improves comparison and prediction of weeding performance of different weeding implements in different crop–weed situations.

Keywords: *mechanical weed control, weed harrowing, selectivity, plant anchorage, uprooting model, methodology.*

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5.1 Introduction

Improvement of mechanical weed control methods is needed to provide reliable and effective alternatives for herbicides and to reduce the need for handweeding in organic farming. Interrow cultivation can reduce herbicide inputs by 50-75% (Buhler *et al*., 1992; Mulder & Doll, 1993) and successfully controls even large weeds between crop rows (Mattsson *et al*., 1990; Pullen & Cowell, 1997; Weber, 1997). However, mechanical control of intra-row weeds is more critical, as (1) weeds are only sufficiently susceptible in the white thread or cotyledon stage (Habel, 1954; Peters *et al*., 1959; Kees, 1962; Koch, 1964a; Neururer, 1977; Gunsolus, 1990; Kurstjens *et al*., 2000; Kurstjens & Perdok, 2000), (2) achievable selectivity is limited in early crop growth stages (Rasmussen, 1992; Rydberg, 1993, 1995; Ascard & Bellinder, 1996), and as (3) weed response to damage depends on weather conditions after tillage (Terpstra & Kouwenhoven, 1981; Cavers & Kane, 1990; Real *et al*., 1993). When compared to chemical control, mechanical intra-row weed control generally requires a larger number of passes (up to 8, Rasmussen, 1991a; Baumann, 1992), more precise timing (Lovely *et al*., 1958; Fernholz, 1990; Gunsolus, 1990), longer periods of favourable weather and more effort and skill of the farmer (Wossink *et al*., 1997; de Buck *et al*., 1999), whereas effectiveness is more variable (e.g. Buhler *et al*., 1995). Therefore, improved knowledge of the attainable weed control as related to crop–weed situations, soil and weather conditions, implement type and implement use is needed to successfully integrate mechanical control in integrated weed management systems.

Weed harrows (Rasmussen, 1991a, 1992, 1993; Baumann, 1992; Rasmussen & Svenningsen, 1995; Rydberg, 1993, 1995), torsion weeders and finger weeders (Schweizer *et al*., 1992; Ascard & Bellinder, 1996; Hallefält *et al*., 1998; Looman *et al*., 1999), rotary hoes (Lovely *et al*., 1958; Gunsolus, 1990; VanGessel *et al*., 1998; Forcella, 2000), vertical row brushes (Kouwenhoven, 1997; Melander, 1997; Fogelberg & Dock Gustavsson, 1999) and pressurised air jets (Lütkemeyer, 2000) exploit differences in crop and weed sensitivity against soil-covering and uprooting. In a given crop–weed situation, the level of weed control and crop damage can be manipulated within certain limits, by changing the implement settings (e.g. working depth, working speed; Rydberg, 1993, 1995; van de Zande & Kouwenhoven, 1994; Jensen *et al*., 1999; Kurstjens & Perdok, 2000), the number of passes (Kirkland, 1994; Rasmussen & Svenningsen, 1995) or the tillage tool (Böhrnsen & Bräutigam, 1990; Rasmussen, 1992; Ascard & Bellinder, 1996; Bleeker *et al*., 2000). The ratio between weed control and crop damage and generally declines with increased crop damage (Rasmussen, 1990; Rasmussen & Svenningsen, 1995). The range within which weed control and crop damage can be manipulated depends on (1) the selective ability of the implement, (2) the achievable range of tillage aggressiveness and (3) the absolute and relative sensitivity of crop and weed plants. Soil conditions may affect all three factors.

These complexities cause major methodological difficulties in mechanical weed control research, as methods to independently quantify plant sensitivity and tillage aggressiveness are lacking. Although several studies systematically investigated the sensitivity of various crops (Lafond & Kattler, 1992; Leblanc & Cloutier, 2001) and weed species (Habel, 1954; Kees, 1962; Koch, 1964b) as related to their growth stage, results are specific for the soil conditions, tillage implement and aggressiveness used. Most studies have quantified effects on crop and weeds by reduction in plant density, biomass or yield. These parameters reflect relative differences in plant sensitivity but do not quantify plant sensitivity in absolute terms.

Meyler & Rühling (1966) measured the bending strength of plants to characterise their resistance against soil-covering. Meyler & Rühling (1966) and Fogelberg & Dock Gustavsson (1998) recorded plant anchorage forces to characterise plant resistance against uprooting. Plant anchorage force depends on root tensile strength, soil strength and root-soil adherence (Ennos, 1989, 1990) and may suitably summarise the effect of species, growth stage and soil conditions on plant sensitivity to being uprooted in an absolute and physically meaningful way. However, a method to predict the relationship between weed control and crop damage based on crop and weed sensitivity parameters and the selective ability of mechanical weeders is still lacking. Such methods are needed to further develop modelling frameworks in mechanical weeding as proposed by Rasmussen (1990, 1991b, 1993).

This paper presents a method to predict the relationship between weed uprooting and crop uprooting from plant anchorage force data and a parameter quantifying implement selective ability.

5.2 Materials and methods

5.2.1 Approach

Plant anchorage forces were measured to explain differing uprooting performance in laboratory harrowing experiments. As simply relating mean anchorage force to uprooting would not be appropriate, a new method to predict selective uprooting by mechanical weeders was developed. Quantification of the selective potential of the crop–weed situation and the selective ability of harrowing proceeds in three steps:

1. The relationship between weed and crop uprooting is calculated from measured crop and weed anchorage force frequency distributions, assuming an idealised harrow that hypothetically pulls each plant with the same force.
2. This relationship is fitted by a non-linear equation, to calculate selectivity parameter (K_{pot}), which quantifies the selective potential of the crop–weed situation independent of crop damage.
3. The selective ability of harrowing (K_{till}) is derived from K_{pot} (anchorage force based predictions with a hypothetical idealised harrow) and uprooting achieved in laboratory harrowing experiments.

Finally, the relationship between crop and weed uprooting in a specific crop–weed–implement situation can be predicted from the non-linear equation with selectivity parameter K calculated as K_{pot} x K_{till}. All parameters except K_{till} can be derived from anchorage force measurements. It is hypothesised that K_{till} is independent of the crop–weed situation and the crop damage level.

Table 5.1 Experimental layout of harrowing experiments.

Treatment		Working depth (mm)	Working speed (m/s)	Prepared soil moisture content (% of dry mass)
2	Standard	20	1.8	12.50
6	Shallow	10	1.8	12.50
7	Deep	30	1.8	12.50
1	Slow	20	1.2	12.50
3	Fast	20	2.4	12.50
4	Dry	20	1.8	8.00
5	Wet	20	1.8	17.00
8	Shallow*dry*fast	15	2.1	10.25
9	Shallow*wet*slow	15	1.5	14.75
10	Deep*dry*slow	25	1.5	10.25
11	Deep*wet*fast	25	2.1	14.75

5.2.2 Harrowing experiments

Two model plant species, *Lolium perenne* L. (ryegrass) and *Lepidium sativum* L. (garden cress), were separately subjected to a series of harrowing treatments in the laboratory. Working depth, working speed and soil moisture content were varied using a reduced central composite design of 11 treatments (Table 5.1). Aluminium bins (l x w x d = 0.40 x 0.60 x 0.13 m) were filled with sieved, homogenised fine black sand (3.2% organic matter content, 3.0% clay, 6.5% silt) of the desired moisture content, compacted to 0.95 t/m^3 dry-bulk density. Each bin contained 357 seeds placed in a rectangular grid on the compacted bottom soil layer, covered by a 10-mm thick compacted layer. At harrowing 3-4 days after emergence, *L. perenne* had one thin 1-70 mm long leaf and *L. sativum* was at the early cotyledon stage (0-25 mm tall). These experiments provided uprooting data from at least two bins per treatment and species. Uprooting data and further experimental details were given by Kurstjens *et al*. (2000). The reciprocal of the variances of logit-transformed observed fractions of uprooted plants were used as weights in linear regression and calculation of weighed root mean square errors (wrmse, in fraction uprooted plants).

5.2.3 Plant growth stages used as model crop and weed

The natural variation in emergence rate between seeds caused differences in plant size within a bin. Both in harrowing and anchorage force experiments, plants were classified into five plant size classes by measuring plant height (of both species) and visually assessing *L. sativum* cotyledon size. Based on these plant size classes, each species was divided into a “weed” and a “crop” group. Germinated seeds (white threads) and plants breaking through the soil surface (*L. perenne*: leaf length < 20 mm) were regarded as weeds. Larger seedlings of the same species were regarded as the crop. The artificial division of a population into a crop and a weed group may have resulted in different anchorage force frequency distributions than those of natural populations.

5.2.4 Anchorage force experiments

As anchorage forces could not be measured in the bins that were to be harrowed, anchorage forces measured in untreated bins were randomly assigned to plants of the same size class in harrowed bins having similar soil moisture content. At each of the five prepared soil moisture contents, 16-261 weeds (average 116) and 146-698 crop plants (average 339) per species were pulled up, to measure their anchorage force. Each plant was seized in a clamp connected to a hand-held Pesola® steelyard (range: 1 N, scale: 0.02 N) by a thin wire. By moving the steelyard in vertical direction at 10-15 mm/s, the vertical pulling force gradually increased until the plant suddenly came loose. At that moment, the maximum force was recorded together with the plants' size class. The topsoil was carefully excavated to measure anchorage force of germinated seeds as well.

In contrast to harrowing experiments, the soil on top of seeds was not compacted because compaction would induce a soil wedge above the seed that would increase anchorage force (data not shown). As this wedge would not occur at harrowing, anchorage provided by the root would probably better represent plant resistance against uprooting. Furthermore, anchorage force experiments used new seeds because of ceased vigour of seeds used in preceding harrowing experiments. As the new seeds emerged more simultaneously than those in harrowing experiments, plants were pulled up at two different times to have a reasonable number of plants in each of the five plant size classes per soil moisture content.

5.2.5 A novel approach to quantify selectivity and describe the relationship between crop and weed uprooting

Rasmussen (1990) defined selectivity (S) as the ratio of per cent weed control and per cent crop damage. As this ratio generally declines with increasing crop covering, it is not suitable to quantify qualitative differences in selectivity at variable intensities of harrowing. If S would be calculated from our weed and crop uprooting data (i.e. % weed uprooting per % crop uprooting), it would decline with increased crop uprooting (Kurstjens *et al*., 2000). However, the relationship between the fraction uprooted weed (U_{weed}) and the fraction uprooted crop (U_{crop}) could be adequately described by an equation of the form (equation (1)):

$$U_{weed} = U_{crop}^{\,(1-K)} \qquad (1)$$

Selectivity parameter K ranges from 0 ($U_{weed} = U_{crop}$, i.e. no selectivity) to 1 ($U_{weed} = 1$ for all values of $U_{crop} > 0$, maximum selectivity) and would not depend on harrowing intensity. This is an important requirement for quantifying and modelling selectivity.

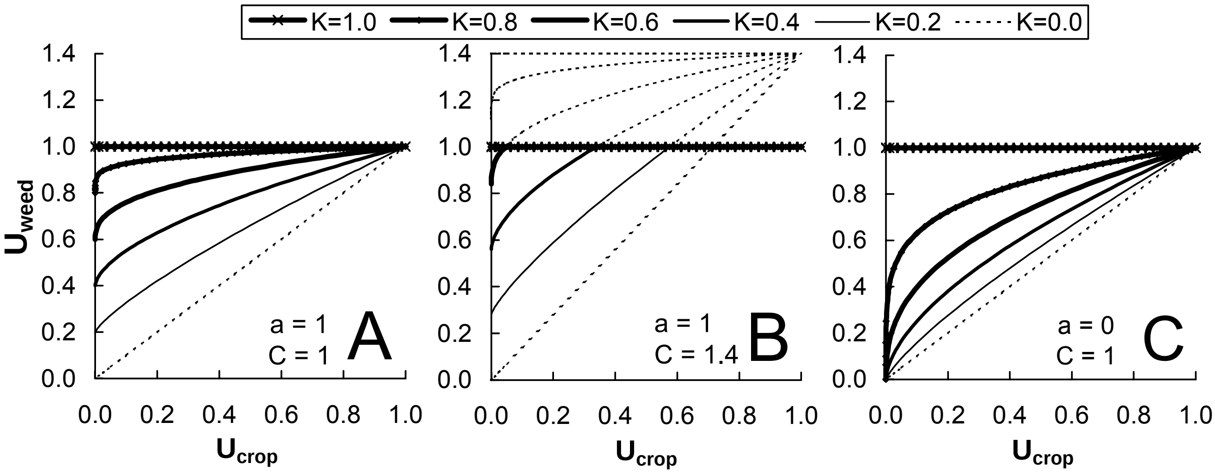

Fig. 5.1 The behaviour of equation (2) at six values of parameter K and various values of parameters a and C. Dashed lines with $U_{weed} > 1$ (graph B) reflect equation (2) behaviour without the minimum function.

Equation (1) can be made more flexible by including parameters a and C (equation (2)):

$$U_{weed} = \min [\, 1 , C \cdot (a \cdot K + (1 - a \cdot K) \cdot U_{crop}^{\,1-K})] \qquad (2)$$

If $0 < C \leq 1$, parameter C represents the fraction uprooted weeds when the crop is completely uprooted. If $C > 1$, C is related to the critical fraction uprooted crop (U_{crit}) at which all weeds are uprooted. The minimum-function limits U_{weed} to 1 in case $C > 1$ and $U_{crop} > U_{crit}$ and probably provides a realistic uprooting curve description in cases of high selective potential (Fig. 5.1B).

Parameter a represents the uprooting selectivity at $U_{crop} = 0$ and is greater than zero if some weed control can be obtained without crop damage (Fig. 5.1A). As uprooting selectivity at $U_{crop} = 0$ is probably related to uprooting selectivity at $U_{crop} > 0$, parameter a is a multiplicator of the selectivity parameter K.

Furthermore, it is hypothesised that K of a specific crop–weed–implement situation can be decomposed into a parameter representing the selective potential of the crop–weed situation (K_{pot}) and the selective ability of the tillage implement (K_{till}), so that $K = K_{pot} \times K_{till}$. Parameters a and C should not depend on implement-related factors. Equation (2) with parameters a, C and K_{pot} describes the potential relationship between weed and crop uprooting (hereafter called: potential uprooting curve) for a crop–weed situation and an idealised mechanical weeder with maximum selective ability ($K_{till} = 1$). This relationship is calculated from weed and crop anchorage force data as described below.

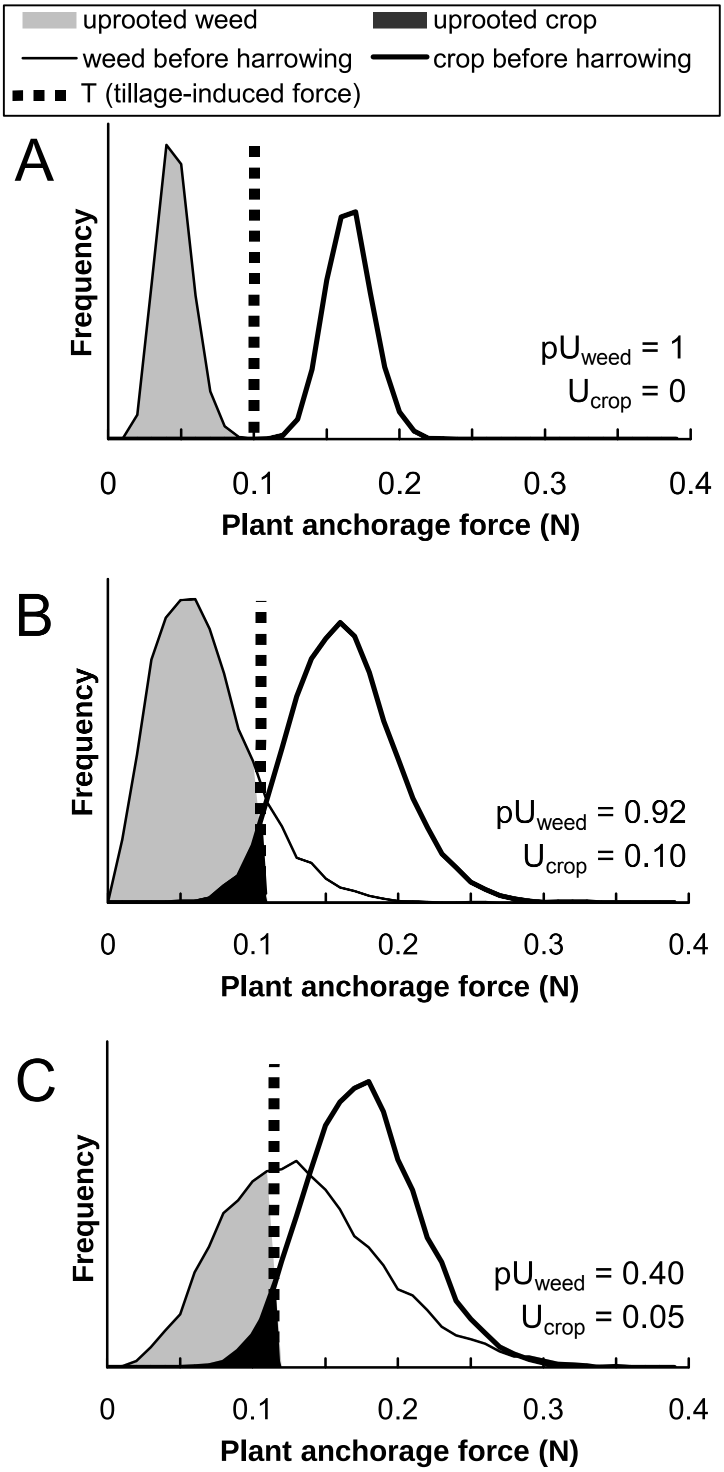

Fig. 5.2 Plant anchorage force frequency distributions illustrating the calculation of potential weed uprooting (pU_{weed}) and crop uprooting (U_{crop}) by a constant tillage-induced force (T): plants with anchorage force < T (left from the vertical dashed line) are uprooted. The square root distributions reflect three examples of potential uprooting selectivity: A: hypothetical case with 100% weed control without crop damage; B: the highest calculated selectivity found with the *L. perenne* 'dry' treatment; C: the lowest calculated selectivity found with the *L. perenne* 'standard' treatment (see Table 5.1 for treatment specification).

5.2.6 The selective uprooting potential of a crop–weed situation

To quantify the selective uprooting potential of a crop–weed situation, potential weed uprooting by an idealised harrow was predicted from anchorage force data. Let us assume that all simultaneously harrowed weed and crop plants are pulled by an equal, constant tillage-induced force (T, in Newton). All plants having an anchorage force lower than T are considered to be uprooted. In case the best-anchored weed would be weaker anchored than the weakest crop plant, 100% weed control without uprooted crop plants would ideally be possible (Fig. 5.2A). However, in reality, these anchorage force frequency distributions (AFFDs) may overlap (Fig. 5.2B-C), resulting in partial crop uprooting and/or incomplete weed control.

Both weed uprooting and crop uprooting are functions of T. The shape of their AFFDs determine the shape of these "dose–response" curves. This paper describes AFFDs by square root distributions, which means that the square root of anchorage force is normally distributed. Square root distributions were chosen to avoid negative anchorage forces when variability is relatively large. This method was implemented in Microsoft Excel 97, using 20.000 random values to describe crop and weed AFFDs.

The potential fraction uprooted weeds (pU_{weed}) at a particular fraction uprooted crop (U_{crop}) is calculated from the weed AFFD and the value of T at which a fraction U_{crop} is uprooted (from the crop AFFD). For each treatment and species in the harrowing experiment, the potential fraction uprooted weeds is calculated from measured crop and weed AFFDs at 100 U_{crop} values ranging from 0 to 0.99. Then, equation 2 is fitted to these calculated uprooting curve data by non-linear regression. This results in an estimated a, C and K_{pot} per species and treatment.

5.2.7 The selective ability of mechanical weeders

The actual value of K is calculated from the observed weed and crop uprooting data from Kurstjens *et al*. (2000), using the values of a and C estimated for the potential uprooting curve. The selective ability of mechanical weeders, expressed by parameter K_{till}, bridges the gap between potential uprooting by an idealised hypothetical weeder and observed uprooting as achieved by real weeders. K_{till} is calculated as K / K_{pot}, where K_{pot} quantifies the selective potential of the crop–weed situation as described above.

The effects of species, working depth, working speed and soil moisture content on K_{pot}, K and K_{till} were analysed by linear mixed models (REML) in Genstat 5 Release 4.1 (Genstat 5 Committee, 1993, 1997).

5.3 Results and discussion

5.3.1 Empirical relationship between uprooting and mean anchorage force

The observed fraction of uprooted plants was negatively correlated to mean anchorage force (Fig. 5.3). The relationship between uprooting and anchorage force in our study showed considerable scatter (both species together: R^2 = 0.48, not shown) and was species-dependent. The species-dependency may partly be caused

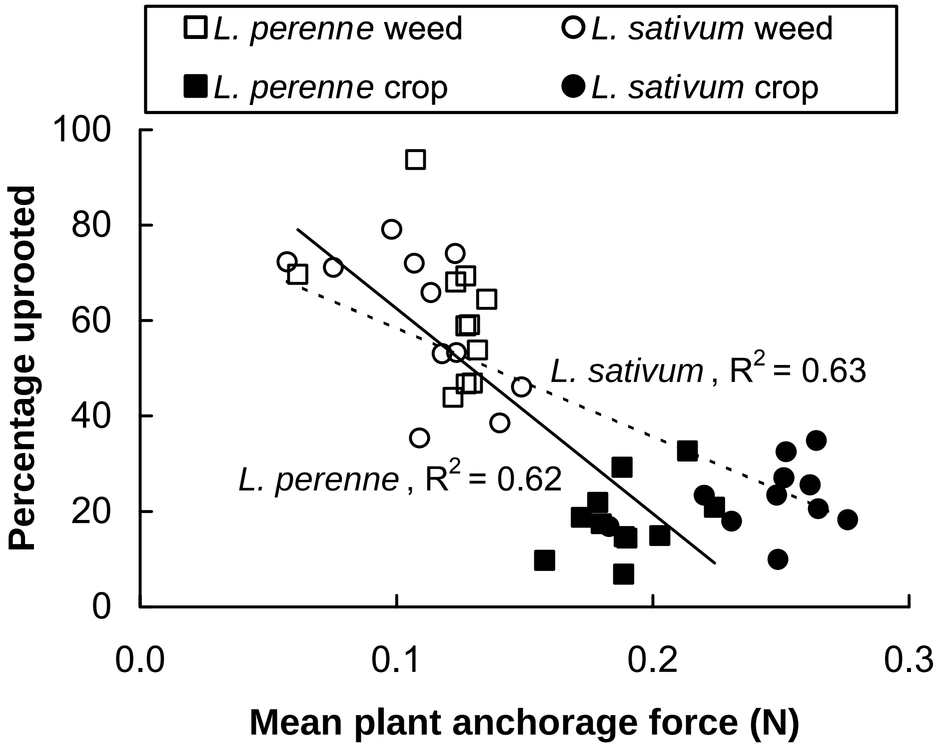

Fig. 5.3 Relationship between the mean observed uprooting percentage and the mean plant anchorage force of weed and crop plants per treatment and species. Weighted linear regression lines.

by the fact that anchorage forces and uprooting data could not be gathered from the same populations, as with Meyler & Rühling (1966) and Fogelberg & Dock Gustavsson (1998). Also these workers found that better-anchored plants were less uprooted by weed harrowing experiments of Habel (1954) and Koch (1964b) and intra-row weed brushing experiments of Fogelberg & Dock Gustavsson (1999) respectively. Although Fogelberg & Dock Gustavsson (1998) concluded that different anchorage forces of carrots and weeds enable selective uprooting, they could not quantify how much weed control could be obtained at how much crop damage. Empirical relationships between uprooting and anchorage force are likely to depend on the aggressiveness of the weeding operation. To provide a conceptually sound method for predicting the uprooting performance of mechanical weeders, the tillage aggressiveness should be quantified as well.

5.3.2 Potential weed uprooting of an idealised harrow

Our prediction method avoids the problem of unknown magnitude of tillage-induced forces and takes account of within-population variability. In field experiments by Kurstjens *et al*. (2002), spring tine harrows, torsion weeders and finger weeders predominantly uprooted the smallest weeds. Anchorage force of sugarbeet in the 2-4 leaf stage was very variable (10% < 0.09 N, 50% < 0.24 N, 10% > 0.39 N;

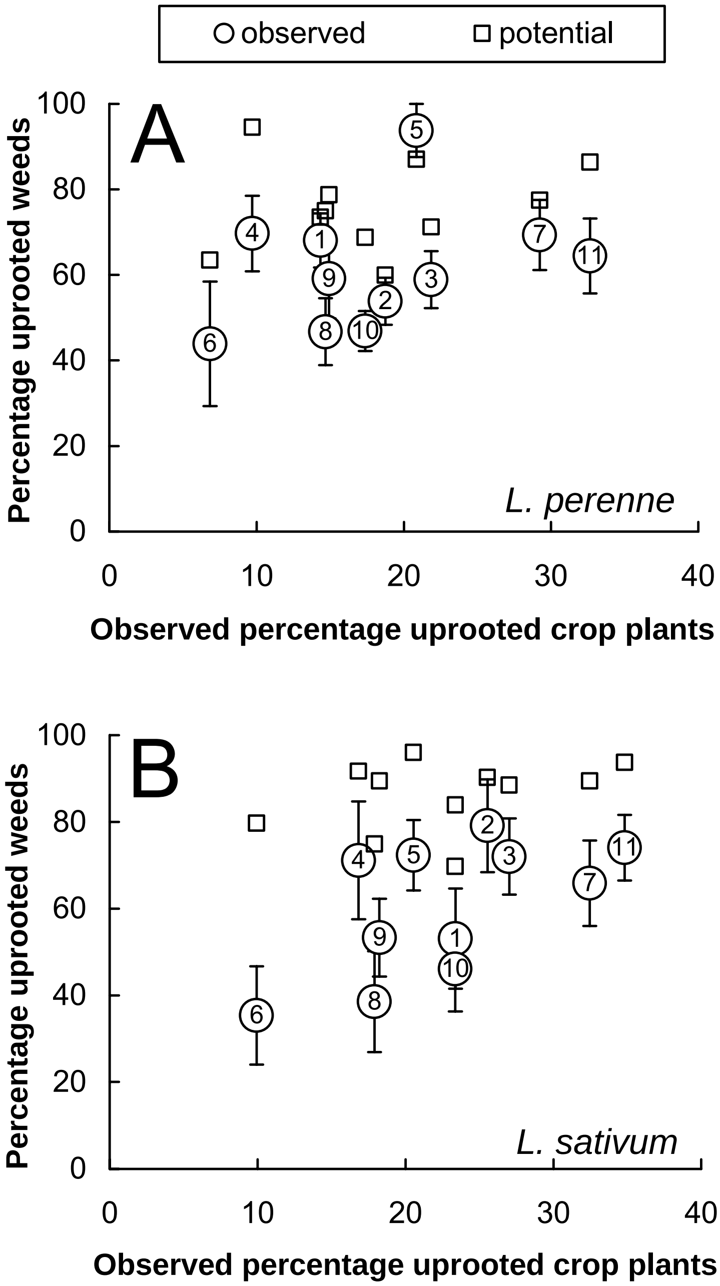

Fig. 5.4 Observed and potential weed uprooting of *L. perenne* (A) and *L. sativum* (B) as related to observed crop uprooting. Numbers refer to treatment numbers in Table 5.1. Error bars are 95% confidence limits of observed means (data from Kurstjens *et al*., 2000). Potential weed uprooting is calculated at the magnitude of tillage force (T) that would yield the observed crop uprooting percentage.

unpublished data). Anchorage of the weakest crop plants restricts weeding aggressiveness, whereas loss of only small crop plants may have but a negligible impact on crop yield. Thus, taking account of within-population variability of anchorage force (Easson *et al*., 1995) or a parameter related to plant sensitivity (e.g. dry mass; Ogden, 1970; Kurstjens *et al*., 2002) seems legitimate.

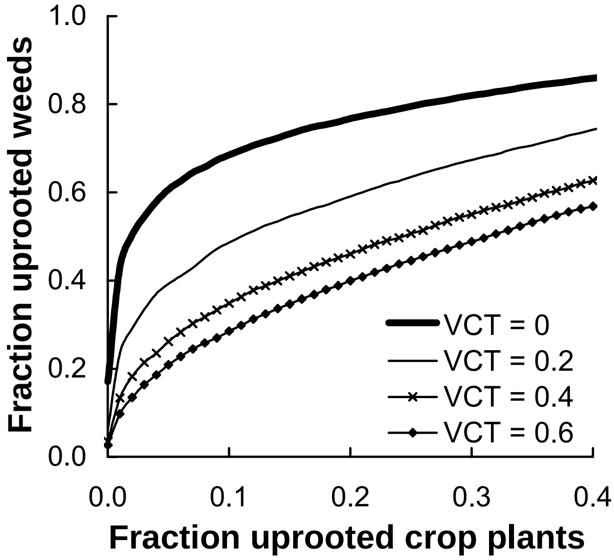

Fig. 5.5 Simulated effect of different levels of variability of tillage-induced forces (VCT) on relationships between weed uprooting and crop uprooting. Tillage-induced forces are described by square root distibutions, with VCT being the variation coefficient on root-transformed scale. The curve with VCT = 0 represents the potential uprooting curve of an idealised harrow with invariable tillage-induced force. Different combinations of weed and crop uprooting on a curve result from varying magnitudes of tillage-induced force. See appendix for more explanation.

Calculating the potential weed uprooting from crop and weed AFFDs would allow for separation of plant sensitivity effects and tillage effects on uprooting selectivity. In Fig. 5.4, variability of potential weed uprooting between treatments explained 33.1% and 49.4% of the variation in observed weed uprooting in *L. perenne* (Fig. 5.4A) and *L. sativum* (Fig. 5.4B) respectively. The remaining variation can be attributed to differences in the selective ability of harrowing and to experimental error.

The calculated potential fraction of uprooted weeds generally exceeded the observed fraction in harrowing experiments (Fig. 5.4), particularly with *L. sativum*. This can be attributed to two major simplifications. Firstly, the method uses a binary dose–response function, in which the uprooting probability for a single plant jumps from 0% to 100% at the point where the tillage-induced force T (i.e. the “dose”) equals the plant anchorage force. Secondly, it is assumed that the harrow pulls each plant in vertical direction with the same magnitude of tillage-induced force. However, in reality, forces in the soil failure zone near a horizontally moving tine are dynamic, spatially variable and not vertical (Payne, 1956; Godwin & Spoor, 1977; Koolen & Kuipers, 1983; Stafford & Young, 1986; Rajaram & Gee-Clough, 1988; Rajaram & Oida, 1992; Rajaram & Erbach, 1996). The assumed homogeneity of tillage-induced forces is probably far too simple, especially with structured soils and flexible tools.

An additional simulation study was conducted that included variable tillage-induced force in the calculations (see appendix). This study indicated that increased tillage force variability decreases the uprooting potential considerably (Fig. 5.5).

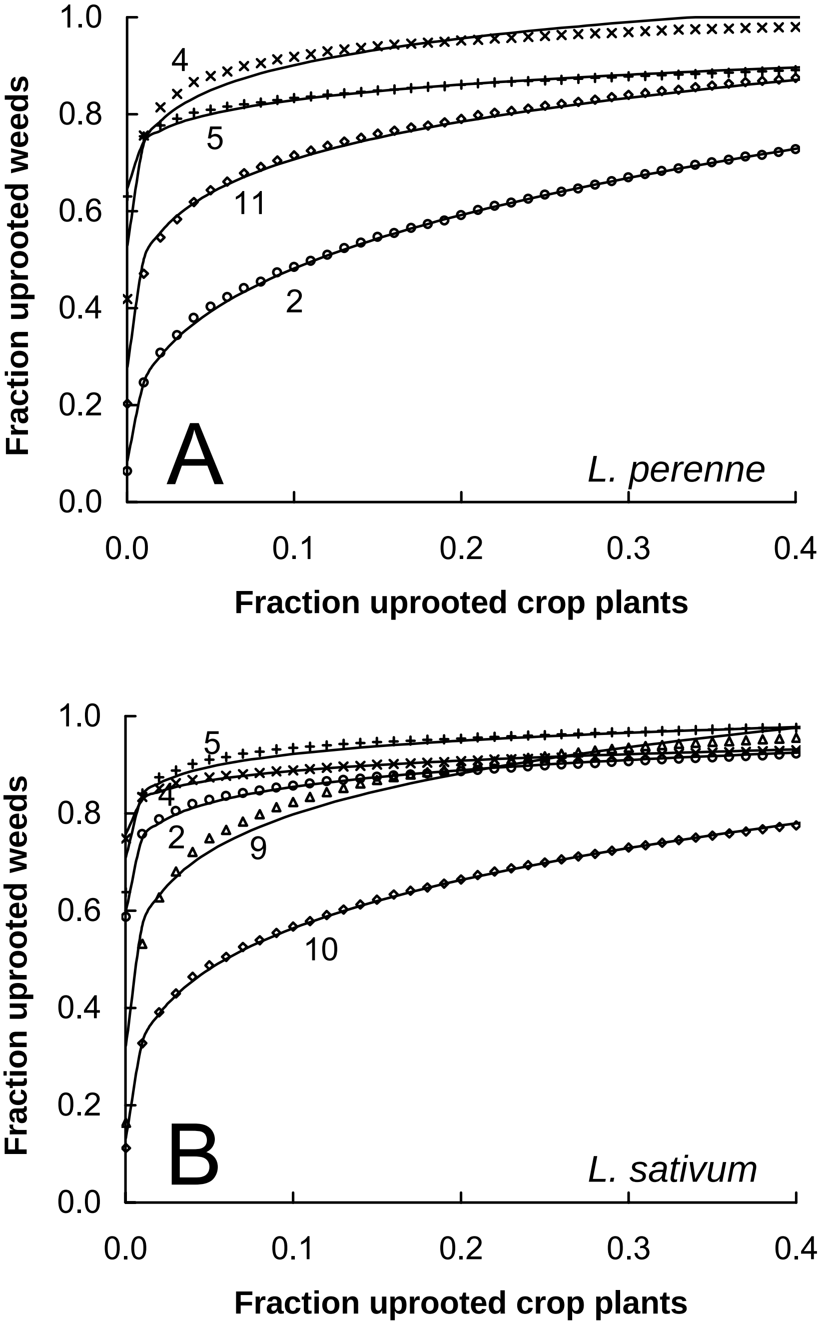

Fig. 5.6 Calculated combinations of crop and potential weed uprooting (symbols) and the fit of equation (2) (lines) with selected *L. perenne* (A) and *L. sativum* (B) treatments. Numbers refer to treatment numbers in Table 5.1. See Table 5.2 for parameter values of fitted curves (a, C, K_{pot}).

Therefore, the calculated potential weed uprooting (assuming a constant T, curve with VCT = 0 in Fig. 5.5) reflects a theoretical maximum to be obtained by an idealised harrow. It could be used as a reference to compare the selective performance of implements at different levels of uprooting.

Table 5.2 Parameter values of equation (2) fitted to the calculated potential uprooting curves of Fig. 5.6, and the subsequently calculated K and K_{till} per treatment and species. rmse = root mean square error (in fraction uprooted weeds).

			Potential uprooting curve					
Species	Treatment		rmse	a	C	K_{pot}	K	K_{till}
L. perenne	2	Standard	0.007	0.024	0.959	0.694	0.648	0.934
	6	Shallow	0.008	0.000	0.995	0.814	0.695	0.855
	7	Deep	0.006	0.000	0.972	0.803	0.725	0.903
	1	Slow	0.009	0.000	0.996	0.823	0.804	0.977
	3	Fast	0.006	0.000	0.993	0.754	0.656	0.870
	4	Dry	0.018	0.000	1.097	0.914	0.805	0.881
	5	Wet	0.006	0.638	0.949	0.858	0.980	1.142
	8	Shallow*dry*fast	0.006	0.000	0.979	0.839	0.614	0.733
	9	Shallow*wet*slow	0.006	0.000	0.973	0.874	0.738	0.845
	10	Deep*dry*slow	0.007	0.012	0.959	0.786	0.587	0.747
	11	Deep*wet*fast	0.010	0.000	0.999	0.850	0.609	0.716
L. sativum	2	Standard	0.004	0.000	0.975	0.943	0.847	0.899
	6	Shallow	0.006	0.000	0.980	0.903	0.558	0.618
	7	Deep	0.007	0.000	0.989	0.905	0.639	0.706
	1	Slow	0.007	0.118	0.959	0.894	0.553	0.618
	3	Fast	0.005	0.000	0.981	0.918	0.764	0.832
	4	Dry	0.004	0.747	0.965	0.883	0.621	0.704
	5	Wet	0.010	0.000	1.016	0.958	0.785	0.820
	8	Shallow*dry*fast	0.010	0.221	0.937	0.826	0.398	0.481
	9	Shallow*wet*slow	0.023	0.000	1.116	0.854	0.566	0.662
	10	Deep*dry*slow	0.006	0.000	0.965	0.767	0.491	0.641
	11	Deep*wet*fast	0.020	0.000	1.064	0.871	0.657	0.754

5.3.3 Effect of species, treatment factors and crop uprooting on selectivity

In most cases, equation (2) fitted the potential uprooting curves of both species very well (Fig. 5.6, Table 5.2). As intended, K, K_{pot} and K_{till} (Table 5.2) did not depend on crop uprooting (*L. perenne*: $P > 0.55$; *L. sativum*: $P > 0.17$). In field experiments by e.g. Rasmussen (1990, 1992) and Rydberg (1995), the ratio between weed control and crop covering generally declined with increased crop covering. As this decrease of selectivity also holds for our uprooting data (Kurstjens *et al*., 2000), K appears a more suitable parameter to quantify qualitative differences in selectivity at variable intensities of harrowing than the selectivity ratio as defined by Rasmussen (1990).

Working depth, working speed and soil moisture content did not affect K_{pot} (Table 5.2, $P > 0.36$). K and K_{till} were not influenced by working depth and working speed ($P > 0.47$) but increased with moister soil (K: $P \approx 0.05$; K_{till}: $P < 0.05$).

Although K_{till} should not depend on plant characteristics, K_{till} of *L. perenne* exceeded that of *L. sativum* ($P < 0.05$). Additional field studies should test whether harrowing different crop–weed combinations (different K_{pot}) at the same location and

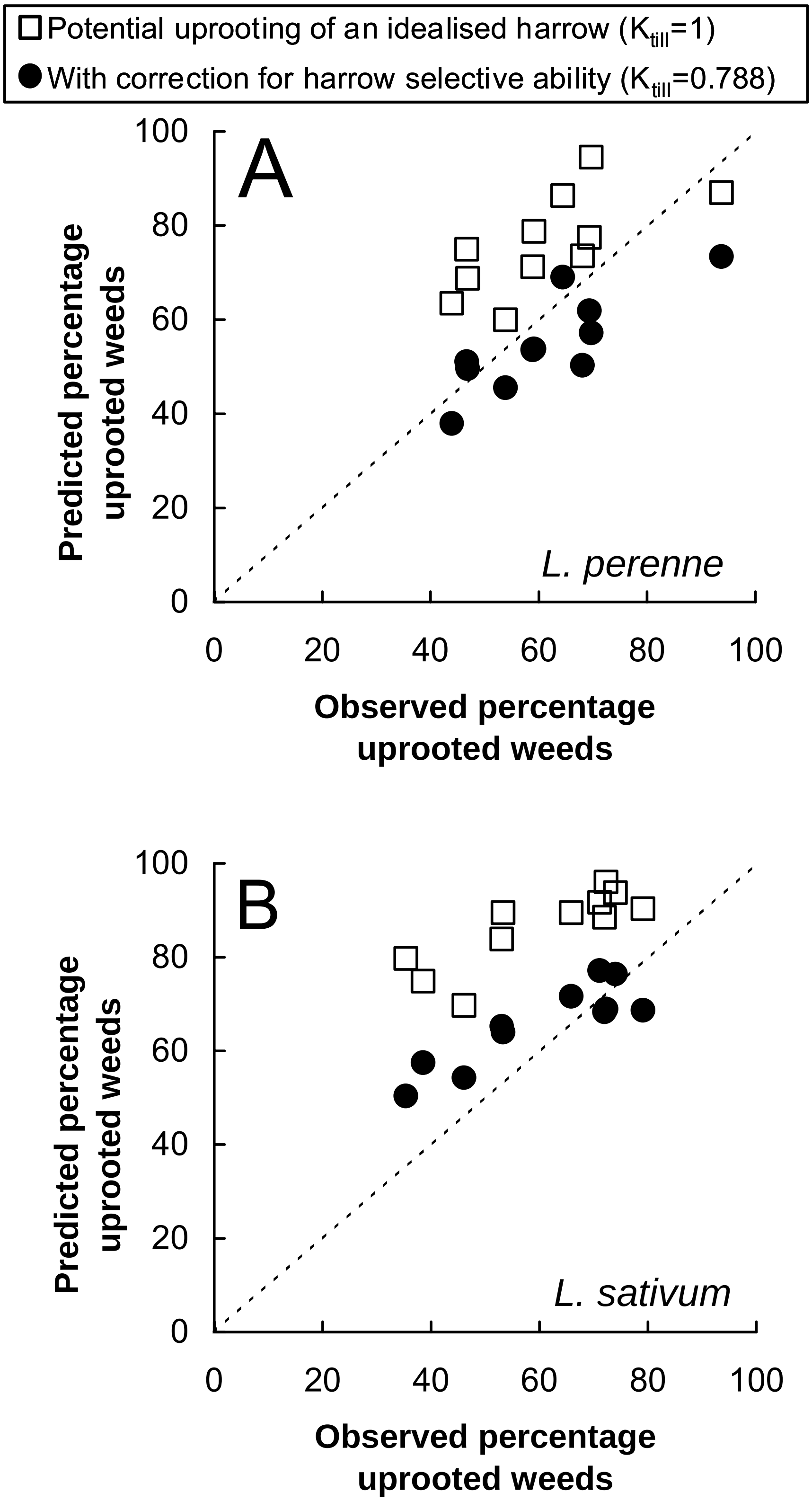

Fig. 5.7 Relationship between the observed and predicted percentage uprooted weeds of *L. perenne* (A) and *L. sativum* (B), assuming an idealised harrow (K_{till} = 1) or an average selective ability of harrowing (K_{till} = 0.788) with K_{pot}, a and C parameter values per treatment and species (from Table 5.2), respectively.

time would yield similar values for K_{till}. If so, this method would improve comparability of field experiments at different sites and times and could be used to predict harrowing performance in other soil, crop and weed conditions.

5.3.4 Predictions with imperfect weeder selectivity

At the fraction of uprooted crop plants observed in harrowing experiments, weed uprooting is predicted from equation (2), using values of a, C and K per species-treatment combination. K is calculated from K_{pot} per species-treatment combination and an average value of K_{till} = 0.788 for all species and treatments. This means that only differences in crop–weed selective potential and quantitative differences in selectivity (as a result of different crop uprooting levels) are accounted for. Hence, treatment effects on the selective ability of harrowing (K_{till}) are neglected.

Predictions taking account of imperfect weeder selective ability were more accurate than calculated potential weed uprooting percentages (Fig. 5.7) and mean anchorage forces (wrmse = 0.092, 0.220 and 0.134, respectively). The remaining error could be attributed to four sources:

Firstly, predictions may be improved by using K_{till} values for specific soil conditions and implements. The authors expect that modelling the effects of soil conditions and implement factors on K_{till} will be easier than modelling their impacts on crop and weed damage directly.

Secondly, anchorage force distributions might have deviated from the assumed square root distributions. Especially an accurate description of the left tail of the crop anchorage force frequency distribution is important for accurate predictions. In our experiment, 18 out of 44 anchorage force distributions (11 treatments x 2 species x 2 growth stages) were best fitted by square root distributions, 19 were best fitted by normal distributions and 7 were best fitted by gamma, beta or lognormal distributions (data not shown).

Thirdly, anchorage forces measured by vertically pulling out plants by a steelyard might not adequately reflect the magnitude of plant reaction forces during tillage, as the dynamics of root and soil failure and the role of the soil layer above the seed differ. The actual forces are related to soil and root deformations (Ennos, 1989, 1990; Easson *et al*., 1995) and cannot be measured *in situ* during harrowing.

Fourthly, plant anchorage in the tilled top layer may contribute to the transmission of tillage-induced forces onto plants, whereas root parts anchored in the undisturbed subsoil seem to offer most of the resistance against uprooting (unpublished data). Separate measurement of plant anchorage in topsoil and subsoil could help to explain the effect of root architecture and differences in resistance against uprooting between species and growth stages, and might provide a more reliable basis for uprooting predictions.

5.3.5 Applications

Uprooting predictions based on crop and weed anchorage forces can be a useful approach to distinguish between the selective ability of the tillage operation and the selective potential of a crop–weed situation. Once separation of these two causes is possible, studying the effects of soil conditions, implement types and adjustments and growth stages of crops and weeds would become less complicated. Although the mechanism and factors involved in the soil-covering process differ from uprooting (Kurstjens & Perdok, 2000), a similar approach may be applied to burial damage.

Models to calculate uprooting from crop and weed AFFDs that include variable tillage-induced forces could be used to estimate the magnitude of tillage-induced forces from anchorage forces and uprooting data. The magnitude of tillage-induced forces may suitably quantify the uprooting intensity independently of plant characteristics. In addition, such models could be used to correct measured AFFDs before harrowing for uprooting of predominantly the smallest plants. When anchorage forces of non-uprooted plants after harrowing are measured as well, plant anchorage in the topsoil tilled by harrowing could be estimated. The vertical gradient in anchorage force may help explain species-dependency in relationships between anchorage force and uprooting. Such extended uprooting models could be a useful tool to study relationships between topsoil and subsoil plant anchorage force, implement draft and tillage-induced forces on plants. Although anchorage force measurements and calculations may be too time-consuming to be practicable in the field, the method is worth to be tested in further experiments.

Once relationships between plant sensitivity parameters and plant traits predicted by models for germination, emergence and early growth are established, this approach may be incorporated in mechanistic models. Such models may support dynamic weed control decisions (implement selection, timing, aggressiveness) and take account of weed and crop development and heterogeneous populations resulting from weed germination flushes and partial control. Forcella (2000) demonstrated the value of weed emergence models to time rotary hoeing to sensitive weed growth stages. Using plant characteristics to predict the relationship between immediate crop and weed damage (uprooting or soil-covering) could be a valuable extension.

With herbicides, a-priori knowledge of the relationship between crop damage and weed control is essential to optimise the timing and the herbicide dose (comparable to the aggressiveness of mechanical weeding). The authors think that predicted relationships between weed control and crop damage can be a useful tool to search for the optimum compromise between cost of crop damage (yield reduction) and cost associated to insufficient mechanical weed control (crop yield reduction by weed competition, costs of additional operations or manual weeding).

Appendix The impact of anchorage force variability within crop and weed populations and variability of tillage-induced forces on harrowing selectivity – a simulation study.

Uprooting model

In chapter 5, a simple model was used to calculate potential uprooting curves from measured weed and crop anchorage forces (see section 5.2.6). Instead of assuming that harrowing exposes all plants to the same constant level of tillage-induced force (T), this appendix uses an extended uprooting model with a (more realistic) variable tillage-induced force. Both the weed and crop anchorage force (A) and the tillage-induced forces (T) were described by square root distributions. This means that the square-root transformed force is normally distributed, with means MA_{weed}, MA_{crop} and MT and standard deviations SA_{weed}, SA_{crop} and ST. The tillage force variability is quantified by the variation coefficient VCT (= ST / MT). Square root distributions were chosen to avoid problems with negative anchorage forces when variability is relatively large. The model was implemented in Microsoft Excel 97, using 20.000 random combinations of crop or weed anchorage force and tillage-induced force, both describing square root distributions.

Illustration of the uprooting model

Figure A5.1 illustrates the shape of square root distributions and the principle of the uprooting model with an example weed and crop population and four VCT levels. In Fig. A5.1A, all plants having an anchorage force lower than the constant tillage-induced force of 0.125 N are uprooted. Increased VCT (Fig. A5.1B-D) causes uprooting of more firmly anchored plants by coincidentally high tillage forces, whereas an increased fraction of the weaker plants remain anchored. This results in more crop uprooting and less weed uprooting (Table A5.1). Simulated uprooting curves in Fig. 5.5 (see chapter 5 main text) were calculated for the example weed and crop population in Fig. A5.1 by varying the magnitude of tillage-induced forces.

Simulated achievable weed control at 5% crop damage

Figure A5.2A shows simulated lines of equal weed uprooting at 5% crop uprooting achieved by an idealised weed harrow (VCT = 0) in various hypothetical crop–weed combinations. These combinations are characterised by the ratio between weed and crop anchorage force (horizontal axis) and anchorage force variability (vertical axis). In this example, the standard error of root-transformed anchorage forces of weeds equals that of the crop ($SA_{weed} = SA_{crop}$). If that were the case for the example crop–weed combination of Fig. A5.1 and Table A5.1 (MA_{weed} / MA_{crop} = 0.77, SA = 0.11), 68% of the weeds would be uprooted at 5% crop uprooting (the point between the 60% and 80% line in Fig. A5.2A). A larger difference between weed and crop anchorage forces (going left in Fig. A5.2A) or less anchorage force variability (going down) would lead to more uprooted weeds. Below the 99%-line, complete weed control could theoretically be achieved with less than 5% crop damage.

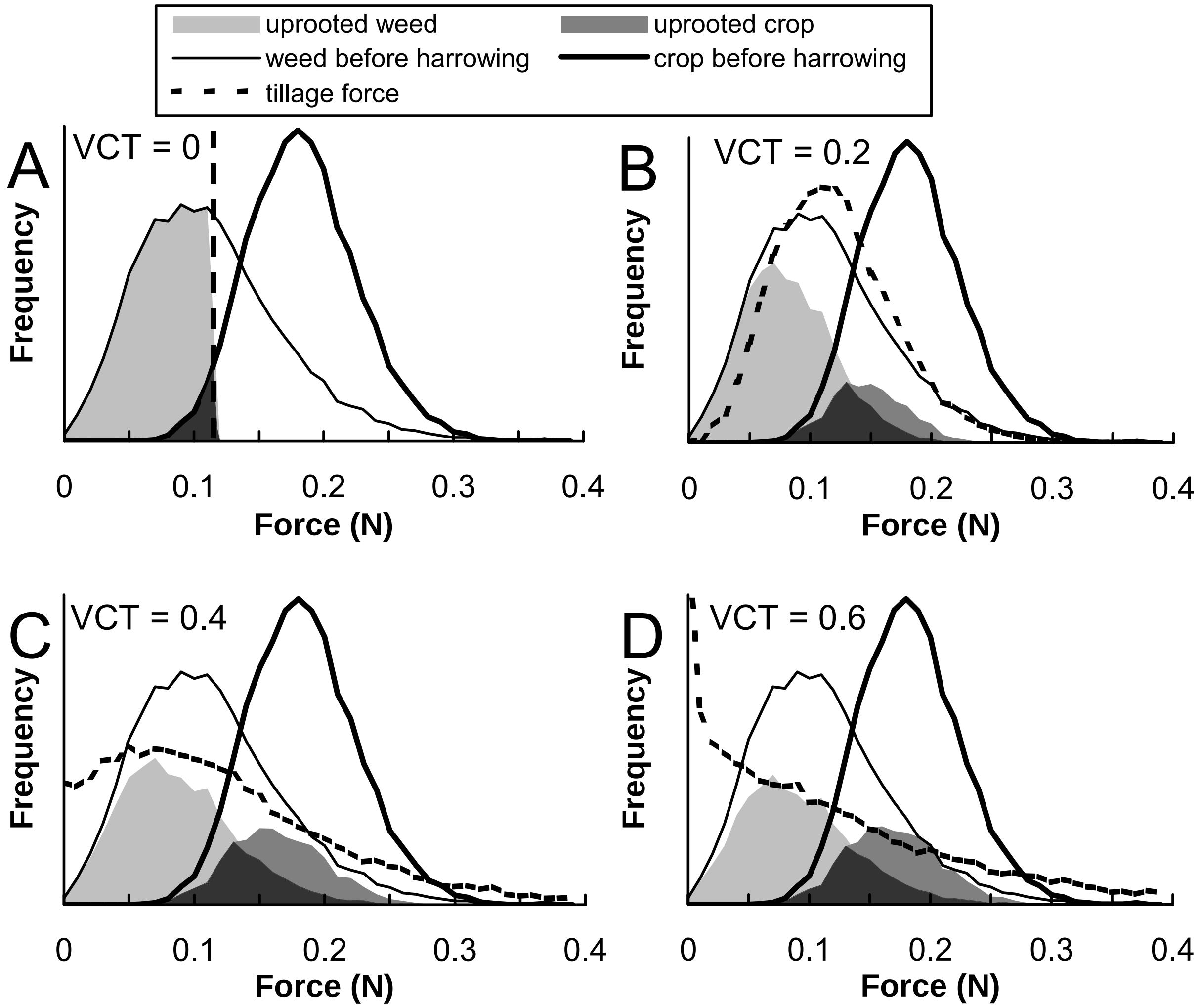

Fig. A5.1 Example frequency distributions of anchorage forces and tillage-induced forces at four levels of tillage force variability (VCT). Uprooting model parameter values and results are given in Table A5.1.

Table A5.1 Parameters and results of example uprooting simulations in Fig. A5.1, using measured anchorage forces of *L. perenne* at 12.5%w/w soil moisture content.

	Tillage-induced force (N) [1]			Percentage uprooted (%)		Anchorage force of non-uprooted plants (N)			
						weed		crop	
Example	mean	se	VCT [2]	weed	crop	mean	se	mean	se
Untreated	-	-	-	-	-	0.117	0.0554	0.189	0.0414
A	0.125	0.0000	0.0	60.5	4.9	0.172	0.0403	0.193	0.0383
B	0.125	0.0486	0.2	55.1	15.7	0.154	0.0510	0.195	0.0397
C	0.125	0.0896	0.4	49.0	22.9	0.140	0.0552	0.195	0.0410
D	0.125	0.1199	0.6	44.3	24.7	0.134	0.0562	0.193	0.0414

[1] mean and standard error of tillage force frequency distributions in Fig. A5.1.

[2] variation coefficient of square-root transformed tillage force (= ST / MT).

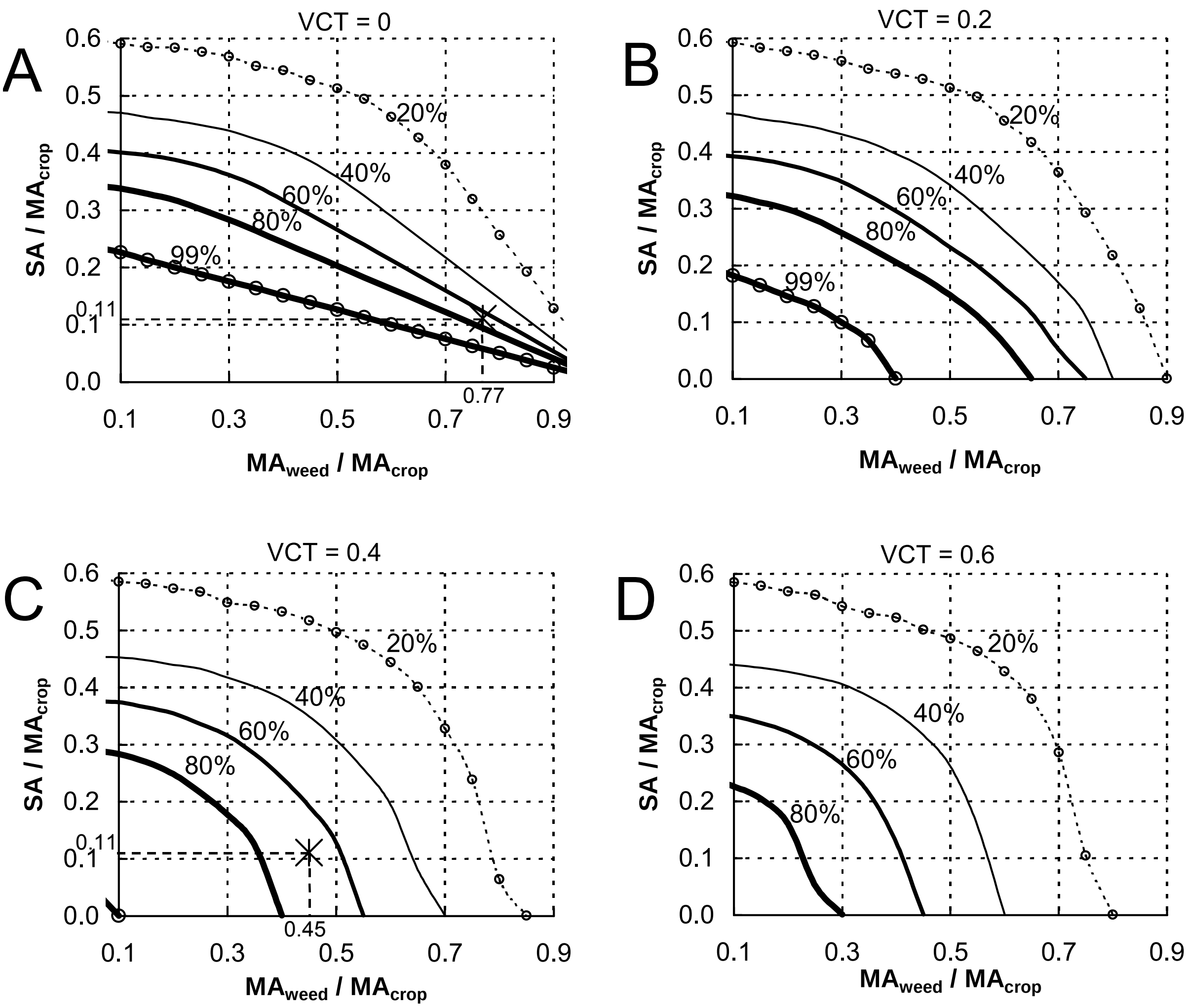

Fig. A5.2 Lines of equal weed uprooting (20%, 40%, 60%, 80%, 99%) at 5% uprooted crop plants, at four levels of tillage-induced force variability (VCT, graphs A-D). The horizontal axis represents the relative magnitude of the mean anchorage force of weeds and crop plants. The vertical axis represents weed and crop anchorage force variability. Simulations use square-root transformed anchorage forces with mean MA and standard deviation SA, with $SA_{weed} = SA_{crop}$.

Increasing VCT (Fig. A5.2B-D) causes the lines to move downward, predominantly at the right side of the graphs. This means that variability of tillage-induced forces on plants has the largest impact on the achievable weed uprooting if the difference between crop and weed anchorage force is small. To achieve the above 68% weed uprooting at VCT = 0.4 (Fig. A5.2C) with the example crop–weed combination of Fig. A5.1 and Table A5.1, the ratio MA_{weed} / MA_{crop} should be reduced from 0.77 (the example population) to 0.45. This means that weeds should be much smaller to achieve the same control effect (reducing the mean anchorage force of weeds by a factor 2.8, assuming SA / MA_{crop} to remain 0.11). Graphs such as Fig. A5.2 demonstrate the importance of a homogeneous crop and weed population and could be used to support weed control decisions in the field.

6 The impact of uprooting and soil-covering on the effectiveness of weed harrowing

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Summary

The impact of uprooting and covering plants on mortality and growth reduction was investigated in the laboratory using Lolium perenne *L. and* Lepidium sativum *L. (harrowed 3-4 days after emergence) and* Chenopodium quinoa *Willd. (harrowed at emergence) as model weed species. Although the predominant initial effect of harrowing was to cover the plants, only 1-17% of the non-uprooted covered plants were killed because the depth at which they were buried by the harrow was shallow. Uprooting was more effective (47-61% mortality) but strongly dependent on soil moisture content. It accounted for 93 and 95% of* L. sativum *and* C. quinoa *mortality, but for only 60% of* L. perenne *mortality.*

In L. perenne*, the species most sensitive to burying, a strong positive relationship was observed between the percentage of plants covered by harrowing and the fresh weight reduction of the total population six days after harrowing. The fresh weight reduction of the total* L. sativum *population was best related to the percentage of uprooted plants, but the percentage of covered plants also appeared to be a good predictor because of its correlation with uprooting. Most of the uprooted plants were also buried. The fresh weight reduction of the total* C. quinoa *population was not related to the covering effect of harrowing and only weakly related to the percentage of uprooted plants.*

The results indicate that the plant recovery process after harrowing needs further study and that field research methods should be refined so that they can better discern initial and final harrowing effects on weeds.

Keywords: *mechanical weed control, plant damage, recovery, growth reduction, mortality.*

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6.1 Introduction

Widespread acceptance of curative mechanical weed control techniques, such as pre- and post-emergence harrowing, to reduce herbicide use in arable crops and field vegetables is impeded by various factors. These include the limited knowledge of and experience in using these techniques, their relatively strong dependence on favourable weather conditions, the requirement for a high cultivation frequency, the attendant risk of crop damage and their higher labour requirement (Wossink *et al.*, 1997). Furthermore in organic farming, because of their limited effectiveness on intra-row weeds, these techniques must be supplemented by expensive hand weeding, especially in slowly growing open crops that are sensitive to weed competition and mechanical damage (Ascard, 1990; Vereijken *et al.*, 1998).

The effectiveness of implements that affect both weed and crop, such as spring tine harrows and torsion weeders, depends on their adjustment, on soil and weather conditions and on susceptibility of weed and crop. Various authors (Habel, 1954; Kees, 1962; Koch, 1964b) have demonstrated the dependence of weed susceptibility on species and growth stage. Nevertheless, harrowing generally controls 40-70% of the weeds (Dierauer & Stöppler-Zimmer, 1994).

Differences in the final effect of harrowing on crop and weeds may arise during the harrowing when plants are uprooted and/or covered with soil (the initial effect), and in the period after harrowing when plants die or regrow (Fig. 6.1). Plants vary in their resistance to being uprooted or covered, depending on their anchorage strength (Meyler & Rühling, 1966; Fogelberg & Dock Gustavsson, 1998, 1999) or their height and flexibility (Meyler & Rühling, 1966; Kurstjens & Perdok, 2000). This has been shown in laboratory harrowing experiments with *Lolium perenne* L., *Lepidium sativum* L. and *Chenopodium quinoa* Willd. on a sandy soil, in which was found that 48-59% of the white threads and plants breaking through the soil surface and 17-26% of the young seedlings were uprooted (Kurstjens *et al.*, 2000). Previous research suggests that the ability to recover from mechanical damage depends on species and the type of mechanical damage (Habel, 1954; Kees, 1962; Koch, 1964b; Cavers & Kane, 1990; Jones *et al.*, 1995, 1996) and on soil and weather conditions after harrowing (Terpstra & Kouwenhoven, 1981; Cavers & Kane, 1990; Real *et al.*, 1993; Jones *et al.*, 1995, 1996, 1999). From this, it can be hypothesised that working depth and working speed not only affect the proportion of uprooted and covered plants, but that the resulting burial depth or upward movement of uprooted plants also influences the regrowth capability of damaged plants.

Reported effects of harrowing on weed control are often the combined impact of the degree of covering and uprooting and the ability of the weeds to regrow (e.g. Meyler & Rühling, 1966; Rasmussen, 1991b; Rydberg, 1993; Kirkland, 1994; Rasmussen & Svenningsen, 1995). Other research has focused on the initial uprooting and soil-covering effects [e.g. the weed controllability ranking of Habel (1954) and Koch (1964b)]. Yet, except for studies relating crop yield loss to the degree of crop covering in cereals (Rasmussen, 1991b; Rydberg, 1993; Rasmussen & Svenningsen, 1995), research on the relation between the initial and final effects of harrowing is very scarce. Habel (1954), Kees (1962), Koch (1964b), Cavers & Kane

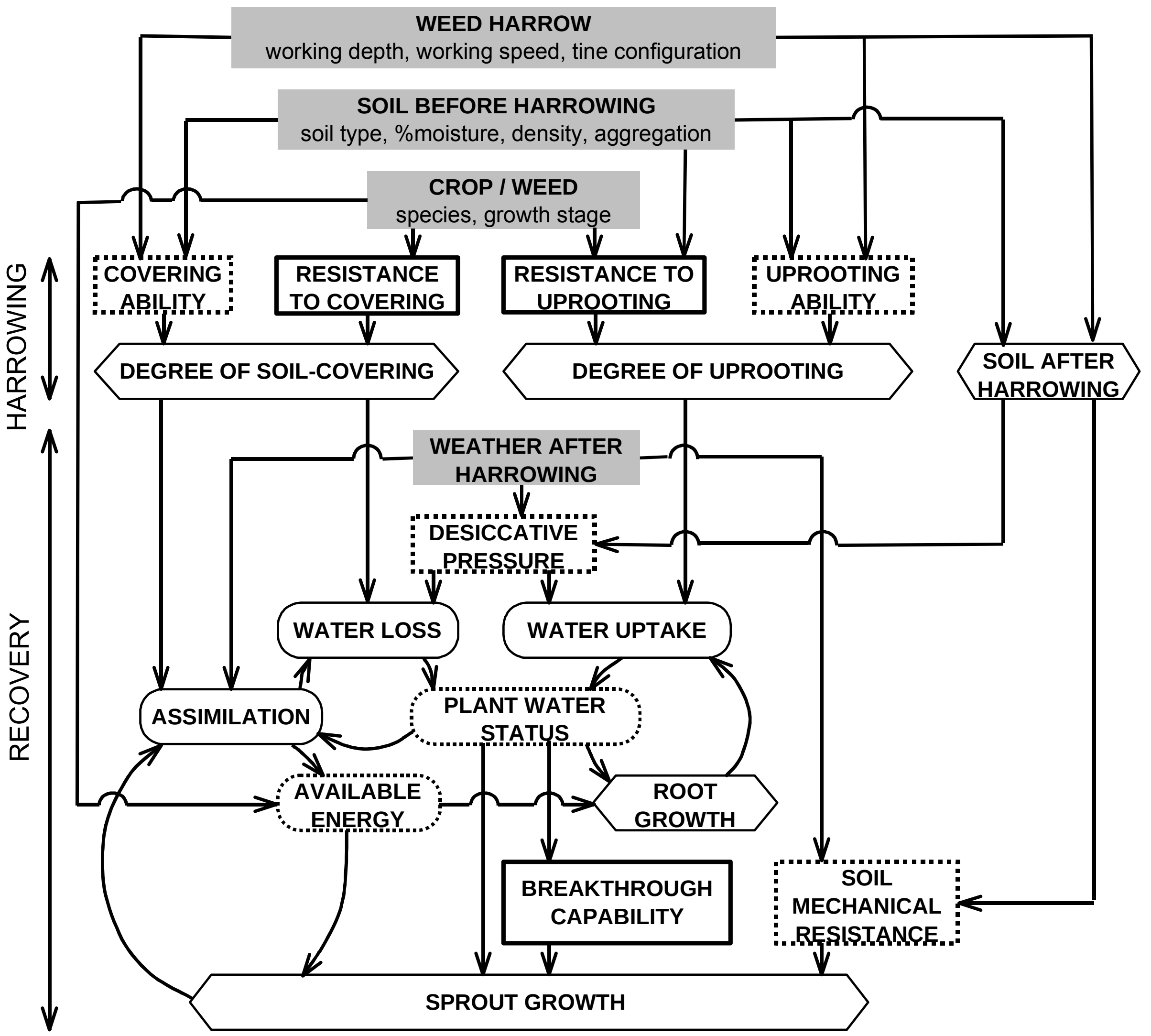

Fig. 6.1 Conceptual model of the harrowing process, followed by the recovery process of plants. The influence factors (shaded boxes) affect the initial and final harrowing effect (hexagonal boxes) via damage intensity parameters (boxes with dashed borders), plant resistance parameters (boxes with solid borders) and dynamic processes (boxes with round corners).

(1990); Cashmore & Caseley (1995), Jones *et al.* (1995, 1996) and Baerveldt & Ascard (1999) studied the effects of simulated mechanical damage in pot experiments. However, the relative importance of soil-covering and uprooting for the effectiveness of weed harrowing remained unclear because of uncertainty about whether the simulated damage accurately resembled the damage caused by cultivation.

To increase the reliability and effectiveness of mechanical weed control, the impact of the damaging process during harrowing (Kurstjens *et al.*, 2000; Kurstjens & Perdok, 2000) and the recovery process after harrowing should be quantified separately. Ways of manipulating these two processes should be studied to exploit specific weaknesses of the weed and strengths of the crop. Furthermore, practical methods to predict the final weed control effect and crop damage, based on assessments during harrowing, should be developed to help the farmer optimise harrowing operations and to reduce the uncertainty associated with the weather.

This paper examines the contribution of the initial uprooting and soil-covering effect of harrowing to the final killing and growth-reducing effect. The effects of working depth, working speed and soil moisture content were studied in laboratory experiments with a model harrow and three plant species on sandy soil. The predictability of the final harrowing effect, the necessity for assessing both the degree of soil-covering and uprooting immediately after harrowing and implications for field research methods are discussed.

6.2 Materials and Methods

6.2.1 Plant species and growth stages

Three species with contrasting growth characteristics were selected to represent weed and crop seedlings at early stages of growth. *Lolium perenne* L. (perennial ryegrass) and *Lepidium sativum* L. (garden cress) were harrowed 3-4 days after emergence, when *L. perenne* had one thin and flexible leaf, 1-70 mm (average 34 mm) long. *Lepidium sativum* was at the early cotyledon stage (0-25 mm tall, average 12.5 mm) and had relatively thick and sturdy hypocotyledons. *Chenopodium quinoa* Willd. (quinoa), a more delicate dicotyledonous plant, was harrowed at emergence when most plants were at the white thread stage.

6.2.2 Bin preparation

The plants were grown in aluminium bins (0.60 m x 0.40 m x 0.13 m) filled with sieved sandy soil (3.2% organic matter content, 3.0% clay, 6.5% silt), having a homogeneous dry-bulk density of 0.95 kg/L and a level surface. The seeds were placed in a rectangular grid of 21 rows of 17 seeds at 10 mm depth. To prevent evaporation and to obtain similar growth stages at harrowing for all treatments of a species, the bins were sealed by glass plates and kept in a climate chamber for periods of various lengths.

6.2.3 Harrowing and measurements

Before harrowing, two sown bins, which had their long side-walls removed, were placed between two unsown bins on a testing frame. The position and size of each emerged plant were measured using an electromechanical computer-linked 3D co-ordinate measurement device (SpaceArm™, FARO Technologies, Lake Mary, Florida, USA). Subsequently, a model harrow with 23 rigid vertical tines spaced at 25 mm tilled the bins at a pre-set working depth and working speed. Immediately after harrowing, all visible plants were redigitised without disturbing them, while assessing the extent to which each individual plant had been covered with soil (the estimated percentage of leaf area under the soil, in increments of 10%). Per treatment, one bin with *L. perenne* and *L. sativum* and both bins with *C. quinoa* were returned to the climate chamber for six days, without glass plates. The temperature and air humidity were similar for the 16-hour day (light intensity: 143 μE m^{-2} s^{-1}) and 8-hour night period but differed among species: *L. perenne*: 12 °C, 85% r.h.; *L. sativum*: 17 °C, 85% r.h. and *C. quinoa*: 17 °C, 55% r.h. The lower temperature for *L. perenne* was chosen to restrain leaf growth. Lower air humidity was chosen for *C. quinoa* because previous experiments with *L. perenne* and *L. sativum* under relatively humid conditions had shown little mortality.

Six days after harrowing, surviving plants were gently tugged by hand to qualitatively classify their anchorage status (loosened, firmly anchored or weakly anchored/re-anchored), while digitising their rooting location. To determine the soil moisture profile, three soil samples were taken and each was divided into five layers. After sampling the soil and removing the tilled topsoil, any plants that remained covered with soil were digitised too. All sprouts were cut 10 mm above the seed and their fresh weight was measured individually. Loosened and firmly anchored plants were collected separately and oven-dried for 24 hours at 65 °C to determine their average dry weight.

6.2.4 Classification of initial plant damage

Co-ordinate transformation and plant matching software identified plants before and after harrowing and at harvest and combined information on each plant's position, anchorage status, size, degree of soil-covering at harrowing and fresh weight. A plant was classified as uprooted if its anchorage status was "loosened", or if a "weakly anchored/re-anchored" anchorage status coincided with more than 6 mm distance between the original plant (or seed) position and the rooting point position after harrowing. This 6 mm corresponds to the maximum distance between measured positions of identical non-uprooted plants before and after harrowing. To calculate the displacement of white threads, seed positions of *C. quinoa* were digitised before covering the seeds with soil. The final percentage of emergence of the untreated bins of the corresponding soil moisture content was used to correct plant numbers for plant transportation in and out of the bin and for non-germinated seeds.

Based on the uprooting status and covering status, each plant was assigned to one of five damage classes (Table 6.1). All non-desiccated plants that were (partly) visible six days after harrowing were considered to have survived the harrowing treatment.

6.2.5 Experimental design

Plants of the three species were separately subjected to a number of treatments with different combinations of working depth, soil moisture content and working speed (Table 6.2). *Lepidium sativum* and *L. perenne* experiments had a reduced central composite design of 11 treatments, centred around the standard treatment. The same experimental factors and levels were used with *C. quinoa* but the four interaction treatments (shallow*dry*fast, etc. shown in Table 6.2) were omitted. Each

Table 6.1 Classification of initial plant damage.

Classification	Description
Undamaged	Not uprooted, 0-20% covered
Partially covered	Not uprooted, 30-90% covered
Not-uprooted, covered	Not uprooted, 100% covered
Uprooted, visible	Uprooted, 0-90% covered
Uprooted, covered	Uprooted, 100% covered

Table 6.2 Experimental lay-out.

Treatment		Working depth (mm)	Working speed (ms)	Soil moisture content (% of dry mass)	
				Prepared	At harrowing
Standard	a,b	20	1.8	12.50	10.7
Shallow till	a,b	10	1.8	12.50	10.3
Deep till	a,b	30	1.8	12.50	11.0
Slow	a,b	20	1.2	12.50	10.7
Fast	a,b	20	2.4	12.50	10.4
Dry	a,b	20	1.8	8.00	4.7
Moist	a,b	20	1.8	17.00	15.7
Shallow*dry*fast	a	15	2.1	10.25	7.0
Shallow*wet*slow	a	15	1.5	14.75	13.2
Deep*dry*slow	a	25	1.5	10.25	7.7
Deep*wet*fast	a	25	2.1	14.75	13.6

a Treatments in the *L. sativum* and *L. perenne* experiments
b Treatments in the *C. quinoa* experiment

treatment was replicated once (*L. perenne* and *L. sativum*) or twice (*C. quinoa*) for each species. Each replication comprised one bin, sown with 357 seeds of one species.

The experimental design was analysed as an unbalanced split-plot with bins as main plots and individual plants as subplots. The effects of species, working depth, soil moisture content of the tilled layer at harrowing and speed were analysed at the main-plot level, whereas effects of uprooting and soil-covering were analysed at the subplot level. It should be noted that the uprooting and covering status were not randomly assigned to plants, because predominantly the smallest plants were uprooted and covered (Kurstjens *et al.*, 2000; Kurstjens & Perdok, 2000).

6.2.6 Statistical analysis

Mortality ($M = (n - s) / n$, with s = number of surviving plants and n = total number of plants) per species and damage class were analysed by generalised linear mixed models with two variance components (bins and plants), a binomial variance function allowing for overdispersion and a logit link [$\text{logit}(M) = {}^{e}\log((n - s) / s)$]. The IRREML directive of the CBW Genstat procedure library 4.1 (Goedhart & Thissen, 1998) and the Genstat 5 Release 4.1 statistical package (Genstat 5 Committee, 1993, 1997) were used. As mortality was analysed on a logit scale (Z), mean standard errors (in Fig. 6.3A) were back-transformed using the approximation (Engel, 1997):

$$\text{var}(M) = \frac{\exp(2Z)}{(1+\exp(Z))^4} \cdot \text{var}(Z)$$

The effects of working depth (WD), working speed (WS) and soil moisture content of the tilled layer at harrowing (MC) on mortality per species (P) and damage class (DC) were analysed using model (1):

$$\text{logit}(M) = P{\cdot}DC + P{\cdot}DC{\cdot}WD + P{\cdot}DC{\cdot}WS + P{\cdot}DC{\cdot}MC \qquad (1)$$

This model does not include the treatment effects on the initial effects of harrowing, e.g. the percentage of plants in each damage class. The significance of the linear terms and the pairwise differences between species and damage classes were evaluated by *t*-tests.

Average fresh weight of surviving plants of each damage class per bin ($\overline{W}_{DC,B}$) was analysed similarly by weighted loglinear regression, using the average fresh weight of undamaged plants in the same bin ($\overline{W}_{U,B}$) as the offset variable. As the number of surviving plants per damage class per bin ($n_{DC,B}$; $n_{U,B}$) varied, a weighting factor (w) was derived from fresh weight variances ($\sigma^2_{DC,B}$; $\sigma^2_{U,B}$):

$$w = \frac{1}{\text{var}\left(\dfrac{\overline{W}_{DC,B}}{\overline{W}_{U,B}}\right)} = \frac{1}{\left(\dfrac{\overline{W}_{DC,B}}{\overline{W}_{U,B}}\right)^2 \cdot \left[\left(\dfrac{\sigma^2_{DC,B} / n_{DC,B}}{\overline{W}_{DC,B}}\right)^2 + \left(\dfrac{\sigma^2_{U,B} / n_{U,B}}{\overline{W}_{U,B}}\right)^2\right]}$$

These weights were used to calculate approximated mean standard errors in Fig. 6.3B. The weights and standard errors are an approximation because the covariance between fresh weights of undamaged plants and fresh weights of damaged plants within the same bin was assumed to be zero.

The joint effect of mortality (M) and fresh weight reduction rate of surviving plants (S) can be expressed as the fresh weight reduction rate of the total plant population (T), by calculating $T = 1 - (1 - S) \times (1 - M)$. The relations between initial effects and final effects (M, S, T) were analysed per species by simple linear regression (normal

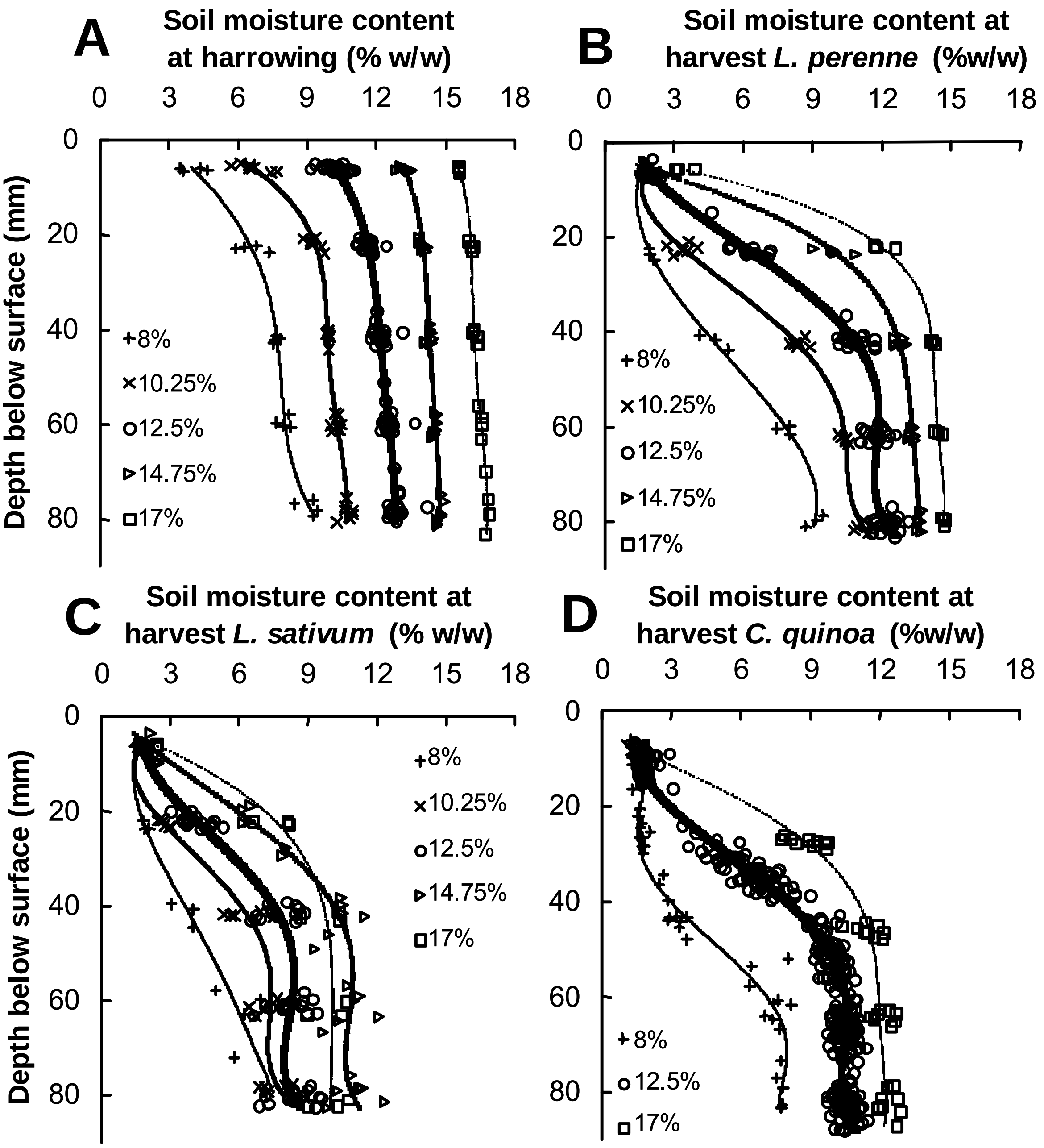

Fig. 6.2 Soil moisture profiles for all prepared soil moisture contents at harrowing (A) and at harvest *of L. perenne* (B), *L. sativum* (C), and *C. quinoa* (D).

error distribution, no weights), using mortality, fresh weight reduction, covering and uprooting data per treatment.

The following models were used to estimate the percentage variance explained by the percentage uprooted plants (U, equation (2)), the percentage of plants found to be completely covered immediately after harrowing (C, equation (3)) and by plant response to mechanical damage (residuals from equation (4)):

$$M, S, T = P + P\cdot U \qquad (2)$$

$$M, S, T = P + P\cdot C \qquad (3)$$

$$M, S, T = P + P\cdot U + P\cdot C + P\cdot U\cdot C \qquad (4)$$

6.3 Results

6.3.1 Soil moisture profile

Comparing the soil moisture profile sampled from other bins directly after harrowing (Fig. 6.2A) with the soil moisture profile at harvest (Fig. 6.2B-D) revealed that the topsoil desiccated considerably. At all prepared moisture contents the top 10-mm of the soil was almost air-dry.

6.3.2 Mortality of uprooted and/or covered plants

Figure 6.3 shows the state of the plants that were uprooted and/or soil-covered by harrowing, six days after harrowing. Many more uprooted plants (whether or not covered) had died than non-uprooted covered plants (47-61% compared with 1-17%, Fig. 6.3A, $P < 0.001$). Burial increased the mortality of uprooted *L. perenne* ($P < 0.01$) but slightly decreased the mortality of *C. quinoa* ($P < 0.01$) uprooted by harrowing at emergence. Partial (30-90%) soil-covering of non-uprooted plants was not lethal but slightly reduced *L. perenne* fresh weight (Fig. 6.3B, $P < 0.05$). In *L. perenne*, 60% of the total mortality was attributable to uprooting, whereas uprooting accounted for 93% and 95% of the mortality of *L. sativum* and *C. quinoa,* respectively.

The critical burial depth at which plants are assumed to die can be derived from the frequency distribution of measured burial depths presented by Kurstjens & Perdok (2000). The critical burial depth of non-uprooted plants of *L. perenne* and *L. sativum* was 12 mm and 17 mm respectively. Within the limited range of median burial depths measured (5-11 mm), there was no correlation between mortality of non-uprooted covered plants and the median burial depth ($R^2 < 0.04$, Fig. 6.4A). Neither was mortality correlated with the percentage of non-uprooted plants buried deeper than 12 mm ($R^2 < 0.05$, Fig. 6.4B).

6.3.3 Fresh weight reduction of surviving uprooted and/or buried plants

Surviving uprooted plants showed larger reductions in fresh weight than non-uprooted plants that survived burial (Fig. 6.3B, $P < 0.05$). Burial reduced fresh weights of non-uprooted ($P < 0.01$) and uprooted ($P < 0.001$) plants of *L. perenne* and *L. sativum*, but burying had no effect on fresh weight of *C. quinoa* (Fig. 6.3B). *Lolium perenne* was more sensitive to burying than *L. sativum* and *C. quinoa* ($P < 0.001$). Fresh weights of small (25-35 mm tall) non-uprooted covered *L. perenne* plants (data not shown) were reduced more (by 30%, $P < 0.05$) than those of plants

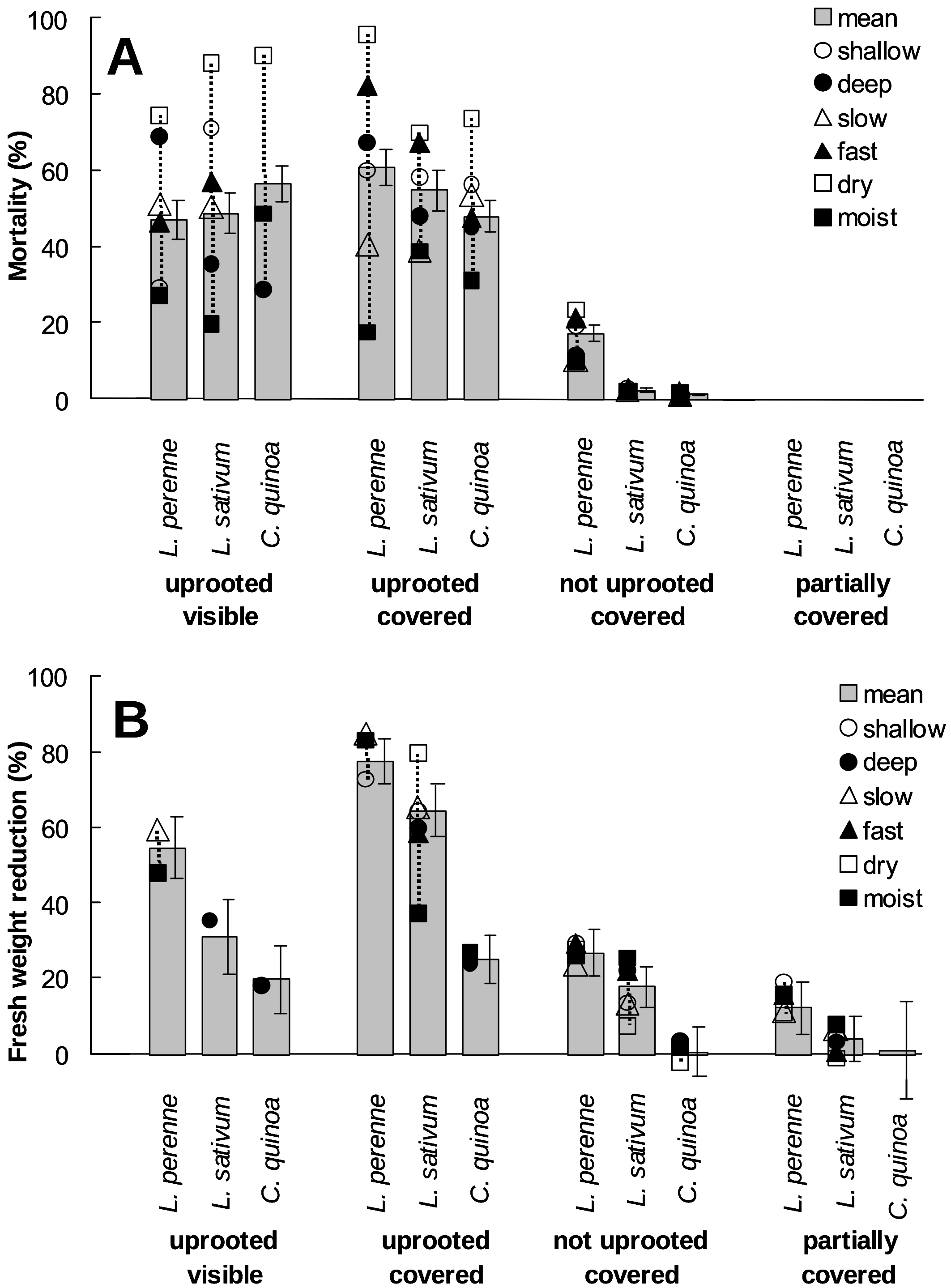

Fig. 6.3 Effect of species and the type of damage caused by harrowing on mortality (A) and fresh weight reduction of surviving plants (B) relative to undamaged plants of the same treatment, six days after harrowing. Means from all treatments and predicted effects of working depth, working speed and soil moisture content (from model (1)). Predictions based on less than 15 plants are not shown. Error bars depict means ± approximated mean standard errors. Treatments are described in Table 6.2.

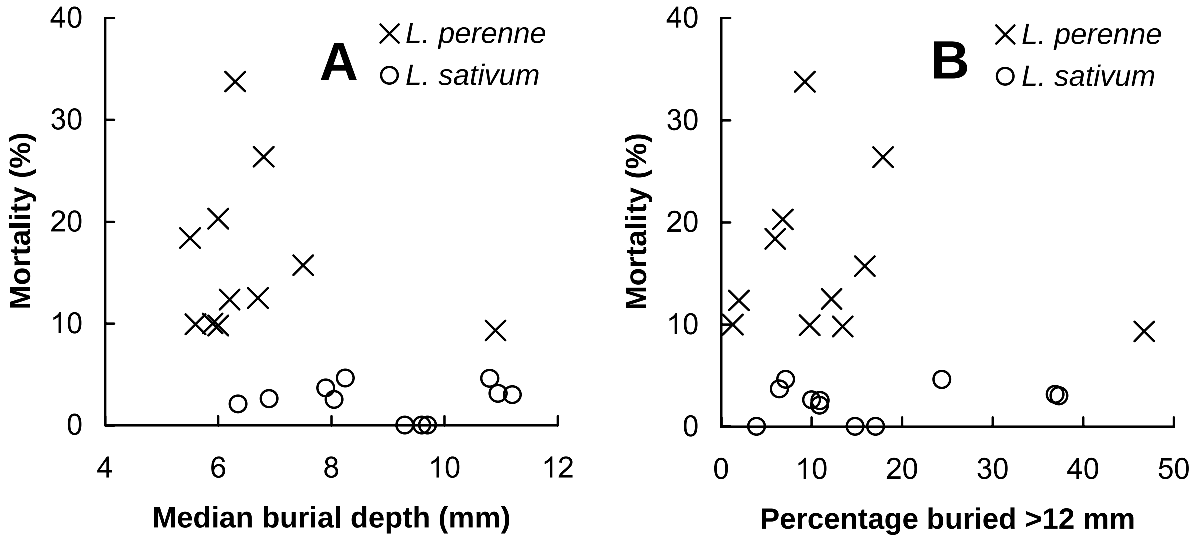

Fig. 6.4 Relation between mortality of non-uprooted covered plants and their median burial depth (A) or the percentage buried deeper than 12 mm (B). Burial depths originate from Kurstjens & Perdok (2000).

breaking through the soil surface (0-25 mm tall, reduced by 22%) and of large (45-70 mm tall) *L. perenne* plants (reduced by 25%).

The fresh weight of uprooted *L. sativum* plants with anchorage status “weakly anchored/re-anchored” was reduced less (visible plants by 29%, covered plants by 48%) than fresh weight of uprooted plants having the anchorage status “loosened” (visible plants by 60%, covered plants by 72%, $P < 0.001$, data not shown). The same holds for covered uprooted *L. perenne* (by 63% and 78%, respectively, $P < 0.001$, data not shown). It appeared that dry weight reductions caused by uprooting (data not shown) were smaller than the corresponding fresh weight reductions, as uprooted plants had a higher dry matter content than non-uprooted plants (*L. perenne*: uprooted 19.5% and non-uprooted 15.1%, *L. sativum*: uprooted 16.8% and non-uprooted 12.1%).

6.3.4 Effects of working depth, working speed and soil moisture content

Working depth had no significant effect on mortality of uprooted covered plants (Fig. 6.3A). Mortality of uprooted visible *L. perenne* increased with increasing working depth ($P < 0.05$), whereas uprooted visible *L. sativum* showed an opposite trend ($P < 0.05$). Increasing the working speed increased the mortality of uprooted covered *L. perenne* ($P < 0.01$) and uprooted covered *L. sativum* ($P < 0.05$), but did not affect mortality of uprooted visible plants. On moister soil, more uprooted plants survived ($P < 0.05$). Soil moisture content (of the tilled layer at harrowing) affected the survival of visible uprooted plants more than the survival of covered uprooted plants ($P < 0.01$). The survival of uprooted covered *L. perenne* was affected more by soil moisture content than uprooted covered *L. sativum* ($P < 0.01$).

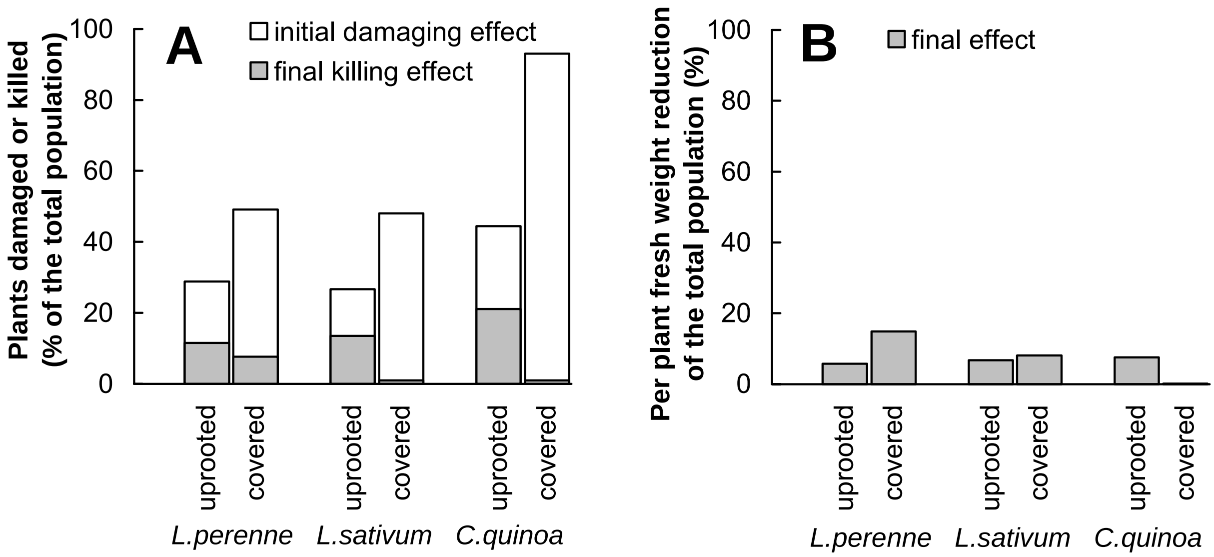

Fig. 6.5 The initial damaging effect and final killing effect of harrowing (A) and effect on the per plant fresh weight reduction of the total population (B) per species, for uprooted plants (both covered and visible) and non-uprooted covered plants.

As only a small proportion of the non-uprooted covered plants were killed, no effects of working depth, working speed and soil moisture on mortality were observed, except for *L. perenne*. With *L. perenne*, increased working speed and lower soil moisture content decreased survival ($P < 0.05$).

Fresh weight reduction was much less affected by treatment factors than mortality. Drier soil slightly promoted fresh weight reduction of uprooted covered *L. perenne* ($P < 0.01$) but decreased fresh weight reduction of uprooted covered *L. sativum* ($P < 0.001$). Faster harrowing slightly decreased fresh weight reduction of uprooted covered *L. perenne* ($P < 0.05$). Growth reduction of non-uprooted plants and uprooted visible plants was not significantly influenced by treatment factors.

6.3.5 Correlation between initial and final effects

Figure 6.5A and B show the mortality and the per plant fresh weight reduction of the total population six days after harrowing (grey bars) in relation to the uprooting and soil-covering effect achieved at harrowing (white bars). The final effect of harrowing on the total plant population was calculated from the number of plants per species and damage class at harrowing [based on Kurstjens *et al.* (2000) and Kurstjens & Perdok (2000)], and the mortality rates and fresh weight reduction rates per species and damage class (Fig. 6.3).

The final effectiveness of the harrowing treatments on the total population was low (max. 21% mortality and 15% fresh weight reduction, Fig. 6.5A and B). Although more plants were covered than uprooted, covering contributed less to mortality than uprooting (Fig. 6.5A). If, however, all covered plants had been killed, covering would have had the largest impact on mortality. For each species, a very similar proportion

Table 6.3 The fraction of the variance in the final harrowing effects explained by initial harrowing effects (Eqn 2 and 3) and differences in regrowth of damaged plants (residuals from Eqn 4). The furthest right column shows the correlation between covering and uprooting.

Response variable:	Mortality			Fresh weight reduction of surviving plants			Fresh weight reduction of total population			Uprooting
Explanatory variable: / Species	Covering	Uprooting	Regrowth	Covering	Uprooting	Regrowth	Covering	Uprooting	Regrowth	Covering
L. perenne	0.76	-	0.25	0.05	0.14	0.81	0.80	-	0.08	-
L. sativum	0.53	0.16	0.44	0.29	0.79	0.20	0.70	0.91	0.05	0.45
C. quinoa	-	0.09	0.85	0.04	0.22	0.33	-	0.45	0.20	-

(49-54%) of the potential mortality effect of uprooting was attained under the conditions of these experiments (Fig. 6.5A). In *L. perenne* and *L. sativum*, covering had a greater effect on the fresh weight reduction of the whole population than on mortality, but for uprooting the opposite was true (compare Fig. 6.5A and B).

Although burial killed few plants, the percentage of plants covered by harrowing was a much better predictor of the mortality of *L. perenne* and *L. sativum* than the percentage of plants uprooted by harrowing (Table 6.3, Fig. 6.6A and B). This is because the mortality of covered uprooted plants was better related to covering (Fig. 6.7A, *L. perenne*: R = 0.70, *L. sativum*: R = 0.63) than to uprooting (Fig. 6.7B, *L. perenne*: R = –0.13, *L. sativum*: R = 0.15). The mortality of *C. quinoa* correlated poorly with covering and uprooting (Fig. 6.6A and B), so most of the variation (85%) was not related to initial effects (Table 6.3). This might be attributable to a negative correlation between uprooting and mortality of uprooted covered plants (Fig. 6.7B, R = –0.84). Furthermore, much of the variation in *L. sativum* mortality (44%) was not related to covering and uprooting. Increased soil moisture content increased the percentage uprooted plants (Kurstjens *et al.*, 2000) but decreased mortality (Fig. 6.3).

The fresh weight reduction of surviving plants and the percentage of plants covered by harrowing correlated poorly (Fig. 6.6C), but uprooting appeared to be a good predictor of *L. sativum* fresh weight reduction (Fig. 6.6D). Given that Fig. 6.7C and D reveal no correlation between fresh weight reduction of any particular damage class and covering or uprooting, it seems probable that differences in fresh weight reduction were caused by treatment effects on the uprooting performance of the harrow. A negative interaction between covering and uprooting ($P < 0.05$) explained a considerable part (49%) of *C. quinoa* fresh weight reduction. In *L. perenne*, the largest part of the variation in fresh weight reduction was not related to covering and uprooting.

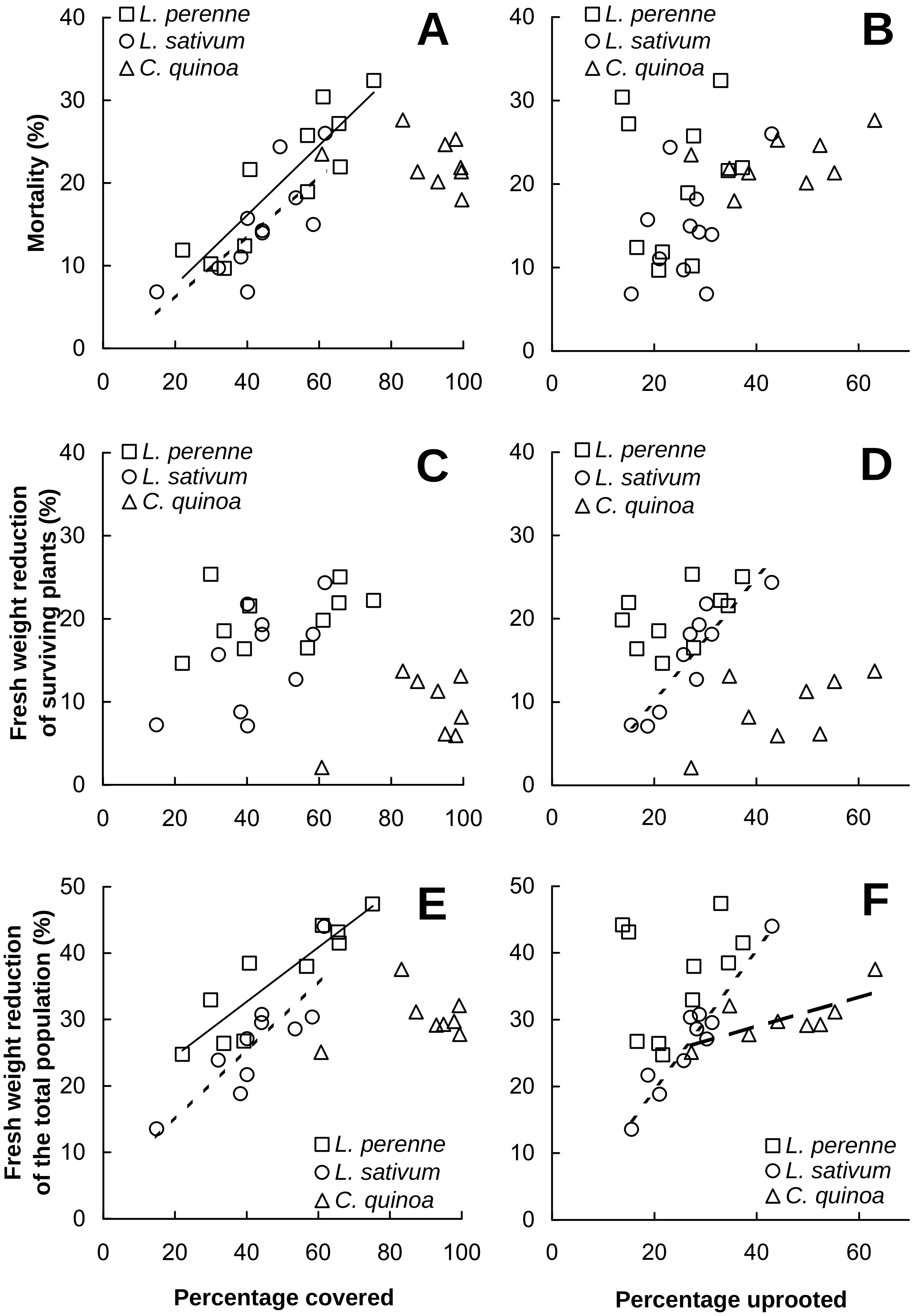

Fig. 6.6 Relationship between the initial effects (covering and uprooting) and the final effects of harrowing (mortality, fresh weight reduction of surviving plants and fresh weight reduction of total plant population). Only significant relationships (*P* < 0.05) are shown.

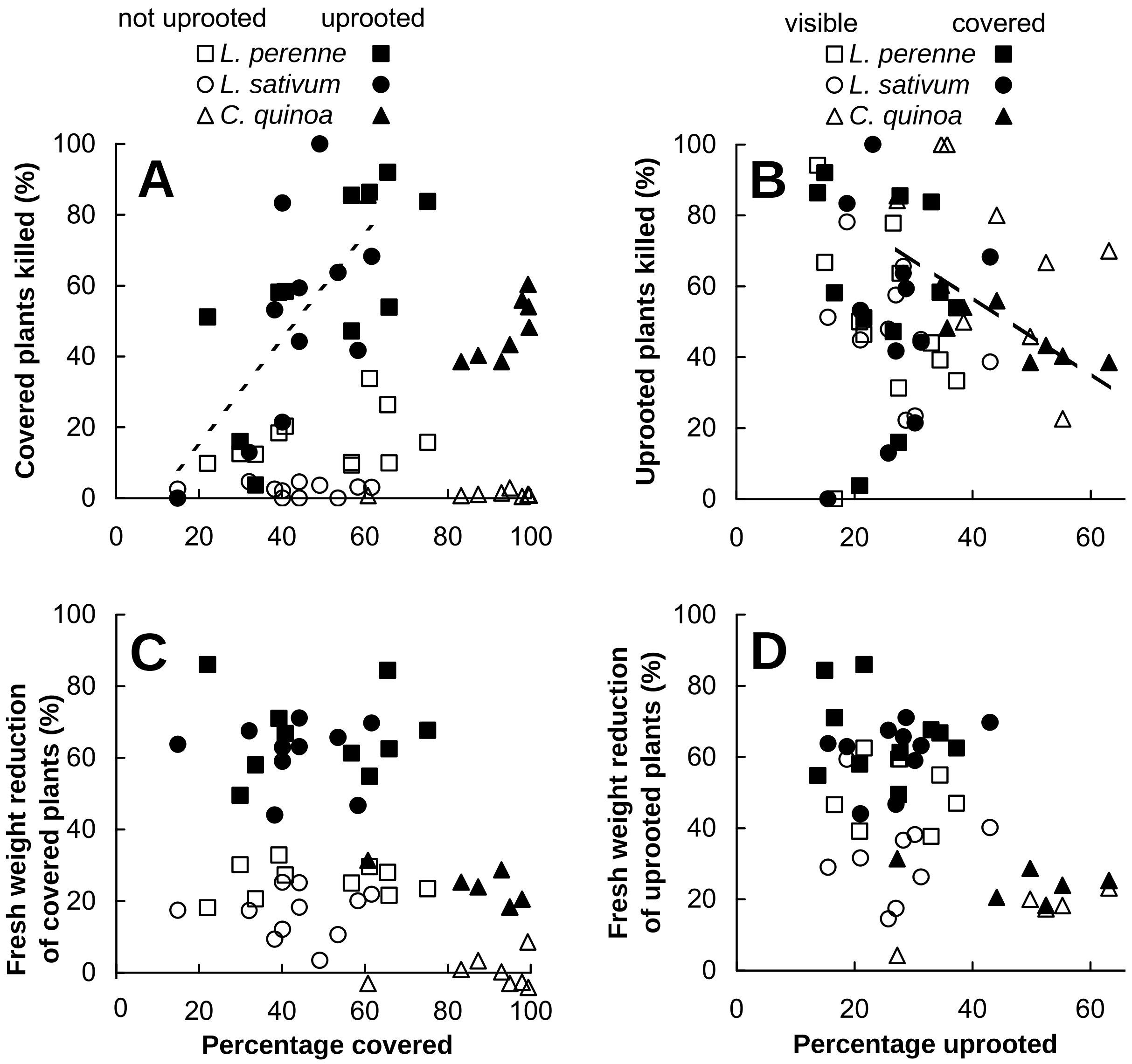

Fig. 6.7 Mortality (A, B) and fresh weight reduction of surviving plants (C, D) of covered plants and uprooted plants as related to covering and uprooting. Only significant relationships ($P < 0.05$) are shown.

In contrast, there were strong correlations between fresh weight reduction of the total *L. perenne* population (all damage classes pooled) and covering (Table 6.3, Fig. 6.6E), and the fresh weight reduction of the total *L. sativum* population and uprooting (Fig. 6.6F). In *L. perenne* and *C. quinoa* there was a negative interaction between the effect of covering and uprooting ($P < 0.05$).

6.4 Discussion

6.4.1 The importance of covering and uprooting

Soil-covering has generally been perceived as the most important effect of harrowing. Although it was also the dominant initial effect in our experiments, more than 97% of the non-uprooted covered seedlings and white threads of *L. sativum* and *C. quinoa* broke through the soil cover and suffered little or no growth stagnation. More of the uprooted plants died, therefore, uprooting contributed more to the final effect of harrowing than covering.

However, plant species, growth stage and soil and weather conditions after harrowing may influence the impact of burying and uprooting on the final effectiveness of harrowing. Tall, flexible *L. perenne* seedlings suffered more from being buried than sturdy *L. sativum* seedlings, but burying did not affect white threads of *C. quinoa*. In experiments in which growing weeds were buried under 1 cm of soil, only 1% of *Papaver rhoea*s L., 8% of *Chenopodium album* L. and 13% of the *Sinapis arvensis* L. seedlings were able to break through the soil cover, whereas *Polygonum convulvus* L., *Galium aparine* L., *Ranunculus arvensis* L. and *Veronica hederifolia* L. seedlings were less sensitive to burial (Habel, 1954). In many cases, weeds with 2-4 or 6-8 leaves were more sensitive to burying than seedlings (Habel, 1954). More recently, it was found that burying uprooted and non-uprooted plants under 1 or 2 cm of potting compost reduced the dry weight of *Stellaria media* L. Vill. and *Papaver rhoeas* at the six-leaf stage and *Poa annua* L. and *Poa trivialis* L. at the three-leaf stage by 95-100% when pots were moistened daily (Jones *et al.*, 1995). As the critical burial depths derived from our experiments coincide with the findings mentioned above and those of Terpstra & Kouwenhoven (1981) and Baerveldt & Ascard (1999), we conclude that the limited impact of covering was caused by the shallow burial depth resulting from harrowing.

Habel (1954) pointed out that covering with soil in field conditions might be less effective because in his soil bin experiments he could not prevent quick desiccation of the covering layer and wilting of the plants. In our experiment, covering seems to have protected uprooted white threads from desiccation. However, with larger seedlings, growth impedance by light deprivation (Jones *et al.*, 1999) and water stress (induced by uprooting) are of overriding importance. In addition, the mechanical resistance of the covering soil layer may be important, especially for big and flaccid seedlings. Rain and desiccation after harrowing might influence the mechanical resistance via soil weight and soil coherence (aggregate size, slaking, crusting). Jones *et al.* (1996) showed that after simulated damage, covering large *Stellaria media* (10-cm diameter) and *Papaver rhoeas* (6-8 leaves) under 1 cm soil can be more effective if followed by repeated wetting than if followed by dry conditions. This demonstrates the need for further research to investigate ways to increase the impact of the shallow burial depths created by harrowing.

It is unclear whether the recovery process aggravates or removes the initial selectivity between species and growth stages created by the damaging process. Under our experimental conditions, the recovery process enhanced the burial-induced final selectivity between *L. sativum* and *L. perenne*, as *L. perenne* was covered more than *L. sativum* (Kurstjens & Perdok, 2000) and was more sensitive to being buried. In contrast, *C. quinoa* harrowed at emergence was covered and uprooted more than *L. perenne* and *L. sativum* seedlings, but the fresh weight reductions of the total populations were similar. Kirkland (1994) observed that under moist conditions, spring wheat (*Triticum aestivum* L.) was better able to recover from harrowing than wild oat (*Avena fatua* L.). Further research is needed to examine whether different responses of crops and weeds to burial and uprooting can be exploited to increase the final selectivity by adjusting the type and degree of mechanical damage to the weather conditions expected after cultivation.

6.4.2 Predictability of the harrowing effect

To be able to adjust the harrow optimally and to choose weed control strategies, farmers need to be able to predict the efficacy of harrowing from the condition of the weeds immediately after the harrowing. However, few studies have examined the relationship between the initial and final effects as influenced by soil and weather conditions. Studies revealing that crop yield losses are correlated to crop covering (Rasmussen, 1991b; Rydberg, 1993; Rasmussen & Svenningsen, 1995) generally apply to established cereal crops.

In our study, we found that the reduction in the fresh weight of the total *L. perenne* and *L. sativum* population was closely related to covering. Although fresh weight reduction of the total *L. sativum* population correlated better with the percentage of plants uprooted, the percentage of plants covered was a useful predictor because the uprooting and covering of seedlings by harrowing were interrelated (Kurstjens *et al.*, 2000). For control of weeds at emergence, the percentage of plants covered was not a useful predictor because, although nearly all the white threads were covered, only uprooting resulted in mortality or in growth reduction. Although burying might be more effective under conditions other than those in our experiments, the fact that many covered plants were also uprooted suggests that uprooting primarily caused the effectiveness of covering.

Although uprooting was more effective than burying, the impact of uprooting strongly depended on soil moisture content. In the experiments of Jones *et al.* (1995, 1996), the response of partially covered and uprooted plants with or without their roots buried was much more sensitive to environmental conditions than the response of covered plants that had not been uprooted. From this, we infer that variable field conditions caused by wetting and drying of the topsoil and varying timing and amounts of rain will make the impact of uprooting less predictable than our experiment suggests.

Our finding that under constant environmental conditions, variable plant response to mechanical damage caused only a minor part of the variation in the fresh weight reduction of the total population implies that initial effects of harrowing are adequately assessed by counting the number of crop and weed plants in four classes: (1) neither buried or uprooted, (2) buried but not uprooted, (3) not buried but uprooted and (4) buried and uprooted. However, the practical significance of biomass reduction of the total population as a measure of the final effectiveness of harrowing is disputable, as reduced weed numbers and retarded weed growth could have different implications for the necessity and aggressiveness of future weed control measures. In the experiments of Lambin *et al*. (1993), harrowing did not reduce weed numbers but only suppressed growth. Suppressed weeds may be killed by the next harrowing if weather conditions are favourable. We observed that if they remained covered for six days, non-uprooted plants were more weakly anchored. This might make them more vulnerable to uprooting by a subsequent cultivation, especially if they are sealed in compact topsoil.

However, the mortality and fresh weight reduction of plants that survive are much less predictable than their combined effect (which is a reduction in the fresh weight of the total population). In our experiments, these parameters correlated poorly, with R varying between –0.48 (visible uprooted *C. quinoa*) and 0.58 (non-uprooted covered *L. perenne*; data not shown). It seems likely that the relationship between the mortality and growth reduction of surviving plants will be very complex because the recovery process is dynamic (Fig. 6.1) and because the degree of uprooting and burial varies greatly within a treatment (due to spatial heterogeneity and non-uniform plant populations).

6.4.3 Implications for field research methods

The effect of plant height on mortality and growth reduction of uprooted plants could not be studied in our experiments because uprooted plants could not always be identified individually. This means that the fresh weight reduction of surviving uprooted plants was overestimated because white threads and plants breaking through the soil surface were uprooted (Kurstjens *et al.*, 2000) and covered (Kurstjens & Perdok, 2000) to a larger extent than seedlings. As working depth and soil moisture influenced the size of the plants that were uprooted, the effects of these two factors on survival confounded the effects of plant size.

As such problems would also arise in field experiments, additional laboratory studies are required to investigate the effect of environmental conditions after mimicked burial and uprooting on the recovery capability of contrasting plant species. Such studies should cover a wide range of growth stages, including the white thread and early seedling stage and burial depths of 10 mm and less. The effects of soil temperature, soil moisture, mechanical aspects of plant and soil behaviour and changes in the amount of re-allocable plant energy reserves over time deserve consideration, as in emergence modelling studies of Benech Arnold *et al.* (1990), Boiffin *et al.* (1994), Forcella (1993) and Vleeshouwers (1997). Although individual plant dry weights would represent growth reductions better, assessments would be very time consuming and prone to errors due to adhering soil particles and minute dry weights (limited time between harrowing and harvest).

In addition to studying the fundamentals of the recovery process under controlled conditions, new approaches should be developed for field experiments to assess the initial effects (both uprooting and covering), and to study the relationship between initial and final effects. In particular, methods for assessing uprooting need to be refined to be practicable in field experiments and to yield reliable results for weakly anchored white threads and small seedlings. Examining the loose soil layer, as Habel (1954) did, would not give reliable results if uprooted seedlings and white threads are barely visible. However, with sandy soil uprooted plants and white threads could be counted after the soil had been dried and sieved. Using a modified vacuum cleaner to remove tilled soil (Fogelberg & Dock Gustavsson, 1999) might disturb weakly anchored plants, especially if the soil is cohesive.

One possible way to prevent sensitive plants from being uprooted during soil removal from counting plots might be to place small transparent drying chambers on some of the counting plots after harrowing. This would mean that forced desiccation of the tilled layer would kill uprooted plants within a day. Final weed counts from desiccated and non-desiccated plots might then allow uprooting and covering to be assessed, without having to remove the soil from the plots. A standardised drying or irrigation method might even provide a way of quantifying the attainable range of harrowing effectiveness or provide reference conditions when studying the effects of weather conditions after harrowing.

The thickness of the soil layer on plant leaves is critical for the effectiveness of covering but is difficult to measure *in situ*. The length of the period of covering could be a derivative measure for burial depth and fresh weight reduction, and could be assessed by repeatedly photographing the same treated spot, followed by digital image analysis.

6.4.4 Conclusion

From our study, we conclude that the limited impact of burial was the main factor limiting harrowing effectiveness under the conditions in our experiments. Although covering was the dominant initial effect of harrowing, it can be concluded that uprooting contributed most to the final plant mortality, as 47-61% of the uprooted plants but only 1-17% of the non-uprooted covered plants were killed. This implies that finding ways to reduce weed regrowth and make weed regrowth more predictable deserve more emphasis in mechanical weed control research. In order to understand the causes of the variable effectiveness of harrowing, it is important to distinguish between covering and uprooting, mortality and growth reduction, and initial and final effects.

7 General discussion

7.1 Scientific aspects

Mechanical weed control research has been dominated by empirical studies comparing the effects of several treatments. Although several complexities and fundamental questions have been encountered, there are few basic studies on the mechanisms of mechanical weeding and quantitative approaches to analyse and predict weeding effectiveness and selectivity.

This study provided basic knowledge of the covering and uprooting process as related to soil failure and movement during tillage, and insight in how geometrical and mechanical characteristics affect plant sensitivity. In addition, it resulted in several advancements that help relieve methodological difficulties in the assessment and analysis of mechanical weeding effectiveness and selectivity, and that support model development:

1. The distinction between uprooting, covering, plant recovery and competition provides a useful framework for explaining different plant responses to mechanical weeding (Fig. 7.1). Most studies have dealt with these processes as a “black box” by observing the cumulated effect of these processes. This makes understanding the effects of soil-, plant-, implement- and weather-related factors and their interactions more difficult.
   In this thesis, the covering process (chapter 3), uprooting process (chapters 4, 5) and the plant recovery process (chapter 6) were separated and analysed. However, distinction of uprooting and covering is only relevant if (1) the type of damage depends on implement type and use and on weed, crop and soil conditions, and if (2) plants respond differently to covering or uprooting damage. Experimental evidence supporting these preconditions is still limited, as few have paid attention to the level of uprooting and covering damage independently, or have studied the impact of uprooting and covering damage on plant growth and mortality (e.g. Habel, 1954; Kees, 1962; Koch 1964a, 1964b; Cavers & Kane, 1990; Cook *et al*., 1993; Fogelberg & Dock Gustavsson, 1999; Jensen *et al*., 1999).
2. In addition to studying the effect of various factors on weed control or the outcome of individual processes directly, it was attempted to define and quantify intermediate parameters: plant sensitivity and the damaging capacity of weeding (Fig. 7.1). Their independent quantification would improve the assessment of effects of other components within the weed management system (e.g. pre-emergence flaming, false seedbeds, delayed planting) on mechanical weeding performance, and facilitate the application of a sensitivity–dose–response

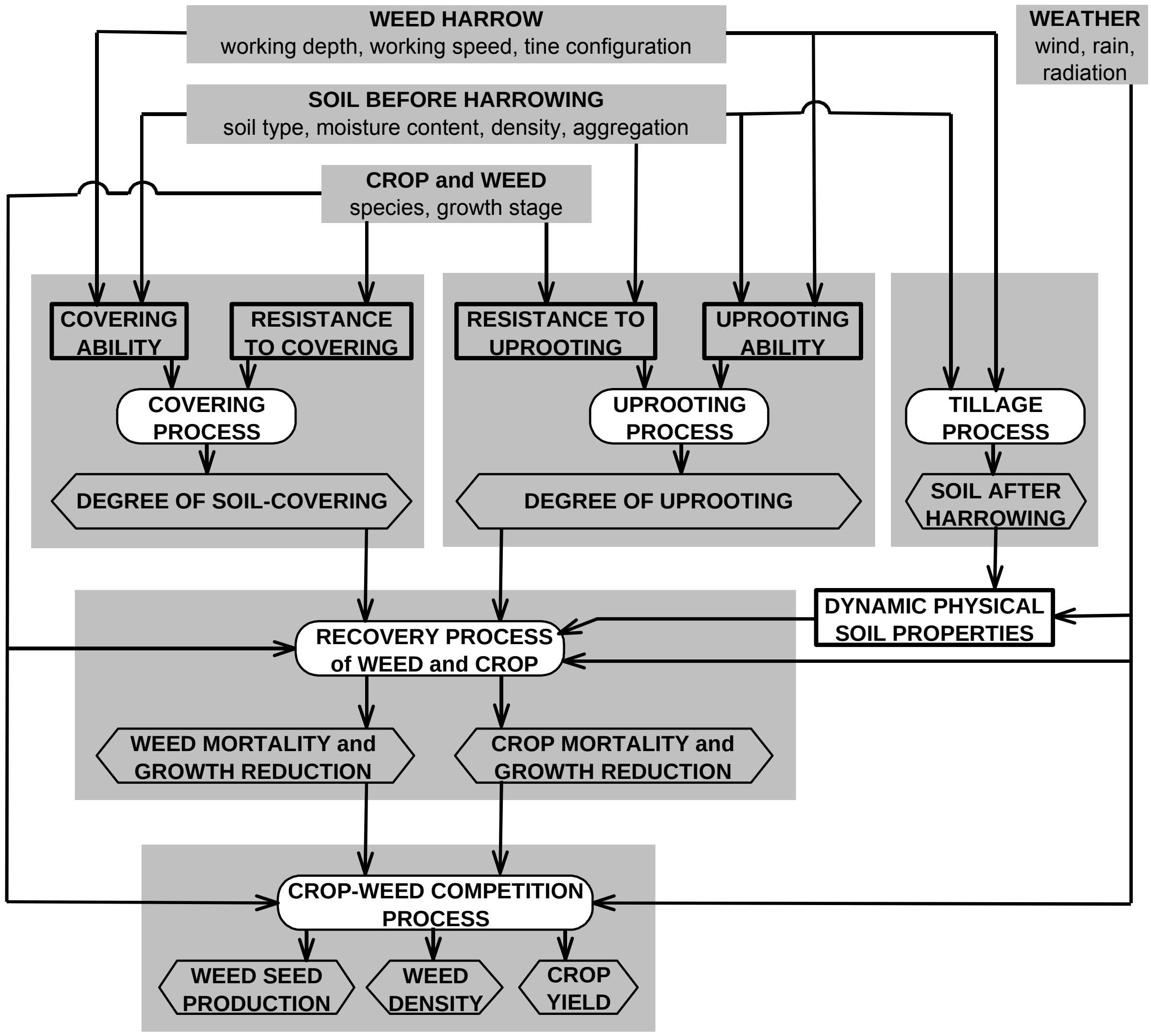

Fig. 7.1 Conceptual model of processes involved in mechanical weeding for weeds and crop plants separately. The different response of weeds and crops to each of these processes induces selectivity directly after harrowing (degree of soil covering and uprooting), after a few days (mortality and growth reduction) and later in the growing season (weed and crop and productivity under competition).

approach[4] to model uprooting and covering by mechanical weeding. Combining the weed and crop dose–response curves would yield the relationship between weed damage and crop damage.

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[4] Dose–response curves are widely used in herbicide research to describe the relationship between the applied amount of active ingredient per surface area and the percentage weed control or weed biomass with a particular weed vegetation (Streibig *et al*., 1993). Extending this approach to sensitivity–dose–response means that the relationship between a sensitivity-related plant characteristic and control is modelled as well (e.g. de Ruiter *et al*., 1999).

This study independently quantified plant sensitivity and damaging capacity by plant anchorage force measurements combined with a simple uprooting model (chapter 5), and by measuring forward soil displacement (unpublished data). The first attempt seems promising with respect to uprooting, especially if an extended uprooting model with variable tillage-induced force (chapter 5 appendix) could estimate the magnitude of tillage-induced forces (i.e. the “dose”). However, with respect to covering, such a mechanistic approach would be more complicated, as plant sensitivity and tillage intensity involve multiple characteristics (soil level upheaval, plant bending) with more complex spatial patterns (chapter 3). The second attempt appeared less promising, as empirical relationships between measured tillage intensity parameters (i.e. median soil forward displacement distance, moved soil mass, soil speed, soil kinetic energy) and response (i.e. uprooting or covering) were not very accurate. The lack of a clear empirical relationship could be ascribed to unsuitability of the parameters or to blurring by concurrent variation of plant sensitivity and tillage intensity.

Systematic studies of crop sensitivity at various growth stages (Lafond & Kattler, 1992; Leblanc & Cloutier, 2001) are valuable, especially when operational characteristics like working depth, working speed, tine pitch, soil moisture content and soil friability are quantified. Although the percentage crop uprooting or crop covering may be a more suitable reference for tillage intensity than operational characteristics (Rasmussen, 1990, 1991b; Rydberg, 1993), both still needs to be related to suitable crop sensitivity characteristics. As weed susceptibility to mechanical weeding drops quickly in early growth stages, further research on how crop and weed sensitivity decreases over time is important to predict how selectivity changes over time (Rasmussen, 1996). Using weed emergence models to optimise timing of rotary hoeing (Oriade & Forcella, 1999; Forcella, 2000) and research on site-specific and within-population variability and the effect of soil and weather conditions on emergence and early development are important. A suitable quantification of plant sensitivity to uprooting, and soil covering is essential to link ecological and physiological knowledge to knowledge on physical damaging processes, and to develop physical weed control models.

3. The uprooting model and an equation to describe the relationship between weed control and crop damage (chapter 5) allowed for independent quantification of the selective potential of a crop–weed situation and the selective ability of a weeder, independent of the crop damage level. Although the method should be tested in field situations and applied to covering damage as well, it may improve possibilities for comparing harrowing performance across sites and times, and for analysing the effects of soil conditions and implement adjustments.

   Present methods have assessed qualitative differences in selectivity by comparing weed control at the same crop damage level, through adjusting machines to the same crop damage level or through creating overlapping ranges of crop damage (Rasmussen, 1992). However, adjusting machines to the same crop damage level is difficult, particularly if crop damage parameters cannot be assessed immediately (e.g. final yield reduction). Moreover, the factor used to create different levels of crop damage (e.g. number of passes on the same day) may itself affect selectivity in a qualitative way or interact with the adjustment factor to be examined (e.g. working depth). Although this approach is confined to the damaging selectivity of harrowing, it is a useful extension of the modelling framework elaborated by Rasmussen (1990, 1991b, 1993) and coworkers.

4. Our experimental method offered new possibilities to study plant recovery from the varying types of damage as created by harrowing (chapter 6). As studies quantifying both immediate and final damage to crops and weeds (e.g. Fogelberg & Dock Gustavsson, 1999; Jensen *et al*., 1999) are of great importance to predict crop and weed response to mechanical damage, simple and practicable assessment methods need to be developed and widely used in field experiments. Such assessments combined with local weather data could help build a research database to examine the effects of weather and soil conditions after harrowing.

   To support decision-making in the short term, more should be known about:

   a) The critical degree of covering and depth of intra-row topsoil loosening that does not retard crop growth or makes it more susceptible to subsequent weeding treatments.
   b) The critical degree of crop plants loss that cannot be sufficiently compensated to avoid crop yield loss, taking account of within-population variability.

   Improved knowledge of plant response to mechanical damage under various weather conditions deserves a strong research effort. As the mechanisms involved in the recovery process (Fig. 6.1) may be similar to those involved in plant emergence, transplanting shock and growth under extreme water stress, knowledge from disciplines such as seed and plant physiology, soil physics, micrometeorology, soil mechanics and ecology may provide relevant insights, methods and models for further study on the recovery process of mechanically damaged plants (e.g. Hsiao, 1993; Kramer & Boyer, 1995).

5. Even with the fine, homogeneous flat sandy soil in our study, soil moisture content considerably affected uprooting and covering selectivity and plant recovery. Although the damaging mechanism on other soils is expected to be similar, soil that breaks into relatively large clods may induce different phenomena than the relatively loose and fragile soil in our study. As a result, the spatial patterns on inhomogeneous, uneven, denser and/or heavier soils may be different. Research on the effects of seedbed structure and moisture conditions on crop and weed sensitivity to uprooting and covering is recommended.

6. Assessments on individual plants revealed the importance of within-population variability in plant sensitivity to covering (chapter 3) and uprooting (chapters 4, 5), which occur within commonly used counting quadrats. Furthermore, the analysis of small-scale spatial effects in tine–soil–plant interactions from a biomechanical viewpoint offers possibilities for mechanistic modelling of the covering and uprooting process (chapters 3, 5). The innovative experimental techniques offered new possibilities to measure *in-situ* burial depth of plants and

study uprooting of white threads. Although the representation of natural crop and weed populations in field situations was compromised, our methods have many advantages over common approaches in field studies with mechanical weeding. Finding appropriate methodologies to achieve these scientific advantages in field experiments still poses a great challenge.

7.2 Practical aspects

This fundamental study did not aspire to directly solve farmers' problems. In optimising single selective mechanical weeding treatments, a farmer basically deals with two issues. First, if weeds cannot be sufficiently controlled without crop damage, she/he should estimate how much crop damage is allowed. Second, she/he should maximise weed control at a certain level of crop damage. This requires prediction and/or assessment of:

- the attainable weed damage at different levels of crop damage,
- the achievable range of damaging intensity,
- the response of mechanically damaged plants,
- effects on weed-crop competition,
- effects on crop sensitivity and weed controllability at the subsequent weeding operation,
- effects on subsequent weed germination and emergence.

Furthermore, a farmer should optimise multiple weeding treatments in the course of the growing season, considering the availability and cost of machines and labour, workability and other farm activities. Several options for weed prevention and curative weed control should be integrated into an efficient, flexible, reliable and practically feasible weed management system, suited to the crop rotation and environmental conditions specific for her/his farm.

This study could cover only part of these aspects and did not link up with farmers' decision-making directly. Nevertheless, it indicated some possibilities worth to be tested in field experiments and provided insights that may improve mechanical weeding:

1. Results in chapters 3 and 4 suggest that damaging selectivity could be improved by tuning implement adjustments to the specific weaknesses of the weeds and strengths of the crop with respect to their geometrical and mechanical characteristics (flexibility, height, anchorage). After complementation by further studies, qualitative insights in the covering and uprooting mechanism could be translated into a simple stepwise procedure to help farmers chose a situation-specific damaging strategy. Scoring the relative sensitivity of weeds by a schedule like Table 7.1 could support this. Such an approach could complement indexes of weed controllability (Koch, 1964b) and general guidelines for crops and growth stages feasible for harrowing (Walter, 1990; Wicks *et al*., 1995). These indices and guidelines do not support the optimization of implement adjustment and timing in relation to soil and weather conditions, and do not help farmers to gain causal understanding.

Table 7.1 Assessment schedule for weed and crop characteristics that determine their relative sensitivity to mechanical weeding, with scores for an imaginary crop–weed combination. A mark in the rightmost column indicates a great relative advantage of the crop, which could be exploited to improve selectivity.

Crop and weed susceptibility characteristic	Relative advantage				
	weed		no difference		crop
Tall plant					X
Difficult to bend downward		X			
Strong anchorage in topsoil			X		
Strong anchorage in deeper layer	X				
…					

The degree to which specific strengths of the crop and specific weaknesses of the weeds can practically be exploited depends on the following factors:

a) The magnitude of differences in each characteristic in favour of the crop.
b) The possibility to target relative strengths of the crop without addressing one of its relative weaknesses.
c) The optimum intensity of the uprooting and covering action as compared to the range that can be achieved by the implement.
d) Plant response to uprooting or covering damage as related to weather conditions after harrowing.

Principally, situations in which plant sensitivity characteristics and weather-dependent plant response result in the same preferred damaging strategy offer the best potential for exploiting specific weaknesses of weeds. Knowledge of plant response to damage may therefore be used to develop tactical guidelines for adapting the damaging strategy to expected weather.

2. This study revealed that the lateral position of plants relative to the tine pattern is important for two reasons. Firstly, uprooting could be selective in early crop growth stages, especially if tines avoid contact with crop plants and if working depth is precisely controlled (chapter 4). Secondly, there are zones with a high covering effect combined with a low uprooting effect, and zones showing the opposite (compare Fig. 3.5 and Fig. 4.6). With improved steering accuracy, this phenomenon may be used to impose different damaging strategies in the crop row.

   The current design of spring tine harrows allows tines to be forced out of the crop rows when crop plants are sufficiently robust (Rasmussen, 1991a; Cook *et al*., 1993). This self-steering effect is largely responsible for the effectiveness of selective harrowing at later crop growth stages, as it would allow deeper harrowing and higher working speeds. Unfortunately, this does not work at early, sensitive crop stages, whereas selectivity improvement in these situations has high practical relevance.

On fragile smooth soil, a precisely controlled and uniform working depth could help avoid covering and uprooting of young crop plants by limiting the soil level upheaval and by creating tillage-induced forces only in the soil layer above the crop seeds. Therefore, implements with accurate (< 1 cm) steering and depth control should be developed with a limited number of functional adjustments (i.e. working depth, tool–crop row distance), which can be set quickly, independently and accurately. These adjustments should enable the creation of wide and independent ranges of uprooting and covering intensity. Ways should be sought to increase covering depth without significantly increasing surface level upheaval and to increase exposure of uprooted plants.

3. This study implies that seedbed structure and tillage should be looked at in much more spatial detail. In row crops, “micro tillage” tools that manipulate narrow and shallow zones on centimeter scale with great accuracy may be more appropriate than the more crude tillage and mechanical weeding techniques currently available. A dedicated detailed design of the crop row zone should facilitate a more homogeneous crop emergence and rapid crop anchorage in subsoil, guide flexible tines and provide a stable structure suitable for shallow disturbance in a wide range of soil moisture contents.
4. This study demonstrated that variability of plant sensitivity to mechanical damage within crop and weed populations has a great impact on the achievable selectivity of mechanical weeding. Therefore, ways to reduce this variability (through e.g. seedbed properties, crop seed homogeneity and cultivations triggering weed emergence flushes) should be further explored. Furthermore, weed control decisions (e.g. allowable crop damage, timing determined by the controllability of the largest weeds) should take more account of within-population variability.
5. The contribution of this study to the development of prediction models may have considerable practical value in the long term. Current bioeconomic models in weed management generally use highly simplified assumptions on mechanical weed control effectiveness (Swinton & King, 1994; de Buck *et al*., 1999). If suitable models for the uprooting, covering, recovery and competition process at the plant level are developed and integrated, they may be used to support mechanical weed control decisions, help design situation-adapted weed control strategies and balance costs, risks and impacts on the environment. Impacts of changes at the level of single cultivations (e.g. improved uprooting selectivity in early crop growth stages, improved smothering of covered weeds in wet periods) on other weed control measures and the overall performance of the weed management system could be explored before testing systems in the field.
6. Insight in mechanical weeding processes and how their selectivity can be manipulated is of great practical relevance, as empirically finding the optimal treatment or strategy in each situation would not be feasible. Even if it were (despite of the many factors involved), it would be difficult to appropriately transfer such knowledge to farmers as long as the different responses of weeds and crops to mechanical weeding are not well understood.

7.3 Challenges for technical development and future research

7.3.1 Improvements at three integration levels

Weed management systems consist of various preventive and curative components aimed at various stages in the life cycle of weed and crops. Mechanical weed control can be improved at three integration levels:

1. The mechanical weed control component itself, by optimising the timing and performance of single cultivations and series of subsequent cultivations through:
   - Improving the selective damaging performance in given crop–weed situations.
   - Optimising the balance between weed control and crop damage through tillage aggressiveness combined with timing.
   - Minimising regrowth of damaged weeds.
2. Adapting or improving other components that affect mechanical weed control, aiming at:
   - Lower crop susceptibility, higher weed susceptibility and decreased weed density, by e.g. delayed planting, crop transplanting instead of sowing, row-applied fertiliser, seed treatment, stale or false seedbeds, pre-emergence flaming, photocontrol, phytotoxins released from green manure or compost, solarisation, weed seed removal at harvest, tillage practices that reduce the number of germinable weed seeds in the topsoil.
   - Compensation of occasionally deficient weeding effectiveness by e.g. competitive crop cultivars, intercropping, late flaming, biological control and predation, herbicides.
   - Improving workability and attainable work quality of mechanical weeders, e.g. by creating flat, well-structured seedbeds, accurate sowing and planting, controlled traffic systems with light vehicles, autonomous precision guidance.
3. The selection and integration of multiple components in a weed management system at the field and farm level, in a growing season of specific crops, and over a multiyear crop rotation.

7.3.2 Sustainable weed management systems

Selective mechanical weeding is one amongst many options to make weed management systems more efficient and environmentally sustainable. Like any other component, selective mechanical techniques have specific possibilities and limitations regarding effectiveness, costs, applicability and side effects.

The importance of a specific technique for a weed management system as a whole depends on the available alternatives and their possibilities and limitations with the given climate, soil, weed infestation, crops and production practices. As having all options and associated machinery and skills available at each farm or regional co-operative structure would not be feasible, a suitable selection should be made. Knowledge of the possibilities and limitations of each technique is essential to do so and compose a coherent system without "gaps" leaving weeds insufficiently controlled in certain parts of their life cycle, in particular weather and soil conditions, or with restricted machinery and labour availability.

This study and many others have contributed to this knowledge on various levels of integration, from basic studies on mechanisms (e.g. this study; Fogelberg, 1998) to multiyear comparisons of integrated weed management systems (e.g. Melander & Rasmussen, 2001). However, component-oriented studies only provide indications of possibilities and are always situation-specific. Therefore, general conclusions on the prospects of mechanical weeding must be drawn with care.

Besides knowledge of components and understanding of their interactions, methods to systematically design and evaluate weed management systems with respect to several aspects are required to improve weed management. Given the complex behaviour of weed populations as influenced by soil, weather and various agricultural interventions, this may seem unattainable. Nevertheless, many production systems have been managed by very simple concepts. For example, with effective and cheap selective herbicides being available, the concept "kill weeds when present" has been practicable in many situations. However, with herbicide-resistant weed populations building up and stronger restrictions on herbicides (costs, available compounds and permitted use), concepts for chemical weed control have become more complex (i.e. economic thresholds, site-specific application, applying minimum lethal herbicide doses adapted to weed growth stages and soil and weather conditions).

The author thinks that the design of situation-specific weed management systems can be optimised when suitable concepts are developed to guide strategic, tactical and operational decisions. Besides the step-by-step methodology for diagnosis, design and evaluation of integrated weed management systems (Ennis, 1977) and philosophies on integrating preventive and curative measures and ecological principles (e.g. Cussans, 1995; Buhler, 1996), more specific and operational concepts should be developed to support the development of practical decision rules.

7.3.3 The need to link fundamental research and practical innovations

The practical relevance of research to improve farmers' weed management practises depends on improvements that can be achieved by other means in a shorter term. Firstly, applied research, expanding farmer experience and increased attention to equal and precise crop row distances, flat seedbeds, timely operations, situation-adapted adjustments and using improved machinery may considerably improve mechanical weeding performance. Secondly, several technical innovations may relieve the demands on the selectivity, effectiveness and applicability of selective intra-row weeders: hoeing machines with precision steering or automatic guidance (van Zuydam *et al*., 1995; Tillett & Hague, 1999; van Zuydam, 1999; Home *et al*., 2001); crop and weed detection techniques applied in automatic intra-row hoes or weeding robots (Lee *et al*., 1997; Bontsema *et al*., 1998; Tillett *et al*., 1998; Kielhorn *et al*., 2000); site-specific herbicide application at lower rates (Christensen *et al*., 1998; Cox & Medd, 1998; Gerhards *et al*., 2000); and the adoption of various cultural methods (Gunsolus, 1990; Fernholz, 1990; Exner *et al*., 1996).

Our model-oriented fundamental approach would require a large research effort and cannot be expected to solve urgent weed control problems in organic agriculture and minor crops within a short term. For short-time utilisation, a complimentary approach will be needed. The author would prefer a combined fundamental-applied approach that aims at developing generally applicable decision rules based on a systematic series of small experiments and detailed assessments. These insights are to be translated into decision rules to be tested in experiments in farmers' fields and gradually improved in interaction with farmers.

The development of operational concepts and practical decision rules on one hand, and quantitative modelling approaches on the other hand, both have a specific and complementary role in improving weed management. By representing and applying scientific and experience-based knowledge in different ways, they can be used by people having different skills and ways of tackling complex problems. More intense co-operation between scientists, extension workers and farmers is necessary to realise the full potential of the various available components in truly integrated weed management systems. Furthermore, if practical decision rules would make mechanical weeding more reliable, models could be less complex and their predictions could be more accurate. Therefore, future research should facilitate both approaches.

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Summary

Introduction

Weed management systems in soil-related crop production consist of various measures to prevent or control weed reproduction and interference with crops. Herbicides have become a dominant component, which enabled farmers to rely less on a combination of alternative methods such as crop rotation, intercropping, tillage, nutrient management and mechanical weeding. Although herbicides have facilitated the development of large, labour-extensive farms able to produce cheap food, concerns about food quality, environmental contamination, problematic herbicide-tolerant weeds, increased costs and decreased herbicide availability have urged farmers to decrease reliance on herbicides.

Weeds between crop rows can effectively be controlled in various ways, but intra-row weed control requires selective methods that kill weeds but spare the crop. As long as alternatives to selective herbicides have limited selective ability, reliability, applicability, and/or cost- and labour-efficiency, weed problems will restrict the production of minor crops and the expansion of organic agriculture.

Several mechanical weeders (e.g. weed harrows, rotary hoes, torsion weeders, finger weeders, and vertical brushes) have shown potential for selective intra-row weed control in various crops, soils and climates. Despite their low cost, high capacity and versatility, adoption is limited by their lower and weather-dependent efficacy, limited selectivity in early crop growth stages and limited effect on well-established weeds. Weed control is generally influenced by many factors, whose effects and interactions are not well understood, and which complicate comparability of field experiments at several times and sites. Although several studies aimed to optimise timing, implement handling, tool selection and tillage intensity (balancing weed control and crop damage), the above limitations have not been alleviated.

Objectives and approach

Improved understanding of the mechanisms responsible for selective damaging and ways to predict weeding effectiveness and selectivity may open new possibilities to improve mechanical weeding. With these objectives, laboratory harrowing experiments with three model plant species in an early growth stage were conducted to study the uprooting and soil-covering process and plant recovery from mechanical damage. It was hypothesised that different crop and weed responses to these processes and to crop–weed competition explain the selectivity of mechanical weeding. Thus, instead of empirically assessing the effects of various soil-, plant- and implement-related factors on weeding effectiveness and selectivity, this study focused on understanding the mechanisms and finding suitable ways to quantify plant sensitivity, weeding intensity and selectivity. This would provide a sound basis for understanding the effects of various factors, improving weeding selectivity and effectiveness, and for developing models and prediction methods.

Materials and methods

Detailed assessments on individual plants were done in laboratory harrowing experiments to (1) distinguish the uprooting, covering and plant recovery process, (2) to study small-scale spatial patterns of plant damage and soil movement and (3) to account for heterogeneous plant responses (in relation to plant size, degree and type of damage). It was attempted to either minimise variability or to account for variability by accurate measurements. Realistic representation of field conditions was not a prior concern.

Three model plant species with contrasting morphological and mechanical characteristics were harrowed at various working depths, working speeds and soil moisture contents on fine, black sandy soil. *Lolium perenne* L. (perennial ryegrass) and *Lepidium sativum* L. (garden cress) were harrowed 3-4 days after emergence and *Chenopodium quinoa* Willd. at the day of emergence. Unlike real weed harrows, the model harrow had 23 rigid tines and 575 mm working width.

Before and after harrowing and after six days in a climate chamber, the size, position, and degree of uprooting and covering damage of nearly 20,000 individual plants and seeds were assessed using a three-dimensional coordinate measurement device. This enabled plant identification throughout the experiments and assessment of their positions relative to the tine pattern of the harrow. Individual plant fresh weight after six days, burial depth immediately after harrowing and the fate of white threads were assessed as well.

Selective covering

Chapter 3 provides a fundamental understanding of the selective covering ability of weed harrows in relation to plant sensitivity characteristics (flexibility, height) and explores how and to what extent covering selectivity could be manipulated.

The percentage covered plants decreased linearly with plant height, whereas burial depth increased with plant height. The decrease was much steeper for plants smaller than 9 mm. The higher flexibility caused *L. perenne* to be more covered than *L. sativum*, although *L. perenne* was nearly three times taller. The median burial depth of *L. perenne* and *L. sativum* was restricted to 6.7 and 9.6 mm, respectively, which was not sufficient to kill many plants.

Covering was attributed to upheaval of the soil surface level and downward bending of plant sprouts. Both showed systematic spatial patterns related to harrow tine configuration and soil movement, resulting in less than 30% covering of plants between the soil ridges and 40-80% covering in ridges between paths of the last two rows of harrow tines. Observing these patterns is essential to understand the effects of working depth, working speed and soil moisture content, and to explain limitations in the attainable magnitude and selectivity of covering.

Increased working depth and working speed and drier soil promoted covering in different ways, so that the selective action could be manipulated considerably. Consequently, the relationship between weed control and crop damage not only depended on plant characteristics, but also on harrow use. Higher working speed particularly promoted covering of taller plants through increased downward bending.

Deeper tillage not only increased downward bending by creating more loose soil to preserve the position of bent plants, but also increased burial of smaller, sturdier *L. sativum* plants through increased soil level upheaval. Drier soil solely promoted covering of flexible *L. perenne* plants and enhanced the working depth and working speed effect.

A regression-based simulation model was used to search optimum working depths, working speeds and soil moisture contents for controlling *L. perenne* “weeds” in a *L. sativum* “crop” and vice versa, as a function of plant height of both species. Quantitative modelling of the mechanics and geometry of soil and plant movement could be a promising next step, as a qualitative biomechanical analysis of the covering process made the relation between soil, plant and implement factors and the shape of the relationship between weed control and crop damage by covering more comprehendible.

Selective uprooting

Chapter 4 indicates that uprooting may be a more important mechanism for selective weed control at early crop growth stages than commonly assumed, especially if working depth and the distance between tine paths and the crop row could be more accurately controlled. Increasing working depth from 10 to 30 mm doubled the average fraction of uprooted plants. Increased working speed and soil moisture content enhanced uprooting as well. Drier soil and shallow harrowing generally improved selectivity between emerging plants and seedlings of the same species.

White threads and plants breaking through the soil surface were more uprooted than seedlings of the same species that emerged about three days earlier (48-60% and 17-26%, respectively). Particularly the larger plants were relatively more uprooted near the paths of the harrow tines, so that selectivity increased with increasing plant–tine path distance. Treatment effects on selectivity primarily arose between the tine paths. Developing improved sowing and tillage techniques to create soil conditions suitable for selective uprooting, and a steep gradient in soil compactness near crop rows to guide flexible tines, may improve selective mechanical weeding in early crop growth stages.

Predicting selective uprooting performance from plant anchorage forces

The prediction of mechanical weeding performance and the analysis of experiments is seriously impeded by the lack of suitable methods to independently quantify plant sensitivity and tillage intensity and to distinguish between the selective potential of specific crop–weed situations and the selective ability of weeders. Chapter 5 presents a possible solution for this problem with respect to uprooting.

As a first step, uprooting was related to the mean anchorage force of similar plants measured in untilled bins. Although uprooting was negatively correlated to the mean anchorage force, such empirical relationships do not account for weeding aggressiveness.

The second step used “crop” and “weed” anchorage force frequency distributions to calculate the fraction of weeds uprooted by an idealised harrow, which hypothetically pulls each plant with the same magnitude of force. This method accounts for within-population variability in crop and weed sensitivity to being uprooted, and circumvents the problem of unknown weeding aggressiveness. The potential uprooting curve (the relationship between the potential fraction of uprooted weeds and crop uprooting as calculated from anchorage force frequency distributions) could be used as a reference for comparing implements. However, as predicted potential uprooting generally exceeded uprooting as observed in harrowing experiments, the assumption that harrowing exerts a constant invariable force on plants appeared unrealistic. Simulations revealed that increased variability of tillage-induced forces would considerably decrease uprooting selectivity.

The third step fitted the potential uprooting curve by a non-linear equation that included a correction parameter (K_{till}) for imperfect selective ability of the weeder. A similar parameter (K_{pot}) presents the selective potential of the crop weed situation. It was hypothesised that the relationship between weed and crop uprooting in specific crop–weed–implement situations can be described by the non-linear equation with the selectivity parameter equalling K_{till} x K_{pot}.

In contrast to the selectivity parameter introduced by Rasmussen (i.e. % weed control / % crop damage), K_{pot} and K_{till} did not depend on crop uprooting and may therefore be more suitable to quantify qualitative selectivity differences at variable harrowing intensities, and to distinguish between crop–weed and implement-related differences in selectivity across sites and times. If plant anchorage force distributions would appropriately reflect the selective potential of crop–weed situations for mechanical weeding, this method could facilitate studies on interactions between various weed management components (such as false seedbeds, pre-emergence flaming) and mechanical weeding. In addition, models to predict emergence and early growth may be developed to predict anchorage force frequency distributions over time and help optimise weeding tactics.

Recovery from uprooting and covering

Mortality and fresh weight reduction of individual plants of various types of mechanical damage was assessed six days after harrowing, to study the relationship between initial and final effects of harrowing. Although harrowing predominantly covered plants, only 1-17% of the non-uprooted covered plants were killed, as harrowing buried plants only shallowly. Uprooting was more effective (47-61% mortality) and accounted for 93% and 95% of *L. sativum* and *C. quinoa* mortality and for 60% of *L. perenne* mortality. Partial covering slightly decreased *L. perenne* fresh weight but caused no mortality. Fresh weight of plants surviving uprooting was more reduced than of non-uprooted plants surviving burial. Drier soil at harrowing greatly decreased survival of uprooted plants. Faster harrowing decreased survival of covered uprooted *L. perenne* and *L. sativum*.

Mortality and fresh weight reduction of surviving plants were generally less predictable than their combined effect. Despite the minor contribution of burial to mortality, mortality of *L. perenne* and *L. sativum* was better related to covering than to uprooting. A large part of the variation in *C. quinoa* mortality and *L. perenne* fresh weight reduction could not be attributed to differences in the fraction of covered or uprooted plants.

The results from chapter 6 indicate that the plant recovery process after harrowing needs further study and that field research methods should be refined so that they can better discern initial and final harrowing effects on weeds. In addition, future mechanical weed control research should consider separate assessment of the uprooting and covering effect, because (1) uprooting and covering were not well correlated, especially with white threads and emerging plants, (2) in our study 70% of the uprooted plants were also covered, (3) the type of mechanical damage and soil conditions affected plant recovery, and because (4) uprooting is a potentially important mechanism for selective mechanical weeding in early growth stages.

General discussion

Instead of empirically exploring the effect of various factors on mechanical weeding selectivity and effectiveness, processes causing selectivity were studied in detail and conceptual frameworks were developed to facilitate experimental analysis and development of prediction methods. The distinction between initial plant damaging by the uprooting and covering process, and the subsequent plant response resulting from plant recovery and crop–weed competition appeared a useful concept. The outcome of the uprooting and covering process was perceived as the balance between plant sensitivity and the uprooting and covering capacity of the tillage operation. These are in turn influenced by various soil, plant and implement factors. Methods to quantify plant sensitivity and damaging capacity are considered important for applying dose–response approaches in mechanical weeding, and for studying interactions between various components of weed management systems.

Quantifying plant sensitivity to uprooting by measuring anchorage forces, and quantifying the uprooting capacity of weeders by the equivalent tillage-induced force estimated using a simple uprooting model, appear successful attempts, which should also be tried in field conditions. Also the method to quantify crop–weed selective potential and the selective ability of weeders may prove an important step forward in predicting mechanical damage by weeding. However, the application of these concepts to covering damage is more complicated and requires further study.

Detailed measurements on individual plants and simulation studies revealed the importance of within-population variability in plant sensitivity. Field assessments and and data analysis should take more account of this. Furthermore, ways to reduce this variability through seedbed properties, crop seed homogeneity and cultivations triggering weed emergence flushes should be explored. Our results also inferred that seedbed structure and tillage should be looked at in much more spatial detail when improving tillage systems to facilitate mechanical weeding. However, on heterogeneous, uneven, denser and/or heavier soils, soil failure and associated spatial patterns of mechanical damage may differ from our experiments.

Although the complex dynamics of the recovery process could not be studied here, the conceptual model depicted in Fig. 6.1 and present knowledge in soil physics, micrometeorology and plant physiology may be used to improve prediction of plant response to mechanical damage under various weather conditions. In the author's opinion, research on plant recovery from damage as induced by mechanical weeders deserves the strongest effort, as this knowledge is required to develop guidelines for allowable crop covering and to optimise weeding tactics in dry as well as in moist conditions.

Although this fundamental study did not intend to directly solve farmers' problems, insights in mechanisms can help farmers to exploit differences in crop and weed sensitivity characteristics by choosing crop-, weed-, and weather-adapted damaging strategies. Deriving situation-specific advices from basic insight in mechanisms would be more feasible than finding the optimum mechanical weeding treatment or strategy for each situation by purely empirical research. Such knowledge would be more difficult to communicate to and between farmers as long as weed and crop response to weeding is not well understood. In the long term, our approach would facilitate the development of dynamic models to support operational, tactic and strategic decisions in weed management.

To solve weed control problems in organic farming and minor crops in the short term, a complimentary fundamental-applied approach is needed, which translates scientific knowledge into practicable decision rules and operational concepts for integrated weed management systems design. In addition, there is potential for improving weeding implements and applying methods to indirectly improve the performance of mechanical weeding techniques or to relieve the demands on their selectivity, effectiveness and applicability.

Samenvatting

Inleiding

Onkruidbestrijdingssystemen in de landbouw omvatten uiteenlopende maatregelen om onkruidgroei te voorkomen of te bestrijden. Herbiciden zijn daarbij een belangrijke component geworden, waardoor boeren minder gebruik hoeven te maken van een combinatie van alternatieve methoden zoals mengteelt, vruchtwisseling, grondbewerking, bemesting en mechanische onkruidbestrijding. Hoewel herbiciden de ontwikkeling van grote, arbeidsextensieve bedrijven en lage voedselprijzen hebben bevorderd, staan boeren onder toenemende druk om hun herbicidengebruik te verminderen. Dat komt door de toegenomen maatschappelijke aandacht voor milieuvervuiling en voedselkwaliteit, maar ook door problemen met resistente onkruiden en door de toegenomen kosten en de afgenomen beschikbaarheid van middelen.

Er zijn verschillende manieren om onkruid tussen gewasrijen effectief te bestrijden. Voor onkruidbestrijding in de gewasrij zijn methoden nodig die voldoende selectief zijn, zodat ze het onkruid bestrijden maar het gewas niet beschadigen. Zolang de alternatieven voor herbiciden onvoldoende selectief, betrouwbaar, toepasbaar en/of efficiënt zijn, zullen onkruidproblemen de teelt van kleine gewassen en de groei van de biologische landbouw blijven belemmeren.

Verschillende werktuigen zoals de onkruideg, de rotary hoe, torsiewieders, vingerwieders en kopborstels, zijn bruikbaar voor selectieve onkruidbestrijding in de rij van diverse gewassen, bij uiteenlopende grondsoorten en omstandigheden. Hoewel ze goedkoop, veelzijdig en slagvaardig zijn, is hun toepassing beperkt door hun lagere en weersafhankelijke effectiviteit, hun beperkte selectiviteit in vroege gewasstadia en hun beperkte bestrijding van groter en meerjarig onkruid. Omdat de mate van onkruidbestrijding wordt bepaald door vele factoren, zijn veldexperimenten op verschillende tijdstippen en lokaties moeilijk vergelijkbaar. Het inzicht in de effecten en interacties van die factoren is nog beperkt. Ondanks pogingen om bewerkingstijdstip, werktuiginstellingen, werktuigkeuze en bewerkingsintensiteit te optimaliseren, zijn de bovengenoemde beperkingen nauwelijks verminderd.

Doelstelling en benadering

Een beter inzicht in de werkingsmechanismen die een verschillende onkruid- en gewasbeschadiging teweeg brengen, en methoden om de effectiviteit en selectiviteit te voorspellen, kunnen nieuwe mogelijkheden bieden voor het verbeteren van de mechanische onkruidbestrijding. Daarom is het ontwortelings-, bedekkings- en hergroeiproces onderzocht in eg-experimenten in het laboratorium. Onze hypothese is dat een verschillende reactie van gewas en onkruid op deze processen en op de gewas–onkruid concurrentie de selectiviteit van mechanische onkruidbestrijding verklaren. In plaats van het empirisch vaststellen van de effecten van allerlei grond-, plant- en werktuiggerelateerde factoren op onkruidbestrijding en selectiviteit, is deze studie gericht op het begrijpen van de achterliggende werkingsprincipes en het vinden van geschikte methoden om plantgevoeligheid, bewerkingsintensiteit en selectiviteit te kwantificeren. Dit verschaft een goede basis voor het begrijpen van effecten van diverse factoren, het verbeteren van de selectiviteit, en het ontwikkelen van modellen en voorspellingsmethoden.

Materialen en methoden

In laboratoriumexperimenten zijn gedetailleerde metingen gedaan aan afzonderlijke planten om (1) het ontwortelings-, bedekkings- en hergroeiproces te kunnen onderscheiden, (2) ruimtelijke patronen van plantbeschadiging en grondverplaatsing te bestuderen, en (3) rekening te kunnen houden met heterogene plantreacties (in relatie tot plantgrootte, mate en type van beschadiging). Er is getracht de variabiliteit te minimaliseren en de resterende variatie nauwkeurig te meten. Het realistisch nabootsen van veldomstandigheden had niet de eerste prioriteit.

Drie soorten modelplanten met contrasterende morfologische en mechanische eigenschappen werden geëgd bij verschillende werkdieptes, rijsnelheden en vochtgehaltes van een zandgrond. *Lolium perenne* L. (raaigras) en *Lepidium sativum* L. (tuinkers) werden 3-4 dagen na opkomst geëgd, en *Chenopodium quinoa* Willd. (quinoa) bij opkomst. De model-eg had 23 starre tanden en was 575 mm breed.

Met een 3D-coördinatenmeetarm werd de grootte, de positie en de mate van bedekking en ontworteling van ongeveer 20.000 planten bepaald, direct voor en na het eggen en na zes dagen in een klimaatkamer. Hierdoor konden planten worden geïdentificeerd en kon hun positie ten opzichte van het egtand-banenpatroon worden bepaald. Ook werd de dikte van de grondlaag op volledig bedekte planten gemeten en werd het effect van eggen op planten in het witte draden stadium bepaald.

Selectief bedekken

Hoofdstuk 3 geeft fundamenteel inzicht in de selectiviteit van bedekking door eggen in relatie tot plantgevoeligheidskenmerken (flexibiliteit, hoogte) en onderzoekt hoe en in welke mate de bedekkingsselectiviteit kan worden gemanipuleerd.

Het percentage bedekte planten nam lineair af met de planthoogte, terwijl de bedekkingsdiepte toenam met de planthoogte. De afname was veel sterker bij planten < 9 mm. Door het flexibeler blad werd raaigras meer bedekt dan tuinkers, terwijl het raaigras ongeveer driemaal zo hoog was dan tuinkers. De mediaan van de bedekkingsdiepte van raaigras en tuinkers was beperkt tot resp. 6.7 en 9.6 mm.

Bedekking werd veroorzaakt door de ophoging van het grondoppervlak en het neerwaarts buigen van planten. Hun ruimtelijke patronen houden verband met het egtandbanen- en grondverplaatsingspatroon. Tussen de door de laatste twee rijen tanden gemaakte rugjes werd minder dan 30% van de planten bedekt, terwijl in de ruggen 40-80% werd bedekt. Voor het begrijpen van de effecten van werkdiepte, rijsnelheid en grondeigenschappen moet men rekening houden met deze patronen.

Een grotere werkdiepte, een hogere rijsnelheid en een drogere grond vergrootten het bedekkingspercentage op verschillende manieren. Omdat de selectieve werking aanzienlijk kon worden gemanipuleerd, is de relatie tussen onkruidbestrijding en gewasschade niet alleen van planteigenschappen afhankelijk. De hogere rijsnelheid bevorderde vooral de bedekking van grotere planten door de toegenomen neerwaartse buiging. Bij een grotere werkdiepte is er meer losse grond, die enerzijds de gebogen positie van planten handhaaft, en anderzijds de bedekking van kleine stevige tuinkersplanten deed toenemen door meer ophoging van het grondoppervlak. Drogere grond bevorderde uitsluitend de bedekking van het flexibele raaigras en vergrootte het effect van werkdiepte en rijsnelheid.

Een op regressieanalyses gebaseerd simulatiemodel werd gebruikt om de optimale combinaties van werkdiepte, rijsnelheid en vochtgehalte te zoeken voor het bestrijden van het “onkruid” raaigras in het “gewas” tuinkers, en omgekeerd, in relatie tot de plantgrootte van beide soorten. Een kwalitatieve biomechanische analyse van het bedekkingsproces gaf inzicht in het effect van grond-, plant- en werktuigfactoren op de relatie tussen onkruid- en gewasbedekking. Daarom zou het kwantitatief modelleren van de mechanica en geometrie van grond- en plantverplaatsing een veelbelovende volgende stap kunnen zijn.

Selectief ontwortelen

Hoofdstuk 4 toont aan dat ontworteling in vroege gewasstadia een belangrijker selectief onkruidbestrijdingsmechanisme kan zijn dan algemeen werd aangenomen, vooral als de werkdiepte en de afstand tussen tanden en gewasrijen nauwkeuriger zou kunnen worden geregeld. Een werkdiepte-toename van 10 tot 30 mm verdubbelde het gemiddelde percentage ontwortelde planten. Een grotere rijsnelheid en een hoger bodemvochtgehalte verbeterde in het algemeen de selectiviteit tussen opkomende planten en kiemplanten van dezelfde soort.

Witte draden en opkomende planten werden meer ontworteld dan kiemplanten van dezelfde soort die ongeveer drie dagen eerder waren opgekomen (resp. 48-60% en 17-26%). Omdat de grotere planten die dicht bij een egtand-baan stonden relatief meer werden ontworteld, verbeterde de selectiviteit bij toenemende egtand-plant afstand. Behandelingseffecten op de selectiviteit ontstonden vooral tussen de egtand-banen. De selectiviteit van mechanische onkruidbestrijding in vroege gewasstadia zou kunnen worden verbeterd door grondbewerkings- en zaai-technieken die gunstige bodemcondities voor selectieve ontworteling scheppen en die een scherpe gradiënt in grondweerstand creëren om flexibele tanden te geleiden.

Het voorspellen van ontwortelingsselectiviteit op basis van verankeringskracht

Het voorspellen van het resultaat van mechanische onkruidbestrijding en het analyseren van experimenten wordt ernstig gehinderd door het ontbreken van methoden om de plantgevoeligheid en de bewerkingsintensiteit onafhankelijk te kwantificeren, en onderscheid te maken tussen de selectieve potentie van specifieke gewas-onkruid situaties en het selectieve vermogen van werktuigen. Hoofdstuk 5 geeft een mogelijke oplossing voor dit probleem wat betreft ontworteling.

Als eerste stap werd het ontwortelingspercentage gerelateerd aan de gemiddelde gemeten verankeringskracht van vergelijkbare planten in onbewerkte grondbakken. Hoewel deze parameters negatief gecorreleerd waren, zijn zulke empirische relaties ongeschikt voor voorspellingen, omdat ze geen rekening houden met de bewerkingsintensiteit.

De tweede stap gebruikte de verankeringskracht-frequentieverdelingen van gewas en onkruid om het ontwortelingspercentage te berekenen voor een hypothetische ideale eg, die aan elke plant even hard trekt. Deze methode houdt rekening met variabiliteit in gevoeligheid binnen de gewas- en onkruidpopulatie, terwijl de onbekendheid van de bewerkingsintensiteit geen probleem oplevert. De potentiële ontwortelingscurve (de relatie tussen de potentiële onkruidontworteling en gewasontworteling berekend uit de verankeringskracht-frequentieverdelingen) zou kunnen worden gebruikt als referentie voor het vergelijken van werktuigen. Echter, omdat de voorspelde potentiële ontworteling vaak hoger was dan de in eg-experimenten waargenomen ontworteling, lijkt de aanname dat een eg op elke plant dezelfde kracht uitoefent onrealistisch. Simulaties geven aan dat de haalbare ontwortelingsselectiviteit sterk afneemt bij een toenemende variabiliteit van de op planten uitgeoefende kracht.

Bij de derde stap werd de potentiële ontwortelingscurve beschreven met een niet-lineaire vergelijking die een parameter (K_{till}) voor het selectieve vermogen van werktuigen bevat. Een vergelijkbare parameter (K_{pot}) kwantificeert de selectieve potentie van de gewas–onkruid situatie. De hypothese was dat de relatie tussen onkruid- en gewasontworteling van specifieke gewas–onkruid–werktuig situaties kan worden beschreven door de selectiviteitsparameter van de niet-lineaire vergelijking (K) te berekenen als: $K = K_{till} \times K_{pot}$.

In tegenstelling tot de door Rasmussen geïntroduceerde selectiviteitsparameter (% onkruidbestrijding / % gewasschade) waren K_{pot} en K_{till} onafhankelijk van de mate van gewasontworteling. Dit maakt deze methode geschikter om kwalitatieve verschillen in selectiviteit te beoordelen bij uiteenlopende bewerkingsintensiteit, en om gewas- en werktuiggerelateerde verschillen in selectiviteit te onderscheiden in proeven op verschillende lokaties en tijdstippen. Als verankeringskracht-frequentieverdelingen de selectieve potentie van gewas–onkruid situaties goed weergeven, zou deze methode gebruikt kunnen worden bij het bestuderen van interacties tussen mechanische onkruidbestrijding en andere componenten van onkruidbestrijdingssystemen (zoals de vals-zaaibed techniek en het branden bij gewasopkomst). In combinatie met modellen voor het voorspellen van de opkomst en de vroege groei van gewassen en onkruiden, zou deze methode kunnen worden gebruikt om onkruidbestrijdingstactieken te optimaliseren op basis van voorspelde verankeringskracht-frequentieverdelingen als functie van de tijd.

Hergroei na ontworteling en bedekking

Zes dagen na het eggen werd de doding en het versgewicht van individuele planten vastgesteld, om de relatie tussen onmiddellijke en uiteindelijke effecten van eggen te bestuderen. Hoewel het eggen vooral planten bedekte, werd slechts 1-17% van de niet-ontwortelde bedekte planten gedood, vanwege de beperkte bedekkingsdiepte. Ontworteling was effectiever (47-61% doding) en droeg voor resp. 93%, 95% en 60%

bij aan de doding van tuinkers, quinoa en raaigras. Gedeeltelijke bedekking verminderde het versgewicht van raaigras, maar was niet dodelijk. Het versgewicht van planten die ontworteling overleefden werd sterker gereduceerd dan dat van niet-ontwortelde planten die bedekking overleefden. Drogere grond tijdens het eggen vergrootte de doding door ontworteling aanzienlijk. Bij een hogere rijsnelheid stierf een hoger percentage van de bedekte ontwortelde tuinkers- en raaigrasplanten.

De sterfte en de versgewichtreductie van overlevende planten was in het algemeen minder voorspelbaar dan hun gecombineerde effect. Ondanks de kleine bijdrage van bedekking aan doding, was de doding van raaigras en tuinkers beter gerelateerd aan bedekking dan aan ontworteling. Een groot deel van de variatie in quinoa-sterfte en raaigras-versgewichtreductie kon niet worden toegeschreven aan verschillen in ontwortelings- en bedekkingspercentages.

Uit de resultaten van hoofdstuk 6 blijkt dat het herstelproces van beschadigde planten verder onderzoek behoeft, en dat veldonderzoeksmethoden moeten worden verbeterd om beter onderscheid te kunnen maken tussen de onmiddellijke en uiteindelijke effecten van mechanische onkruidbestrijding. Bij verder onderzoek zal het afzonderlijk bepalen van de mate van ontworteling en bedekking moeten worden overwogen, omdat (1) ontworteling en bedekking maar beperkt zijn gecorreleerd, vooral bij witte draden en opkomende planten, (2) 70% van de ontwortelde planten tevens bedekt was, (3) het type mechanische beschadiging en bodemcondities de hergroei beïnvloeden, en omdat (4) ontworteling een belangrijk mechanisme voor selectieve mechanische onkruidbestrijding kan zijn in vroege gewasstadia.

Algemene discussie

In plaats van het empirisch verkennen van het effect van allerlei factoren op de selectiviteit en effectiviteit van mechanische onkruidbestrijding, zijn hier de processen die selectiviteit veroorzaken gedetailleerd bestudeerd. Verder is er een aanzet gegeven voor een betere analyse van experimenten en voor het ontwikkelen van voorspellingsmethoden. Het onderscheiden van onmiddellijke beschadiging door ontworteling en bedekking en het daarop volgende herstel- en concurrentieproces bleek nuttig. De uitkomst van het ontwortelings- en bedekkingsproces werd gezien als een balans tussen de plantgevoeligheid en de beschadigingscapaciteit van de bewerking. Op hun beurt worden deze processen beïnvloed door allerlei bodem-, plant- en werktuigfactoren. Methoden voor het kwantificeren van plantgevoeligheid en beschadigingscapaciteit zijn belangrijk voor het toepassen van dosis-respons benaderingen in mechanische onkruidbestrijding, en voor het bestuderen van interacties tussen verschillende componenten van onkruidbestrijdingssystemen.

Het kwantificeren van de plantgevoeligheid voor ontworteling door het meten van de verankeringskracht, en het kwantificeren van de ontwortelingscapaciteit van werktuigen, door de met een eenvoudig model geschatte equivalente bewerkings-geïnduceerde kracht, lijkt een methode die de moeite waard is om onder veldomstandigheden te testen. Ook de methode voor het kwantificeren van de selectieve potentie van gewas–onkruid situaties en het selectieve vermogen van werktuigen zou een belangrijke stap voorwaarts kunnen zijn in het voorspellen van het onmiddellijke effect van mechanische onkruidbestrijding. Echter, het toepassen van deze concepten op het bedekkingseffect is ingewikkelder en vergt verder onderzoek.

Simulatiestudies en gedetailleerde metingen aan individuele planten hebben het belang van plantgevoeligheid-variatie binnen populaties aangetoond. Methoden voor veldwaarnemingen en gegevensanalyse zouden hiermee beter rekening moeten houden. Het lijkt de moeite waard om manieren te verkennen voor het verminderen van deze variabiliteit, bijvoorbeeld door zaaibedeigenschappen, homogeniteit van zaaizaad, en bewerkingen die homogene onkruidkiemingsgolven veroorzaken. Onze experimenten laten zien dat er bij het ontwikkelen van grondbewerkingssystemen en mechanische onkruidbestrijding veel gedetailleerder zou moeten worden gekeken naar zaaibedstructuur en werktuig–grond interacties. Op heterogene, ongelijke, dichtere of zwaardere gronden zouden ruimtelijke patronen van grondverplaatsing, ontworteling en bedekking echter anders kunnen zijn dan bij onze experimenten.

Hoewel de complexe dynamica van het herstelproces niet kon worden bestudeerd, zou het conceptuele model van Fig. 6.1 en bestaande kennis van bodemfysica, micrometeorologie en plantenfysiologie kunnen worden gebruikt om het plantherstel onder verschillende weersomstandigheden beter te voorspellen. Verder onderzoek naar de hergroei van door werktuigen bedekte en ontwortelde planten heeft volgens de auteur de hoogste prioriteit, omdat deze kennis nodig is om richtlijnen te ontwikkelen voor de toelaatbare gewasbeschadiging en het optimaliseren van bestrijdingstactieken onder vochtige en droge omstandigheden.

Hoewel deze fundamentele studie niet streefde naar het rechtstreeks oplossen van praktische vragen, kan een beter inzicht in de werkingsmechanismen van mechanische onkruidbestrijding boeren helpen om verschillen tussen gewas- en onkruideigenschappen beter te benutten. Het afleiden van situatie-specifieke adviezen uit fundamenteel inzicht lijkt beter haalbaar dan het voor elke situatie proefondervindelijk bepalen van de optimale handeling of strategie. Zulke proefondervindelijke kennis zou moeilijk overdraagbaar zijn, zolang men de reactie van gewassen en onkruiden op mechanische onkruidbestrijding niet goed begrijpt. Op de lange termijn voedt onze benadering de ontwikkeling van dynamische modellen voor het ondersteunen van operationele, tactische en strategische onkruidbestrijdingsbeslissingen.

Voor het op korte termijn oplossen van onkruidbestrijdingsproblemen in de biologische landbouw en kleine gewassen is een aanvullende fundamenteel-toegepaste benadering nodig, die fundamentele kennis vertaalt naar bruikbare beslissingsregels en gereedschappen voor het ontwerpen van geïntegreerde onkruidbestrijdingssystemen. Er zijn ook veel mogelijkheden voor het verbeteren van werktuigen en voor het toepassen van methoden die het resultaat van mechanische onkruidbestrijding indirect verbeteren, of methoden die de vereiste selectiviteit, effectiviteit en inzetbaarheid van mechanische onkruidbestrijding verminderen.

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Curriculum vitae

Op 5 december 1968 werd Dirk Anton Gerard Kurstjens geboren in het Noord-Limburgse Blerick. Vanaf zijn tweede jaar groeide hij op in Grubbenvorst, waar zijn ouders een akkerbouw- en loonbedrijf hadden, en later ook een mesttransportbedrijf en een landbouwmachinefabriek. Na het succesvol doorlopen van het VWO aan het Blariacumcollege te Blerick, ging hij in 1987 Landbouwtechniek studeren aan de Landbouwuniversiteit Wageningen. In zijn tweede studiejaar startte hij een onderzoek naar de bodemdruk van mestverspreidingsvoertuigen, wat later uitgroeide tot een groot afstudeervak grondbewerking. Een tweede afstudeervak betrof het methodisch ontwerpen van aardappelsorteermachines op basis van een nieuw sorteerprincipe. Tijdens de stage bij Rumptstad RSI in Stad aan 't Haringvliet ontwierp hij onder andere een aardappelruggenschoffelmachine en een aandrukrol voor een zaaibedbereidingswerktuig. In december 1991 diende zich een mogelijkheid aan om een promotieonderzoek over mechanische onkruidbestrijding te gaan doen. Dit was geen eenvoudige keuze omdat zowel onderzoek doen als ontwerpen hem erg aantrokken.

Na het behalen van het diploma landbouwtechniek (met lof) begon hij in juni 1993 als AIO (assistent in opleiding) bij de vakgroep Grondbewerking van de Landbouwuniversiteit Wageningen. Van augustus 1997 tot en met september 2000 werkte hij vier dagen per week bij IMAG-DLO aan diverse studies en experimenten met betrekking tot thermische en mechanische onkruidbestrijding. De resterende tijd werd besteed aan het schrijven van artikelen voor het proefschrift. Sinds oktober 2000 is hij als postdoc onderzoeker verbonden aan de leerstoelgroep Bodemtechnologie van Wageningen Universiteit. Behalve aan de afronding van het proefschrift werkt hij daar verder aan mechanische onkruidbestrijding en aan grondbewerkingssystemen met betere mogelijkheden voor onkruid- en nutriëntenbeheer ten bate van de biologische landbouw.

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