Australian Government
Rural Industries Research and Development Corporation

Sustainable Weed Management in Organic Herb & Vegetable Production

A report for the Rural Industries Research and Development Corporation

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July 2007

RIRDC Publication No 07/112
RIRDC Project No. UNE-65A

ISBN 1 74151 509 2
ISSN 1440-6845

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Project No. UNE-65A

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Published to Web in July2007

Foreword

The organic industry has identified weeds as the principal agronomic constraint to the production of a variety of crops. However, organic weed management has so far received little research attention in Australia. In response to local industry concerns about the impact of weeds in organic horticultural cropping, a project was established at the University of New England (UNE) to investigate weed management in herbs and vegetable production.

The project was designed to gain an understanding of the current practices and principles of weed management amongst organic herb and vegetable growers in Australia, and to investigate the agronomic and economic performance of a range of weed management techniques commonly used by Australian organic growers.

This report provides details about the research undertaken during the project, including a comprehensive national survey of organic herb and vegetable growers regarding weed management practices, and a series of field trials studying the effectiveness and cost-effectiveness of various weed control methods. These findings are set in the context of previous and current overseas research on non-chemical weed management, and specific issues that require more research are identified. The project has established a foundation for future weed management research in organic herb and vegetable production that previously did not exist.

This project was funded from RIRDC Core Funds, which are provided by the Federal Government.

This report, a new addition to RIRDC's diverse range of over 1600 research publications, forms part of our Organic Systems R&D program, which aims to facilitate the development of a viable organic industry through increasing adoption of sustainable organic farming systems.

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Peter O'Brien
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Acknowledgements

This research has been achieved with the generous help of numerous people at the University of New England (UNE) and other organisations, as well as individuals and groups in the organic industry. We gratefully acknowledged the assistance of the following:

* the administrative, technical and academic staff in Agronomy and Soil Science (UNE) for assistance with experimental work (especially Mr David Edmonds and Mr Michael Faint);
* Mr Peter Green (formerly of Subiaco Herbs) for technical advice on echinacea during the research;
* Subiaco Herbs and UNE for use of their farms for the field trials;
* Mr Peter Burr (UNE), Mrs Helen Mason (Upper Yarrowitch Pastoral Company), Ms Wendy Warner (NSW State Forests) for meteorological data;
* organic industry organisations (BFA, NASAA, OHGA and ORGAA) and their members for help with the industry survey on weed management;
* Mr Ian Reeve (UNE) for providing guidance and suggestions on conducting the survey; and
* Dr Ian Davies, Dr Bob Murison and Mr Duncan Mackay (UNE) for statistical and programming support.

Rural Industries Research and Development Corporation and the University of New England are thanked for their financial support.

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Executive Summary

What the report is about
Weeds are widely reported in the research literature as a key constraint in organic production and anecdotal accounts confirm this.

Who is the report targeted at?
Organic growers seeking to find the most cost effective method of treatment for weeds. Weed control costs as a percentage of gross returns have been found to be an important factor affecting profitability. Thus the examination of alternative methods of weed control is important for organic crop growers.

Background
In the past decade, there has been a surge of interest in organic agriculture and organic produce. As new growers enter the industry, the demand for information about organic production methods is increasing. The costs of weed management in organics vary depending on the farming system, with estimates ranging from 30-50% of expenses in intensive horticulture, to 10-30% in broadacre production. Organic farmers must rely on an integrated, multi-strand approach to controlling weeds based on a wide range of options.

Aims/Objectives
The organic weed management (OWM) survey was conducted to provide information about the weed control methods used by growers, attitudes towards weeds, basic characteristics of the farms and farmers surveyed, and the relationships between parameters. The organic weed management survey was prompted by the numerous anecdotal and research reports that weeds were a key constraint in organic crop production and the general lack of information about OWM practices. It provides a quantitative analysis of current weed management practices used by organic herb and vegetable growers in Australia and also gives an insight into some of the factors that influence those practices.

Methods used
It was considered that the existing knowledge base amongst Australian organic herb and vegetable growers could be accessed through a mail survey. This survey was initially conducted to examine current attitudes and approaches to weed management. Field experiments were then conducted to assess the relative performance of several commonly used weed control treatments in terms of weed growth, crop growth and treatment cost for two crops with differing growth patterns – the short season salad vegetable, lettuce, and the longer growing medicinal herb, echinacea.

Results/Key findings
A moderate response rate was achieved (43%), with the majority of respondents coming from within the sampling frame, i.e. organically certified producers of herbs and vegetables. The reported farm sizes were small (median = 2.4 hectares) and the respondents had relatively little experience with organic farming (median = 6 years). Producers grew a wide range of herb and vegetable crops (median = 3) and reported numerous types of weeds on their farms. The most common weeds were predominantly those with persistent underground parts that resist common forms of organic weed control such as cultivation (by hand or plough) and mulch. Heavily seeding annuals were also frequently reported. Respondents expressed strong concern about weed management, particularly regarding the difficult and time consuming nature of OWM and the impact of weed competition in reducing crop yields.

The respondents reported using a diverse range of weed management techniques, with over 40 specific methods or strategies being mentioned. The most common method was manual weeding, which was sometimes used as a central management technique or as a final "clean up" after relying on other methods such as tillage or mulch for the bulk of the weed control. Other commonly reported methods were organic mulches; tillage (especially rotary hoes); cultural methods such as rotations, bed preparation, timing of operations, cover crops and inter-cropping; slashing and/or mowing; and grazing. Less frequently reported OWM methods included thermal methods, synthetic mulches, organic sprays and farm hygiene practices.

The results for perceived success of weeding methods used were loosely correlated with the regularity of use. Therefore, manual weeding, organic mulches and tillage were reported to be the most successful weeding methods. No relationship was found between the perceived expense of a weeding method and the regularity of use of that method. This suggests that growers were not primarily motivated by the cost of a weeding method; instead, they were more concerned that it was successful in controlling weeds. Synthetic mulches and thermal weeding were considered to be the most expensive weed control methods.

Results from the OWM survey and the US-based Organic Farming Research Foundation (OFRF) survey (Walz 1999) highlight a number of possible research issues of concern to organic growers. Improved control of particularly problematic weeds, such as couch, sorrel and nutgrass, was a common area of concern. Studies on the biology and ecology of such weeds may identify lifecycle vulnerabilities that can be exploited by modified management practices. There also appeared to be some interest from respondents in novel techniques such as flame weeding, steam weeding, improved tillage implements and organic sprays, although these methods require further development too. Cultural strategies such as techniques for weed seed bank reduction and the development of weed suppressing cover crops that don't become weeds themselves were also of interest to respondents.

For lettuce, a crop with a short growing season, cheaper weed control methods such as tillage with limited follow-up hand weeding may be sufficient to ensure a reasonable crop yield. The acceptable economic return of the control treatment suggested that good weed control in the cropping area prior to planting may even be adequate. Hay mulch provided good yields but was less cost-effective due to the high labour requirement for mulch laying and follow-up hand weeding. However, this treatment greatly reduced bolting in the lettuces and may give more flexibility in terms of harvesting than tillage or hand weeding. Paper mulch stunted the growth of lettuce, presumably due to nitrogen immobilisation, although it also provided excellent weed control. It could not be recommended without reformulation with a nitrogenous fertiliser or some other method of improving available soil nutrient levels.

The results from the echinacea trials suggest that more expensive weeding methods are cost-effective for longer-season and higher-value crops. Hand weeding and hay mulch both provided cost-effective weed management. The differing effects of those two treatments on soil structure, carbon and moisture conservation were not evaluated, although these factors may be considered important by growers. The paper mulch again reduced crop yields and, combined with high purchase cost, appeared to be unreliable. The moderate adjusted crop value (ACV) (derived by subtracting the cost of each treatment at each site from the gross crop values) for paper mulch at Yarrowitch suggested that the treatment may have some potential as a weed control method in certain circumstances.

The economic analysis of the treatments is specific to the time and location of the trials, and outcomes may vary depending on the availability of labour, machinery and implements, and suitable mulch materials. However, similar trends have been reported in other organic and conventional trials.

For both crops the ranking of the weed control treatments for their weed biomass accumulation at crop harvest was hand weeding = paper mulch followed by hay mulch, tillage and then the control treatment. Weed control levels ranged from 98% through to approximately 60% for the tillage treatments.

Implications for relevant stakeholders

It was found that manual weeding, organic mulches and tillage were reported to be the most successful weeding methods. This finding should prove useful for organic farmers. The lack of relationship between the perceived expenses of the weeding method and the regularity of its use is significant for producers of products designed for weed control. Growers were far more concerned with the effectiveness of the weeding method.

Recommendations

Given the failure of the questions about time and cost of weed management to elicit reliable data in this survey, and the general importance of economic factors in broader decision-making, another potential research area may be an economic analysis of OWM practices. A more focused study of the economic impact of weeds and the cost and efficiency of various key weed management methods may generate empirical data about the relative cost of weed management in organic production. Such information is not currently available in Australia. The dominant weed control methods reported in the survey - manual weeding, organic mulches, cover crops and tillage - provided the focus for the experimental work reported in this project.

A range of problem weeds are still poorly controlled in such production systems; these include couch, sorrel and nutgrass. An examination of the biology and ecology of these weeds should identify lifecycle vulnerability's which can be exploited for their control. There also appeared to be some interest from the survey respondents in novel weeding techniques such as flame weeding, steam weeding, improved tillage implements and organic sprays; these systems were not examined in the current study but they are worthy of further study. Cultural strategies such as techniques for weed seed bank reduction and the development of weed suppressing cover crops (which do not become weeds) should also be assessed.

1. Introduction

1.1 Background to project

For many decades, Australian farmers have been successfully growing a broad range of crops using organic methods, without the use of synthetic chemicals and with an emphasis on specific management practices that take care of the soil and environment. Organised certification bodies such as the Biological Farmers Association (BFA) and the National Association for Sustainable Agriculture, Australia (NASAA) have been defining organic standards and certifying farms for about ten years. Commodities produced organically on these farms include grains, meat, dairy products, vegetables, tree crops, herbs and textiles. However, the industry is relatively small as a proportion of total Australian agriculture: less than 0.5% at the farm gate and about 0.2% in the shops (Dumaresq and Greene 1997). In contrast, organic food consumption is 10% and 7.8% in Austria and Switzerland respectively (FAO 1999).

In the past decade, there has been a surge of interest in organic agriculture and organic produce. Several indicators of the growth in organic production in Australia are given in Table 1. Organic production in Australia was recently estimated to be valued at $200-250 million annually (Crothers 2000).

Table 1. Indicators of growth in organic production from 1990 to 1995 (Hudson 1996)

Indicator	1990	1995
Total market value ($ million)	28	80.5
Total area certified ('000 hectares)	150	335
Total growers certified	991	1462

Consumer awareness and concern about how food and other commodities are produced has created an increasing demand for organic produce. This perceived concern is based on both the immediate health aspects of consuming organic produce as well as the issue of environmental impacts. Premium prices are often obtained for organic goods, with about 90% of Australian organic farmers receiving up to 50% more than similar conventionally grown produce (Hudson 1996). This economic incentive has influenced some conventional (i.e. non-organic) farmers, many receiving historically low prices for their commodities, to turn to organics (Crawshaw 1997). In parallel with the consumer-driven interest in organics, there has been an environmentally-informed political push to become more 'sustainable'. This escalating attention on sustainability has created new challenges for growers. In response to observed declines in soil quality and yields, despite increased inputs, conventional growers have turned to alternative systems such as organic production.

As new growers enter the industry, the demand for information about organic production methods is also increasing. Technical details sought by growers include soil fertility management, plant and animal species selection, rotation sequences, pest and disease control, and post-harvest handling. Weeds are widely reported in research literature as a key constraint in organic production and anecdotal accounts confirm this. The costs of weed management in organics vary depending on the farming system, with estimates ranging from 30-50% of expenses in intensive horticulture, to 10-30% in broadacre production (E. Wynen, pers. comm.). It is noteworthy that conventional growers are also very concerned about weeds, with an Australian study of wheat farmers finding that 90% of growers considered weeds to be their number one problem (Jones *et al.* 2000). This suggests that herbicides do not automatically solve a farmer's weed problems.

In weed management, an organic grower may use similar methods and strategies to conventional growers. Organic farmers must rely on an integrated, multi-strand approach to controlling weeds based on a wide range of options. Weed management must be carried out at different spatial and temporal scales. Whole-farm strategies such as broadcasting lime occur alongside slashing headlands and chipping patchy weed outbreaks. Some options can be undertaken during the cropping season, others between cash crops and others carried out continuously over several years. All operations should be aimed at minimising weed seed set or transfer of vegetative weed propagules.

In addition to the 'tools' of direct and cultural weed management, several key principles underpin the organic approach to management. They are timeliness of operations, vigilance, being thorough and understanding weed-crop ecology. The saying that "organic farming is not a lazy persons approach" (Marshall 1992) could refer equally to the mind as well as the body. Indeed, many non-chemical techniques are not inherently sustainable. Tillage, for example, can negatively impact on soil biology and physics. Good farm management skills are paramount.

1.2 Objectives of research

The use of various weed management methods by organic growers has only received limited attention from researchers in Australia and overseas and an understanding of farmers' perceptions about weed management have not been explored in great detail. In addition, there has been almost no research on the agronomic and economic effectiveness of the various weed control methods used by organic growers, although several studies from overseas have reported findings based on comparative trials of different weeding methods in vegetable production, including some that present an economic evaluation of the methods tested.

Given the importance of successful weed management to organic growers and the current lack of readily available information about organic weed management (OWM) in Australia, collecting such information from the knowledge base of current growers was considered to be an important task. A mail survey of herb and vegetable organic growers in Australia was conducted regarding their attitudes to weeds and the strategies used for managing weeds. The aims of the survey were:

* to determine the range of weeding methods used by organic herb and vegetable growers in Australia,
* to determine the attitudes of those growers towards weeds,
* to characterise the types of farms and farmers surveyed (e.g. by farm size), and
* to identify meaningful relationships between the parameters in order to better understand why growers use the weed control methods they do.

A series of field experiments were also designed and conducted, based on the findings of the survey and the published literature on non-chemical weed management. The objectives of the field trials were to assess the relative performance of several commonly used weed control treatments in terms of weed growth, crop growth and treatment cost for two crops with differing growth patterns – the salad vegetable lettuce and the medicinal herb echinacea.

2. Organic weed management survey

2.1 Introduction

2.1.1 Context of the survey

The demand for relevant and practical information about organic farming practices is likely to become greater as more growers enter the industry (Hudson 1996), presumably with little or no experience in commercial organic production. However, numerous reports in Australia (Dumaresq 1997, Penfold 1997, Simmons and Newman 2000) and overseas (Groeneveld *et al.* 1997, FAO 1999, Rahman 1999, Walz 1999) state that institutional organic research and extension is poorly developed, with relevant information difficult to obtain. Organic farmers have been reluctant to use traditional information sources such as government agencies and commercial agronomists for a range of reasons such as unavailability of appropriate information and ideological conflict (Anderson 1990, Walz 1999). Instead, information has often been sought from selected sources overseas (Steiner 1974, Balfour 1975, Fukuoka 1978, Coleman 1989).

Knowledge about organic agriculture in Australia exists, although it is not always readily available to newer organic growers. Organic farmers have been managing commercially successful farms in Australia for at least two decades and longer overseas, often without institutional support. These experienced farmers have individually and collectively, through a network of certification organisations and other growers' groups, developed a pool of knowledge about many aspects of organic production (Derrick 1997, Wynen 1998, FAO 1999). To gain a better understanding of organic production methods, communication with those who already have expertise is advisable (Wynen 1998)

Weed management is widely acknowledged as a major constraint in organic agriculture. The lack of relevant, accessible information and concerns about the impact of weeds on production have highlighted the need for further research and extension of organic weed management (OWM) practices. Experimentation (Bond *et al.* 1998a, Melander 1998b, Rasmussen 1998, Baerveldt and Ascard 1999) and reviews of existing literature (Ascard 1990, Marshall 1992, Köpke 1999) have been used for this purpose.

Another technique for obtaining information about organic production methods is the use of surveys to capture the experiences and ideas of current growers. Several surveys of organic growers have been carried out overseas, especially in the USA, but also in Europe. These surveys consisted of both mail surveys (Table 2.1) and interviews (Peacock 1990, Brophy *et al.* 1991, Ridgely and Van Horn 1994, Lockeretz 1995, Lockeretz 1997, Burton *et al.* 1998, Liebig and Doran 1999, Kozower 2000, Nilsson *et al.* 2000). A smaller number of organic grower surveys have been reported in Australia including mail surveys (Table 2.1) and interviews (Wynen 1988, Derrick 1992, Moxham 1992).

Some of these surveys refer to the issue of weed management, however, only the reports by Burnett (2001) and Walz (1999) specifically seek information about OWM methods and present quantitative data about the weed control methods used. The survey of Australian organic broadacre growers by Burnett (2001) has only been published in a rudimentary form in industry publications with very limited data. The report by Walz (1999) presents data from a survey of over 1,000 organic growers in the USA. In addition to reporting that weeds are the most important concern or research issue for organic growers, Walz also provides information about the most commonly reported weeds and the most frequently used methods for controlling weeds organically.

A range of surveys of conventional growers have been published, including several focused on weeds and weed management (Table 2.1). Herbicides are the predominant method of weed control reported, although a number also refer to other weed management options such as grazing, tillage, timing of sowing, crop rotations, biological control, hand weeding and enhancing crop competitiveness (Martin *et al.* 1988, Sindel and Michael 1988, Jones *et al.* 2000). One report, based on interviews with graziers, states that respondents "considered they did not have suitable alternatives" to the continual use of the same herbicide (Ayres and Kemp 1998). Many of these reports provide information about growers attitudes to weeds and the methods they use to manage them, with herbicides predominating. Several authors suggest that weed problems are not improving or may be worsening (Lees and Reeve 1994, Sindel 1996, Ayres and Kemp 1998, Jones *et al.* 2000). This general lack of success in longer-term weed control may be related to the observation that weeds are merely suppressed sufficiently to prevent crop yield loss, but weed populations are not depleted over time (Medd 1997).

Table 2.1 Summary of response rates for mail surveys related to weed management and/or organic practices identified in the literature. The distribution method "inserts" refers to the practice of inserting survey materials in newsletters or similar and mailing to all persons or groups on the newsletter mailing list.

Response rate (%)	Type of farming system	Country in which survey conducted	Distribution method	Reference
100	conventional	Australia	direct contact	(Dellow and Seaman 1987)
80	organic	Australia	mail	(Rickson *et al.* 1997)
74	conventional	Australia	mail	(Sindel and Michael 1988)
70	low-input	USA	mail	(Anderson 1990)
70	conventional	USA	mail?	(Fernandez-Cornejo *et al.* 1998)
65	conventional	USA	mail	(Stoller *et al.* 1993)
63	conventional	Australia	mail	(Johnson 2000)
60	conventional	Australia	mail	(Rickson *et al.* 1997)
57	organic	United Kingdom	mail	(Beveridge and Naylor 1999)
53	conventional	USA	mail	(Anderson 1990)
53	organic	USA	mail	(Duram 1999)
51	conventional	Australia	mail	(Trotter and Sindel 1999)
< 50?	organic	Australia	insert	(Simmons and Newman 2000)
48	conventional	Australia	mail	(Sindel 1996)
46	organic	Australia	mail	(Hudson 1996)
46	organic	New Zealand	mail?	(Rahman 1999)
43 (56/30)	**organic**	**Australia**	**mail/insert**	**#**
41	organic	Austria	mail	(Eder and Kirner 2000)
40	organic	Australia	mail	(Anon 2000)
35	mixed	USA	mail	(Stivers-Young and Tucker 1999)
27	organic	USA	mail	(OFRF 1995)
26	conventional	Australia	mail	(Martin *et al.* 1988)
26	organic	USA	mail	(Walz 1999)
23	organic	Australia	mail	(Burnett 2001, V. Burnett pers. comm..)
20?	organic	USA	mail?	(Fernandez-Cornejo *et al.* 1998)
20	organic	USA	mail	(OFRF 1993)
10	conventional	Australia	insert	(Jones *et al.* 2000)
1	organic	Australia	insert	(Geno and Geno 2001)
?	mixed	Australia	mail	(Conacher and Conacher 1982)

The item in bold typeface refers to the survey reported in this chapter. The overall response rate is given and the response rates shown in brackets are for mailed and inserted questionnaires respectively.

Given the importance of successful weed management to organic growers and the current lack of readily available information about OWM in Australia, collecting such information from the knowledge base of current growers was considered to be an important task. This chapter describes a mail survey of herb and vegetable organic growers in Australia regarding their attitudes to weeds and the strategies used for managing weeds. The aims of the survey were:

* to determine the range of weeding methods used by organic herb and vegetable growers in Australia,
* to determine the attitudes of those growers towards weeds,
* to characterise the types of farms and farmers surveyed (e.g. by farm size), and

* to identify meaningful relationships between the parameters in order to better understand why growers use the weed control methods they do.

2.1.2 Methodological issues in mail surveys

Mail surveys are a widely used technique for collecting information from a population, or group of people (Paxson 1995). More specific sample surveys are done by mail than any other survey method, although, phone surveys are more common for surveying the general public for marketing and social research. Some of the reasons for this are the considerably lower cost, the simplicity with which they can be carried out (Dillman 1991) and the advent of new information technologies that enable ready access to mailing lists and word processing programs (Axford *et al.* 1997).

Despite the apparent ease of conducting surveys, there are numerous difficulties that may be encountered in designing and conducting a survey, some which may not become apparent until the survey responses have been returned and analysed (Foddy 1995, Rea and Parker 1997, Pannell and Pannell 1999). These limitations vary in the extent to which they can be overcome. Important considerations in the design of survey questions include constructing intelligible, relevant and unambiguous questions; avoiding contextual influences by logical sequencing of questions, avoiding (or providing) clues to the desired type of response; providing sufficient options in closed or limited-choice questions; and thoroughly testing drafted questionnaires in one or more pilot studies and refining, adding or removing questions as necessary prior to distributing the final survey (Dillman 1978, Foddy 1995, Rea and Parker 1997).

Mail surveys have been criticised for being too general and descriptive (Derrick 1997), and that they yield variable and unreliable responses (Pannell and Pannell 1999). While those criticisms are often valid, careful survey design and implementation can improve the quality of the data, and, in the context of little or no existing information on a particular topic, a mail survey may be the most cost effective method of gathering information from a large and widely dispersed target population. Phone surveys or focus groups may improve the response rate and reduce measurement error, but the time and cost required to sample in that way are considerably greater (Pannell and Pannell 1999).

Four important sources of error in surveying are described by Dillman (1991). These are non-response error, non-coverage error, measurement error and sampling error. They are now discussed individually.

Non-response error

Non-response error, when some members of the sample population do not respond, is the most common source of error to receive attention from researchers (Dillman 1991), because the response rate is generally inversely proportional to non-response error, and a higher response rate usually means that the results are more representative of the whole target population. Many techniques have been devised to increase response rate including effective cover letters, personalisation, assurances of confidentiality, incentives (e.g. offering a prize), pleasant typographic and graphic design standards, printing the questionnaire on coloured paper, prior notification, reply-paid envelopes, follow-ups (i.e. subsequent mail-outs of the survey materials to survey recipients who had not responded within a set period, usually 4-6 weeks), brevity, minimal complex questions and avoiding sensitive or confidential questions (Hox *et al.* 1984, Dillman 1991, Dillman *et al.* 1993, Paxson 1995, Dillman *et al.* 1996, Maynard 1996, Hare *et al.* 1998). Research on the effects of separate techniques on response rates are contradictory and inconsistent, apart from follow-ups and financial incentives (Dillman 1991).

Using Dillman's (1978) Total Design Method, which systematically incorporates most of the survey design features listed above, response rates typically reach 50-70% for general public surveys, and 60-80% for more homogenous groups where low education is not a characteristic of the population (Dillman 1991). Other researchers suggest that expected response rates are more likely to be in the order of 35-50% (Jones *et al.* 2000) or even 30% or less (Pannell and Pannell 1999). A summary of response rates for mail surveys of primary producers identified in the literature is given in Table 2.1, with the response rate for the OWM survey, reported in this chapter, shown in bold typeface.

In general, surveys in Table 2.1 yielding a response rate greater than 50% used follow-ups (Sindel and Michael 1988, Anderson 1990, Rickson *et al.* 1997, Trotter and Sindel 1999) or had small sample size (< 100 responses) with a narrowly targeted population (Duram 1999, Johnson 2000). Low yielding surveys generally did not use follow-ups adequately or at all, targeted geographically dispersed populations, were distributed by inserts rather than direct mail-out or were lengthy and complex. Response rates for surveys targeted at organic growers tend to be lower than surveys targeted at conventional growers. This may be related to the skill and experience of researchers conducting the surveys, the diversity of the target populations, availability and ease of access to well defined subsets of the primary industry sector and differences in the willingness of survey recipients to co-operate with institutional researchers.

Non-response bias may be evaluated by comparing responses between respondents to a mail survey and non-respondents contacted later by phone, or by assessing differences between early and late responders, assuming that late responders are not dissimilar to non-respondents (Rowan and White 1994, Anderson *et al.* 1998).

Non-coverage error

Non-coverage error, is the exclusion of members of the target population from the sampling (Dillman 1991). Walz (1999) reports that her survey was targeted at certified organic growers and that by utilizing the mailing lists of certification organisations in the USA, 90% of the country's organic growers were included in the sampling frame. She also notes that the organisations varied in the access they provided to their membership lists, including some which provided entire lists, some providing partial lists and others which did not want to participate at all. Anecdotal reports by Australian researchers have confirmed this variability in access to Australian certification organisations.

Measurement error

Measurement error is the discrepancy between the observed variable and the corresponding response. Respondents are unable or unwilling to provide accurate answers, commonly due to poor question design and/or poor survey implementation (Dillman 1991). Errors of this type may arise in a range of situations including when respondents interpret words or phrases differently, guesses or estimates are required, previous questions influence later answers, respondents provide answers which may please or impress the researchers but which aren't necessarily true, or they contrive their responses to sensitive questions (Foddy 1995). Weed recognition is relevant to this survey, and other researchers have reported that accurate weed identification by respondents was problematic (Trotter and Sindel 1999). Sindel and Michael (1988), however, reported that only a very small number of respondents to their survey of conventional farmers regarding fireweed (*Senecio madagascariensis*) had trouble recognizing the weed, and those respondents farmed in a region in which the weed was not common.

In the primary production sector, the individual experiences of farmers are often quite varied (Crosby *et al.* 1993) and strongly differing mindsets may polarise responses (Howden *et al.* 1998). Differences in response may be due to demographic and situational factors such as age, gender, education, farming experience, type of farming system used and debt:equity ratio (Black and Reeve 1996). These relationships between response variables were explored using a range of statistical methods including *t*-tests (Rowan and White 1994, Lockeretz 1997), Chi-square tests (Rowan and White 1994, Lockeretz 1997), linear regression (Rowan and White 1994, Hayman and Alston 1999), logistic regression (Anderson 1990, Lacey *et al.* 1993), cluster analysis (Anderson 1990, Cox *et al.* 1993, Lees and Reeve 1994) and principal component analysis (Black and Reeve 1996). Strategies for minimising error in the data entry process, such as reviewing the survey responses for accuracy and during and after data entry, have also been reported (Rowan and White 1994, Walz 1999).

Sampling error
Sampling error occurs as a result of heterogeneity amongst the surveyed population (Dillman 1991) or by the use of an incorrect sampling frame (Stopher and Meyburg 1979). In general the larger the sample size, the smaller the sampling error (Walz 1999). Sampling error is similar to random error in an agronomic field trial and it cannot usually be completely eliminated. The variation that exists between the sample and the whole population can be statistically estimated using confidence intervals (Rea and Parker 1997).

2.2 Methods

2.2.1 Survey design

The sample population for the survey was drawn from the membership lists of three of the certifying organisations operating in Australia, the Biological Farmers of Australia (BFA), the National Association for Sustainable Agriculture, Australia (NASAA) and the Organic Herb Growers of Australia (OHGA). All other certifying organisations were invited to participate but declined.

Given the focus on herb and vegetable production in the research project generally, the survey was targeted at growers of those commodities. BFA provided a list herb and vegetable growers from their membership database, and OHGA membership was almost entirely based on herb and vegetable growers (D. Andrews. pers. comm.). However, NASAA was only able to provide a limited list of general members willing to respond to surveys (R. Dyke, pers. comm.). A small number of other organic growers also returned questionnaires after becoming aware of the survey through colleagues, the media and the internet. A summary of the population sampling criteria, distribution method and number of surveys sent to growers is presented in Table 2.2.

Table 2.2 Summary of the population sampling criteria, distribution methods and number of surveys sent to growers.

Organisations	Sampling criteria	Distribution method	Surveys sent
BFA	vegetable or herb grower	direct mail-out with follow-up	129
NASAA	subset of “interested growers”	direct mail-out with follow-up	212
OHGA	all newsletter recipients	newsletter inclusion	400
Others	self-selected (e.g. media, internet)	direct mail-out upon request	21
Total			762

A draft questionnaire and cover letter were prepared and subjected to an initial evaluation study to assess relevance, ambiguity, comprehensiveness and layout. This pilot study sought comments from ten people directly involved with production, research and extension in the organic community, and two academic researchers with experience in the design and conduct of farmer surveys. Feedback from the reviewers was incorporated into a final version of the questionnaire and cover letter. The survey sought general information about the farming enterprise as well as details about attitudes to weeds and strategies used to manage weeds. A combination of numerical, open-ended and scaled-choice responses was used (Table 2.3). The cover letter, printed on official University stationery, described the overall project, the purpose of the survey and emphasised that the results would be confidential.

The questionnaire was distributed with the cover letter, a reply-paid return envelope and an optional form for people interested in receiving information about the results. As an incentive to reply, a prize of a one-year subscription to a popular national sustainable agriculture newspaper was offered. The survey was announced in the newsletters of all participating certification organisations and in other industry publications as the surveys were being distributed. Copies of the cover letter and questionnaire are provided in Appendix 3.

The survey was either mailed directly to BFA and NASAA growers on 28/9/98 or included in a newsletter posted to OHGA members by the certification organisation (19/10/98). A follow-up mail-out was sent after six weeks (9/11/98) to BFA and NASAA members who had not responded to the first mail-out. The materials sent in the follow-up were the same as the first mail-out, although the cover letter was slightly modified to explain the reason for a second mail-out and to further encourage recipients to complete and return the questionnaire. The survey process is summarised in Figure A3.1 in Appendix 3.

2.2.2 Data processing

The raw data in the survey responses were entered into a relational database program (Microsoft® Access 2000). All variables were checked for errors by plotting for outliers and by selecting a random sample of 50 questionnaires (15% of returned surveys) and confirming accurate data entry. A range of data editing operations were also carried out to standardise the variables, such as combining “acres” and “hectares” into “farm size”. A list of questions presented in the survey questionnaire and variables derived from those questions is given in Table 2.3.

Two approaches were used to present the breadth and complexity of information reported in the open-ended questions about weed management strategies. The first quantitative approach was to prepare a matrix of growers and reported weeding methods, where each cell in the table had a "yes" or "no" in it. This matrix contained responses for the 42 categories of weeding methods that were identified. These methods were reclassified into 15 categories that were more consistent with the scaled-choice questions to enable a comparison of the two question types and also to help satisfy the statistical requirements of the Chi-square test regarding adequate numbers of observations (Rea and Parker 1997).

The second technique for representing the open-ended questions was qualitative. A selection of salient quotes from the surveys is presented, conveying information about attitudes to weeds and how specific methods were used. The following information is given at the end of each quote to provide a general idea of the type of grower making each comment: main type of crop(s) grown (i.e. herb and/or vegetable), number of years experience with organic production and State or Territory in which the farm is located.

Matrices were also constructed for the open-ended questions about crops grown and weeds encountered to facilitate a quantitative analysis. These matrices contained fields such as reported crop or weed name, botanical classification (family, genus, species), growth habit and perenniality. Botanical names were inferred from common names by consulting a number of reference books on weeds (Auld and Medd 1987, Hussey *et al.* 1997, Lazarides *et al.* 1997, TPNP 1999 2041) and crops (Hartmann *et al.* 1988, TPNP 1999, CNCPP 2001).

The scaled-choice questions about weed management gave respondents the opportunity to indicate the regularity with which they used a number of listed weeding methods. A five-point scale was used, ranging from one = "never" to five = "always". Those responses were processed by classifying the listed weeding methods, plus the methods reported in the "other" section, into 15 categories. The perceived success and expense of those methods were also measured on a five-point scale, ranging from "very poor" to "very good" and "not expensive" to "very expensive" respectively. The scaled-choice responses were averaged for all respondents and the methods were ranked in descending order by regularity of usage.

Table 2.3 Summary of questions presented in the survey questionnaire and derived variables used in the analyses.

	Survey questions#	Derived variables
Farm and farmer characteristics	State/Territory; town; postcode; certification status; organic farming experience; farm size; crops grown[1]; weeds encountered[1]; time spent weeding; cost of weeding	Longitude; latitude; days (to return survey); follow-up (returned in response to follow-up request); certification organisation; crop matrix (common name, botanical name, family, herb/vegetable type, growth habit); weed matrix (common name, botanical name, family, perenniality, growth habit, broadleaf/grass type)
Attitudes to weeds	Are weeds a problem?; reasons for problem (five weed impacts listed plus "others" section provided) [2]	Reasons included the weed impacts contamination, difficult/time consuming, harbour pest/disease, interference and competition/reduced yield
Weed management	Strategies used[1]; regularity[3], success[3] & expense[3] of methods used (17 listed plus "other" section provided)	42-column matrix@ of OWM strategies (with yes/no response for each grower); 24-column matrix@ of OWM methods (with "others" reclassified) for each of regularity, success & expense; six-column matrix of tillage implements (with yes/no response for each respondent)

Survey question types: [1]open ended, [2]scaled (0,1,2 or 3), [3]scaled (1,2,3,4 or 5)
@ These matrices were reduced to 15 categories for the analyses

2.2.3 Analysis

Statistical analyses were carried out using S-Plus® 2000 (MathSoft 1999a, MathSoft 1999b, MathSoft 1999c). The results for each variable were summarised using means, standard errors, medians, frequency distributions and proportions. The median provides a more robust summary than mean for non-normally distributed data (Venables and Ripley 1999), such as those encountered in the survey results presented in this chapter. The relationships between variables were analysed using the Generalised Linear Model (GLM) for logistic regression of binomial response variables and log-linear (Poisson) regression of multinomial response variables.

The GLM output contained an Analysis of Deviance table with a Chi-square test for significance of the explanatory variables. The *P*-value is presented in the results section to indicate the level of significance, with a value of 0.05 or less regarded as significant. A goodness of fit test was conducted to ensure that the data conformed to the assumed underlying distribution by comparing the residual deviance with the underlying Chi-square distribution. When the goodness of fit test reported a significant value, i.e. ≤ 0.05, the model was considered unsuitable and the results from the GLM were not used.

Linear regressions were performed using the linear model function in S-Plus. This function calculates several values of interest including an r^2 value, a slope coefficient and *P*-values. Diagnostic plots were generated and assessed to confirm that the data fulfilled the assumptions of the model, particularly homogenous variance and normality.

A non-parametric test, the Pearson's Chi-square test with Yates' continuity correction, was also used in S-Plus to detect differences between categories of respondents. The validity of this test depends heavily on the assumption that the expected cell counts are at least moderately large; a minimum size of 5 is the usual rule of thumb (Beveridge and Naylor 1999, MathSoft 1999c). S-Plus generates an error warning when this condition has not been met. Therefore, tests in which that message appeared were not used in the analyses presented. That limitation prevented general use of this test for analysing the survey data.

The impact of bias due to non-response error was evaluated indirectly using three methods, i.e. by comparing responses with time taken to respond, by comparing pre- and post-follow-up responses and by referring to other surveys or published materials with similar types of data (I. Reeve, pers. comm.). Firstly, the number of days taken to return the survey was compared with several response variables using one-way ANOVA in S-Plus and, when significant differences were detected, orthogonal contrasts were used to separate the means (MathSoft 1999a). Variables thought to be prone to differences in response over time were selected. For example, a farmer reporting a high level of concern about weeds may be motivated to reply quickly, whereas a less concerned (more skilled?) grower may delay replying or not bother replying at all. The suitability of these statistical methods were confirmed using diagnostic plots (e.g. residual-fitted plots, normal quantile plots). Secondly, pre- and post-follow-up responses for growers affiliated with BFA and NASAA were compared using the Chi-square test in GLM. Thirdly, reference is made to published research and industry literature to compare the results presented here with those obtained in other similar surveys of primary producers such as Walz (1999) and the Australian Bureau of Statistics (2000).

The spatial analysis of respondents was carried out using the "buffer" function in the geographic information systems program ArcView 3.1®. This function creates rings around, or inside, geographic features at a specified distance from the edge of those features. Buffers were created at 25 km intervals inland from the coast of Australia and the number of respondents located within each ring was counted.

A number of multivariate analyses were attempted using cluster analysis, principal component analysis and classical multi-dimensional scaling (Venables and Ripley 1999) with the intention of exploring multivariate relationships between weeding methods reported and other factors measured in the survey. However, none of the analyses yielded significant findings. Instead, a series of bivariate analyses of weeding methods (response variable) in relation to 14 farm and farmer characteristics (explanatory variables, see Table 2.4) was carried out using the Chi-square test in GLM.

Table 2.4 List of explanatory variables used in the bivariate analyses.

Type of variable	Explanatory variables
Geographic	Latitude
	Longitude
Demographic	Organic farming experience
	Farm size
	Certification status
Attitude to weeds	Are weeds a problem?
	Benefits of weeds cited by respondent

This survey is referred to as the "OWM survey" to differentiate it from other surveys mentioned in the following discussion.

2.3 Results and discussion

2.3.1 Response rate

The initial number of responses to the survey was 305 (40%) and the follow-up mail-out yielded a further 21 responses. The final number of returned questionnaires was 326 (43%), although some respondents did not complete all the questions, or provided unusable responses to some questions.

The proportion of questionnaires returned is a key indicator of survey success (Paxson 1995). Primary producer surveys in Australia have yielded a wide range of response rates (Table 2.1), influenced by several factors including relevance or importance of survey topic, characteristics of the sample population, sampling method, and survey design and implementation. Surveys using newsletter inserts to distribute questionnaires were likely to receive lower response rates (≤ 30%) (Hayman and Alston 1999, Jones *et al.* 2000, Geno and Geno 2001), although Simmons and Newman (2000) report an imprecise response rate of "less than 50%".

The follow-up procedures recommended in the Total Design Method (Dillman 1978) were not fully implemented in this survey due to the inability to distinguish non-respondents from respondents in the OHGA sample, and the low number of returns elicited by the first follow-up of BFA and NASAA growers, i.e. 6% of BFA/NASAA survey recipients. Increased pressure to respond, such as repeated follow-ups, may reduce the quality of the response, thus reducing non-response error at the expense of measurement error (Dillman 1991, Paxson 1995). A small number of hostile comments in response to the follow-up (e.g. "the proliferation of broadacre monocultures started in universities") indicated that organic growers were unlikely to respond in much greater numbers. Negative or cynical comments about government agencies and universities have been reported in other surveys of organic growers {Duram, 1999 #1928; Burton, 1998 #1575; Walz 1999, V. Burnett, pers. comm.).

Three quarters of all respondents reported herb and/or vegetable production as the dominant cropping system, providing a sample size of 219. In a survey undertaken in early 1995, Hudson (1996) received 146 responses from organic herb and vegetable growers, plus 13 mixed enterprises producing at least some herbs or vegetables. That group represented almost 40% of all responding growers. A majority of herb and vegetable growers reported full organic certification status (79%), a further 16% were either seeking certification or currently in conversion to full organic status, and the remainder were not certified {Hudson, 1996 #1220}.

Table 2.5 shows the percentage of respondents by State or Territory in which their farm was located and the certification organisation with which they were affiliated. The questionnaires were returned from all States and Territories of Australia except the Northern Territory. Most of these growers (84%) were from the eastern mainland States of Victoria, New South Wales and Queensland and the Australian Capital Territory, with about 5% each from Tasmania, South Australia and Western Australia.

Table 2.5 Percentage of herb and vegetable growers that returned questionnaires, categorised by the State in which the farm was located and the grower's certification organisation (n = 219).

Organisation	NSW-ACT	VIC	QLD	TAS	SA	WA	Organisation total
OHGA	21.9	10.5	6.4	2.7	0.5		42.0
NASAA	11.9	8.2	2.7	2.3	1.8	2.3	29.2
BFA	8.7	4.5	6.4	0.9	3.2	2.3	26.0
Other	1.4	0.9	0.5				2.8
State total	43.9	24.1	16.0	5.9	5.5	4.6	100.0

BFA members had a response rate of 55%, NASAA members 57%, and OHGA only 30%. There was a significant difference (GLM Chi-square test, $P = 0.006$) in the response rates between

BFA/NASAA members and OHGA members, which was most likely due to the different methods of distributing the surveys, including the lack of personalisation with newsletter inserts (Dillman 1978). No duplicate questionnaires were received from people with dual membership.

A large proportion of responses were sent from properties in coastal Queensland and NSW (40%), central Victoria (5%) and Gippsland (4%) (Figure 2.1). Loose regional concentrations of organic farms based on similar production types have been reported previously, such as wheat in western Victoria and southern Western Australia, milk in central Victoria and a range of horticultural operations around major urban centres and along the Murray (Hudson 1996, Dumaresq and Greene 1997). A strong tendency was noted for farms to be located near the coast. About 42% of properties were within 25 km of the coast, and two-thirds were within 50 km of the coast. Less than 10% of the farms were located more than 200 km from the coast.

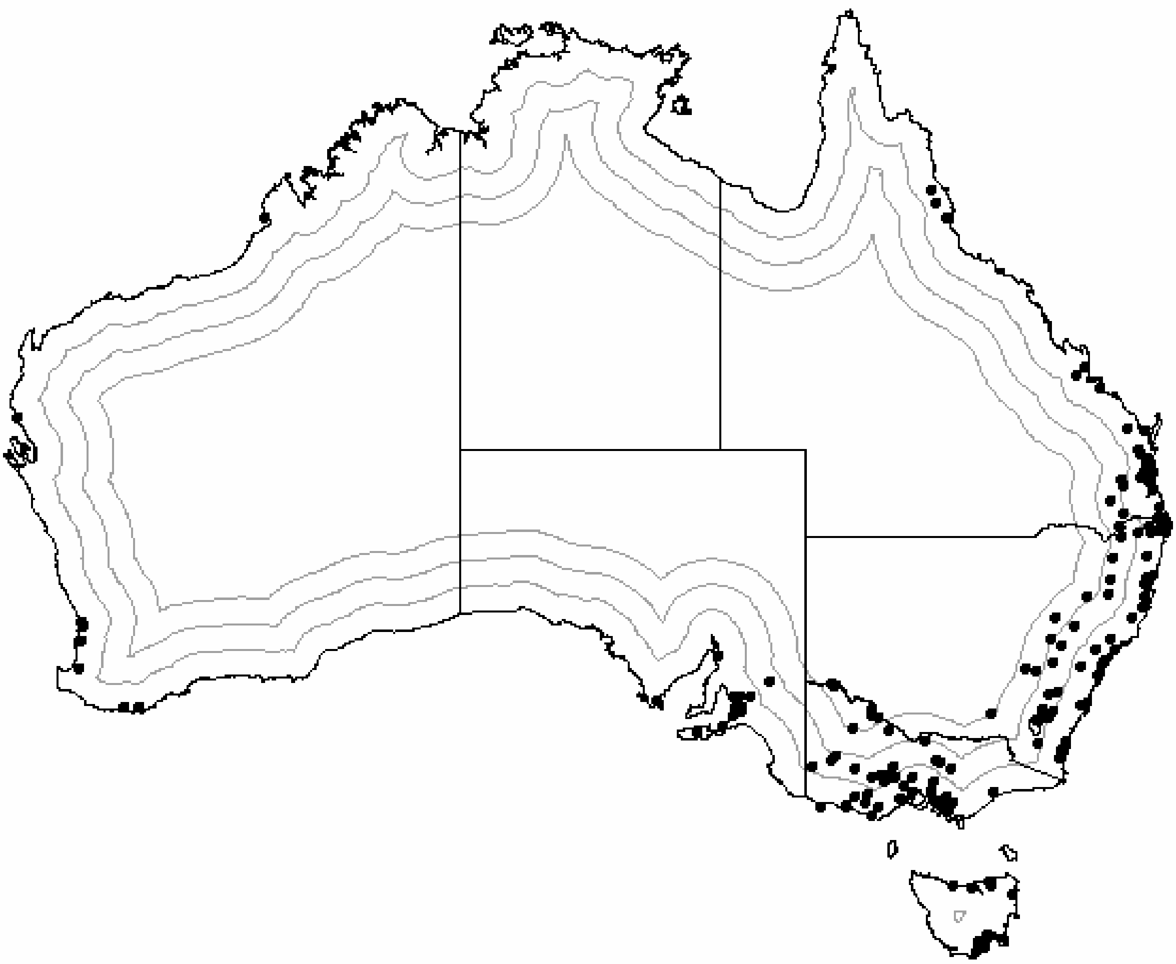


Figure 2.1 Geographic distribution of the survey respondents in Australia. The black dots represent the location of the respondents' properties and the grey lines indicate the distance inland from the coast in 100 km intervals

Non-response error

The results of this survey may be biased against growers who were not very concerned about weeds and who may be very skilled in weed management but were not motivated to contribute to the survey. Many published surveys of primary producers do not report an analysis of non-response bias. However, Hayman and Alston (1999) acknowledged possible non-response bias in their survey of nitrogen usage by conventional farmers in the grains belt of northern NSW, stating that farmers using no or low rates of nitrogen would be less likely to reply to their survey. Reeve (2001) provides a comprehensive analysis of non-response bias in his survey of farmers throughout Australia.

An indirect evaluation of non-response bias was conducted by comparing the number of days taken to return the questionnaire with the variables listed in Table 2.4. An analysis of deviance using the Chi-square test in GLM detected no significant differences ($P > 0.05$) for all the variables. A comparison of the pre-follow-up responses and post-follow-up responses of growers who received questionnaires directly (i.e. BFA and NASAA members) identified no significant differences for all variables analysed ($P > 0.15$). Certification organisation membership was also compared with time to respond and was found to be highly significant ($p < 0.01$). Orthogonal contrasts confirmed that BFA and NASAA members returned their questionnaires sooner than OHGA members or others ($P < 0.01$) as would be expected due to the different distribution methods. Differences within those pairs were not significant ($P = 0.61$ and 0.67 respectively), implying that time to respond did not vary within a given distribution method.

It may be concluded that there was little evidence for differences in responses between early and late responders, and between pre- and post-follow-up responders, and that, therefore, the responses were representative of the target population. A direct evaluation of non-respondent's attitudes, by telephone interview for example, was not undertaken.

Further evaluation of the validity of specific results by comparison with other surveys is presented in the sections below. The match between findings on farm size, years of organic farming experience, crops grown and weed types reported was good. The data for weeding methods were less consistent because the classification of weeding methods and the target populations differ between surveys.

Non-coverage error

The survey's sampled population would ideally include all possible organic herb and vegetable growers in Australia, however some groups of growers were not able to be included. Non-coverage error may have occurred in response to the limited access to the NASAA membership list, in which case non-sampled NASAA members would have provided different responses to the NASAA members who were included in the sampled group. A comparison of the responses of BFA and NASAA members was made using the same parameters and procedure used for testing non-response error. These comparisons showed no significant differences for all variables analysed ($P > 0.41$), despite the more accurately targeted sampling method used for BFA. It was assumed, therefore, that sampled NASAA members were no less representative than respondents from BFA.

Another possible source of non-coverage bias was the omission of members of a bio-dynamic certification organisation that did not participate. These growers may have distinct weed management attitudes and practices compared with regular organic growers. However, some other bio-dynamic growers were also members of the participating certification organisations and were therefore included in the sampled group. Specific reference was made by some survey respondents to their bio-dynamic practices. However, these practices may be under-represented. In future surveys, a yes-or-no question about whether growers practise bio-dynamic agriculture could provide a more reliable means of differentiating such growers and, hence, their particular methods of production.

A third group that was not covered by the survey was organic growers who were not affiliated with an Australian certification organisation. Numerous local organic grower groups exist in Australia, usually with non-commercial gardeners as members. Some of these people may have considerable experience with OWM that could be useful in commercial situations.

Other sources of error

Several sources of potential measurement error were apparent in this survey. Interpretations of certain questions, especially those relating to money and time spent on weed management, were highly variable and therefore generally unreliable. Several growers noted that the estimate did not include labour whilst others noted that it did. The farmer's own labour may be seen as free, in contrast to payments made for casual labour, mulches or tractor fuel and maintenance. Longer-term management operations (e.g. grazing, crop rotation) may not have clearly quantifiable weed control benefits and may be excluded from calculations (Crosby *et al.* 1993).

Inferring weed scientific names from the common names provided by respondents proved problematic in a number of cases, and the item was either classified only to family (e.g. "thistles" classified as Asteraceae only) or genus (e.g. "clover" classified as *Trifolium* sp.). In a national survey, some error is likely in interpreting locally specific common names for a given weed species, as certain common names can be applied to different weed species. The difficulties faced by respondents in correctly naming weeds has been also reported by Trotter and Sindel (1999). Interpreting and categorising the data provided in the open-ended questions is potentially subjective. Respondents may use terminology differently, especially when referring to tillage implements. In a study of no-till farming in the USA, inconsistencies between a farmer's perceptions and practices were reported for corn growers, but not for soybean and wheat growers (Uri 2000).

Sampling error may have been present given the broad diversity of crops, locations and production systems reported in the survey. Obtaining a perfect representation of the OWM methods used by the target population may be more difficult with such a heterogeneous population. Broader sampling may capture further diversity of principles and practices, however it is probable that the most common attitudes and techniques were well represented in the survey results.

The extent to which these potential errors occurred in the OWM survey is probably impossible to accurately quantify. However, comparisons are made in each section of the results with other published surveys, thereby providing an alternative check that the results were meaningful.

2.3.2 Farm and farmer characteristics

Farm size

The percentage frequency of reported farm sizes is presented in Figure 2.2. The organic herb and vegetable farms reported in the survey were generally small in size relative to conventional growers, but were consistent with farm sizes reported in other surveys of organic growers. A third of the properties were no more than 1 hectare in size, and about 70% were 5 hectares or less. Only 10% of the farms were more than 20 hectares. Apart from two large properties, a 202 hectare potato farm and a 426 hectare mixed vegetables and grains enterprise, farm size peaked at about 60 hectares. The mean farm size, 9.7 hectares, was strongly skewed upwards relative to the median of 2.4 hectares. The mean may give the impression that farms were about 4 times larger than what was reported by the median.

A 1995 mail survey of organic growers reported a mean organic farm size of 219 hectares, but this figure included orchards, broadacre cropping and pastoral enterprises (Hudson 1996). Broadacre and livestock farms made up 22% of the respondents, but 87% of the total reported area farmed. However, the median farm size reported in the OWM survey was very similar to farm sizes reported in several other organic surveys (Anderson 1990, Lockeretz 1995, Fernandez-Cornejo *et al.* 1998).

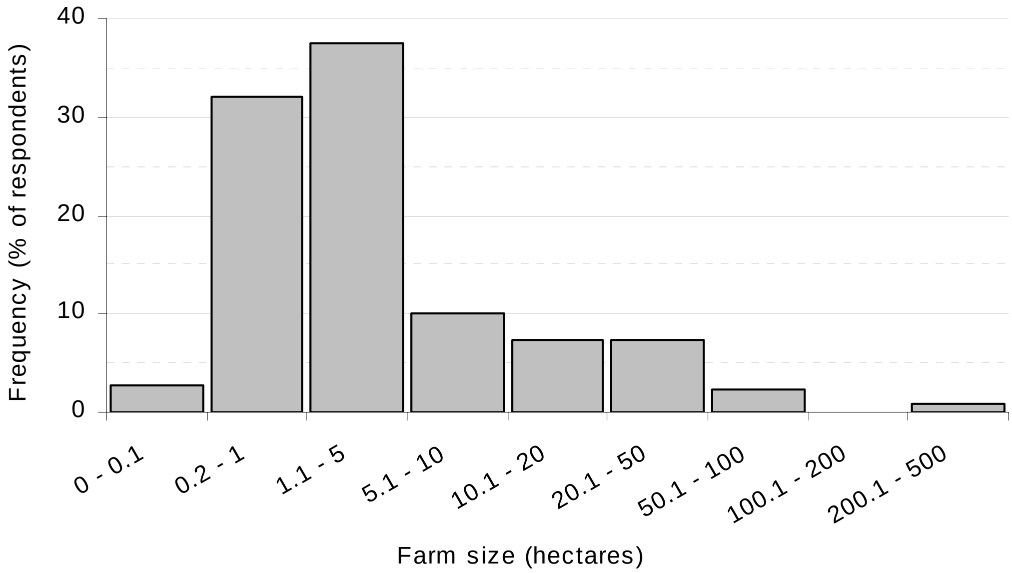


Figure 2.2 Frequency of farm sizes (hectares) reported by organic herb and vegetable growers.

Farm size statistics for vegetable growers across Australia during the same period are shown in Figure 2.3 (ABS 2000). The broad categories in the Australian Bureau of Statistics (ABS) figures mask the distribution of farm sizes for about half of the population. The absence of a separate category in the ABS report for herb production also makes comparison with the OWM survey slightly complicated. However, it is clear that the size of Australian vegetable farms generally was larger than the organic herb and vegetable properties reported in the OWM survey. Almost 50% of the farms in the ABS sample were larger than the largest organic farms. The combined total area farmed organically by OWM survey respondents was 2,124 hectares, which was 1.6% of the total national area of vegetable production of 130,220 hectares (ABS 2000). Given the moderate non-response rate in the OWM survey, it is possible that the proportion of organic growers would be greater if a higher response rate was achieved.

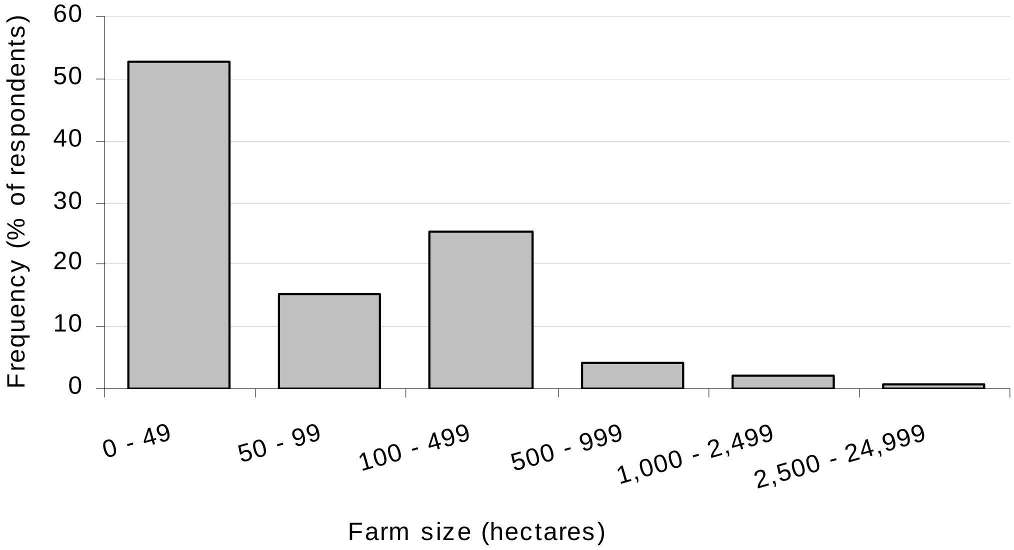


Figure 2.3 Frequency of farm sizes (hectares) reported by vegetable growers throughout Australia (ABS 2000).

Differences in farm sizes between organic and conventional growers have been reported in overseas surveys (Anderson 1990, Lockeretz 1995, Burton *et al.* 1998, Fernandez-Cornejo *et al.* 1998), as shown in Table 2.6. The comparisons by Anderson (1990) and Lockeretz (1995) indicate that organic farms may be at least 4 times smaller than conventional farms.

Table 2.6 Median organic and conventional farm sizes (hectares) reported in mail surveys conducted in the USA.

Median farm size reported (hectares)		
Organic farms	Conventional farms	Reference
4	91	(Anderson 1990)
1.6	20.4	(Lockeretz 1995)
< 4.9 (mean = 20)	> 10 (mean = 40)	(Fernandez-Cornejo *et al.* 1998)

The small organic farm sizes shown in Table 2.6 were consistent with the median farm size in the OWM survey. The small farm sizes may be due to several factors including historically small and variable markets for organic produce (Hudson 1996), the relative inexperience of individual organic growers (see below), and higher labour costs (Hudson 1996, Lockeretz 1997, FAO 1999, Brumfield *et al.* 2000). The higher labour costs were incurred mainly during conversion (Padel and Lampkin 1994) and often because of the needs of weed management (Nilsson *et al.* 2000), however these needs were not necessarily ongoing (Padel and Lampkin 1994).

While many new growers entering the organic sector are likely to do so on smaller acreages, there was evidence that average farm sizes are increasing. A regression analysis using GLM of farming size against farming experience reported in the OWM survey detected a highly significant ($p < 0.001$) increase in farm size as the number of years experience increased. In Australia, the organic industry average has risen from about 150 hectares in 1990 and 230 hectares in 1995 (Hudson 1996), to approximately 4,400 hectares in 2000 (Kinnear 2000). However, several very large cattle grazing operations in NSW and Queensland, comprising about 7 million hectares (Kinnear 2000), are new to the organic sector and they may account for a significant proportion of the rise in average farm size. Average organic farm sizes in Canada and the USA, countries that also have ready access to extensive grazing lands, were 81 and 136 hectares respectively in 2000 (Willer and Yussefi 2001). In the European Union, average organic farm sizes have increased from 20 hectares in 1990, to 24 hectares in 1995 and to 28 hectares in 2000, a 40% increase over the decade.

Lockeretz (1995, 1997) suggests that the relative inexperience of organic farmers may mean that they have not had the time to build up large farming enterprises and that the considerably greater off-farms incomes for organic growers compared with conventional growers reduces the need or time available to run a large farm. In a survey of organic farmers in Colorado, USA, based on a more experienced group of growers (mean = 18 years), Duram (1999) reports that at least half of the respondents were interested in buying or leasing more land. A national organic grower survey in the USA (Walz 1999) found that 56% of respondents planned to increase their acreage under organic production, compared with 49% in a previous survey (OFRF 1995).

Organic farming experience

The percentage frequency of reported organic farming experience is presented in Figure 2.4. The herb and vegetable growers in the survey had generally been farming organically for only a few years and appeared to be relatively inexperienced. A third of the respondents had no more than 4 years experience, and about 70% have 9 years or less. Only 10% of the growers had more than 15 years experience. The mean number of years of experience was 7.8, which was only weakly skewed upwards relative to the median of 6 years. The combined total farming experience of the respondents was 1,702 years.

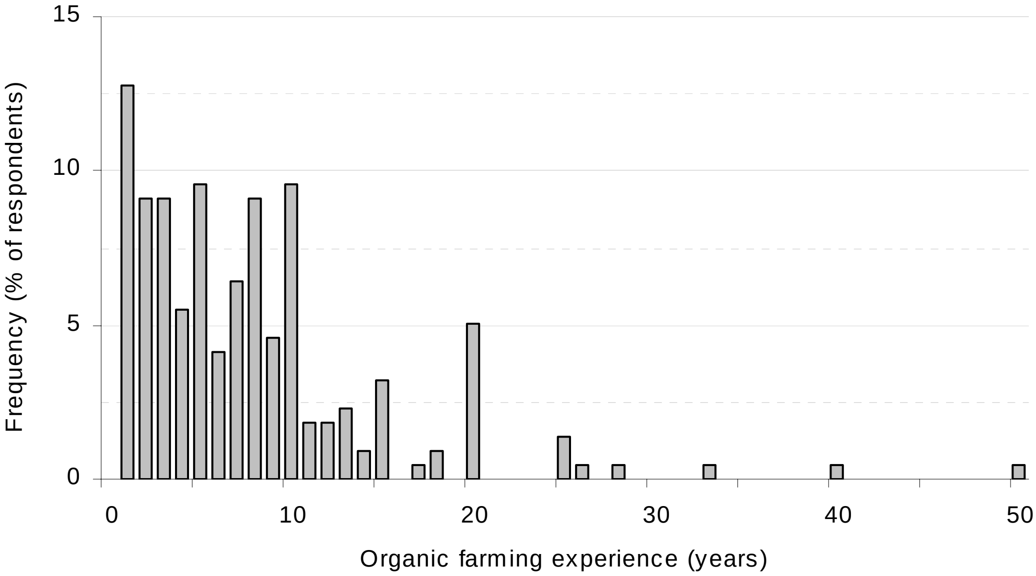


Figure 2.4 Frequency of reported organic farming experience (years).

The level of experience reported in the OWM survey was generally consistent with that reported for organic growers in other published surveys from Australia (Hudson 1996) and the USA (Figure 2.5). Hudson (1996) reported that 44% of respondents had less than five years organic farming experience, and a further 34% had between 5 and 10 years experience. Compared with the results for the three Organic Farming Research Foundation (OFRF) biennial surveys (OFRF 1993, OFRF 1995, Walz 1999), shown in Figure 2.5, the OWM survey sample had more growers in the 1-5 and 5-10 year categories, but less in the other categories, indicating that the Australian sample was slightly less experienced. The findings reported by Fernandez-Cornejo *et al*. (1998) point to higher levels of experience amongst their sample of organic growers, however, this was quite different to the OFRF and OWM findings and may be due to different sampling methods. Fernandez-Cornejo *et al*. (1998) derived their sample from the database of a previously conducted US Department of Agriculture survey rather than directly from organic certification organisations.

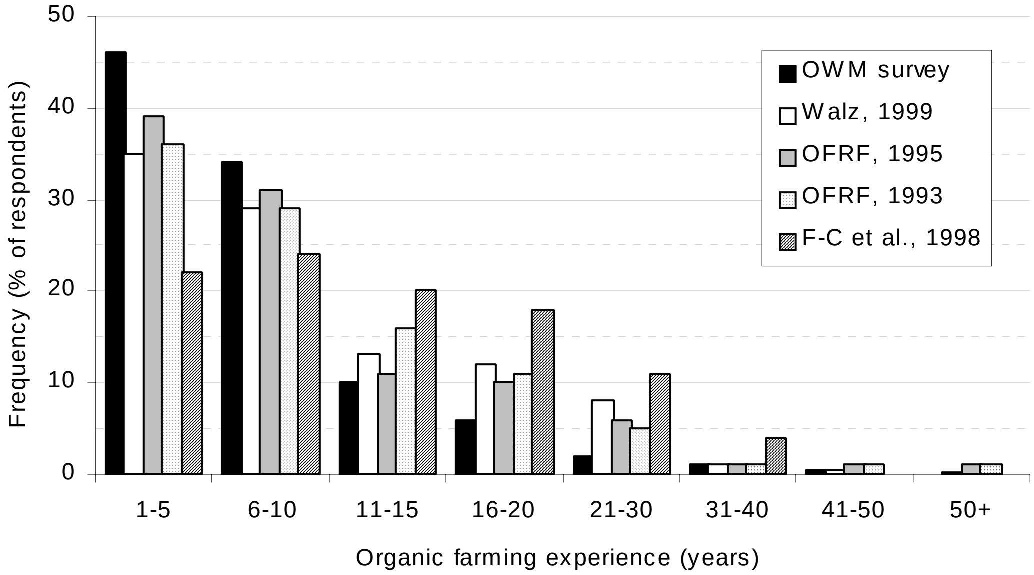


Figure 2.5 Comparison of frequency of reported organic farming experience (years) between the OWM survey and selected US organic grower surveys. Legend: black bars = OWM survey, white bars = OFRF (1993), grey bars = OFRF (1995), dotted bars = Walz (1999) and striped bars = Fernandez-Cornejo *et al*. (1998).

In comparison with conventional growers, organic farmers were less experienced. In the USA, Anderson's (1990) study showed means of 8 years and 22 years for organic and conventional growers respectively, while Lockeretz reported (1995) medians of 5 years and 19 years respectively. In Australia, a mail survey of conventional wheat farmers indicated that 55% of respondents had at least 30 years experience (Hayman and Alston 1999). The report by Lockeretz (1995) also noted that many of the organic farmers were new to farming, rather than converts from conventional farming; they therefore represent a source of new ideas and new activities for rural areas.

Time and cost of weed management

Questions about the time and money spent on weed management were included in the survey. Estimating these values posed a noticeable problem for respondents (e.g. "no idea"), with 22% and 44% unable to estimate time and cost respectively. When estimating the monetary value of weed management, some growers stated whether labour costs were included, while others did not. It was not always clear which farm operations were specifically related to weed management and which were not, and respondents were unlikely to evaluate time and costs using a consistent framework (Crosby *et al.* 1993, Pannell and Pannell 1999).

Growers reported spending between 0 and 6,500 person-hours/hectare/year on weed management, with a median of 270 person-hours/hectare/year and a mean of 600 person-hours/hectare/year. Reported costs ranged from $0 to $39,000/hectare/year, with a median of $400/hectare/year and a mean of about $2,200/hectare/year. The reported values for weed management costs were poorly correlated with farm size ($r^2 < 0.001$), so greater spending was not simply based on a bigger farm. An experienced organic vegetable grower has reported that weed management can cost up to $10,000/hectare for a cropping season (Anon 2001), and other research on herb and vegetable production has found that hand weeding alone can cost from $3,800/hectare (Buntain 1999) to $7,500/hectare (Melander 1998a) over one cropping season. It was assumed that the survey responses to these questions were of limited reliability and, therefore, these figures need to be treated with some caution. Nevertheless, they show that weed control is a significant cost in organic herb and vegetable production.

Crops
Over 130 different commodities or groupings (e.g. "culinary herbs") were reported, from which 115 crops were recognised. The most commonly reported herbs and vegetables are shown in Table 2.7 and respectively. Staple vegetable commodities such as tomatoes (Lycopersicon esculentum), beans (*Phaseolus* spp., *Vicia* spp. *Vigna* spp.), pumpkins (*Cucurbita* spp.), potatoes (*Solanum tuberosum*) and peas (*Pisum sativum*) were commonly grown by respondents, as were several commercially popular culinary herb varieties including garlic (*Allium sativum*), mint (*Mentha* spp.), thyme (*Thymus* spp.) and parsley (*Petroselinum crispum*). Garlic, the most frequently reported herb, was grown on organic farms for indirect uses in addition to commercial sales. Such uses included companion planting for pest management and as an industrial crop for use in the on-farm manufacture of organically approved pesticide. Echinacea (*Echinacea* spp.), lemon balm (*Melissa officinalis*) and chamomile (*Chamomilla recutita*, *Chamaemelum nobile*) were the most widely reported medicinal herbs. Walz (1999) reports that the most common vegetable crops in the OFRF survey conducted in the USA were cucurbits, tomatoes, alliums, brassicas and *Capsicum* species, whereas Fernandez-Cornejo *et al.* (1998) found that their sample of US organic vegetable growers mostly reported tomatoes, sweet corn (*Zea mays* var. *rugosa*), lettuce (Lactuca sativa), carrots (*Daucus carota*) and onions (*Allium cepa*).

Table 2.7 Percentage frequency of herb crops grown by survey respondents (n = 219). The ten most commonly reported herb varieties are shown.

Herb variety	% of respondents
unspecified	34.2
garlic (*Allium sativum*)	12.8
mint (*Mentha* spp.)	11.0
echinacea (*Echinacea* spp.)	10.5
thyme (*Thymus* spp.)	7.3
parsley (*Petroselinum crispum*)	6.4
lemon balm (*Melissa officinalis*)	5.9
chamomile (*Chamomilla recutita*, *Chamaemelum nobile*)	5.5
sage (*Salvia officinalis*)	5.5
basil (*Ocimum basilicum*)	5.0
rosemary (*Rosmarinus officinalis*)	5.0

Data published by the Australian Bureau of Statistics (2000) on the amount of land used for the production of specific vegetables indicate that many of the most commonly grown crops in Australia were similar to frequently grown crops reported in the OWM survey (Table 2.8). Notable exceptions from the list of common vegetables in the OWM survey were carrots and onions (and other alliums), which were ranked 4th and 9th respectively in the ABS report. One respondent observed that "crops like shallots [*Allium cepa*, *Allium fistulosum*] have minimal leaf coverage [and are vulnerable to weeds], but plants like beetroot [*Beta vulgaris*] which have a broad leaf area will not have as many weeds" (vegetable grower, 8 years experience, Queensland). Interestingly, beetroot was ranked highly (7th) in the organic survey but was 18th in the ABS data. It is possible that organic growers tend to grow crops in which weed control is easier. The choice of crop will be influenced by factors including climate, soil, farming experience, market demand and ease of marketing.

Table 2.8 Percentage frequency of vegetable crops grown by survey respondents (n = 219). The ten most commonly reported vegetable varieties are shown. Australian Bureau of Statistics (2000) data on area (hectares) and ranking of national production for each vegetable in 1998 is also presented.

Vegetable variety	% of respondents	National vegetable production in 1998	
		Ranking (by area)	Area (hectares)
unspecified	35.6	-	-
tomato (*Lycopersicon esculentum*)	21.9	2nd	8,023
beans (*Phaseolus* spp., *Vicia* spp. *Vigna* spp.)	12.8	6th	6,623
pumpkin (*Cucurbita* spp.)	12.8	7th	5,929
potato (*Solanum tuberosum*)	11.9	1st	42,558
peas (*Pisum sativum*)	11.0	5th	7,014
lettuce (*Lactuca sativa*)	10.5	8th	5,714
beetroot (*Beta vulgaris*)	9.1	18th	879
sweet corn (*Zea mays* var. *rugosa*)	8.7	10th	5,579
zucchini (*Cucurbita* spp.)	8.7	12th	2,683
cucumber (*Cucumis sativus*)	8.2	17th	1,037

The diversity of commodities grown by respondents was spread widely amongst growers (Figure 2.6). Three quarters of the farmers reported growing between one and five herb and vegetable crops, 17% reported growing 6-10 crops, 5% reported 11-15 crops, and 2% reported growing between 16 and 21 different crops. An earlier OFRF survey showed that a third of USA organic farmers reported growing up to five crops, 19% grew 6-10 crops and also 11-25 crops, 11% grew between 26 and 40 crops and 10% reported at least 40 different crops (OFRF 1993).

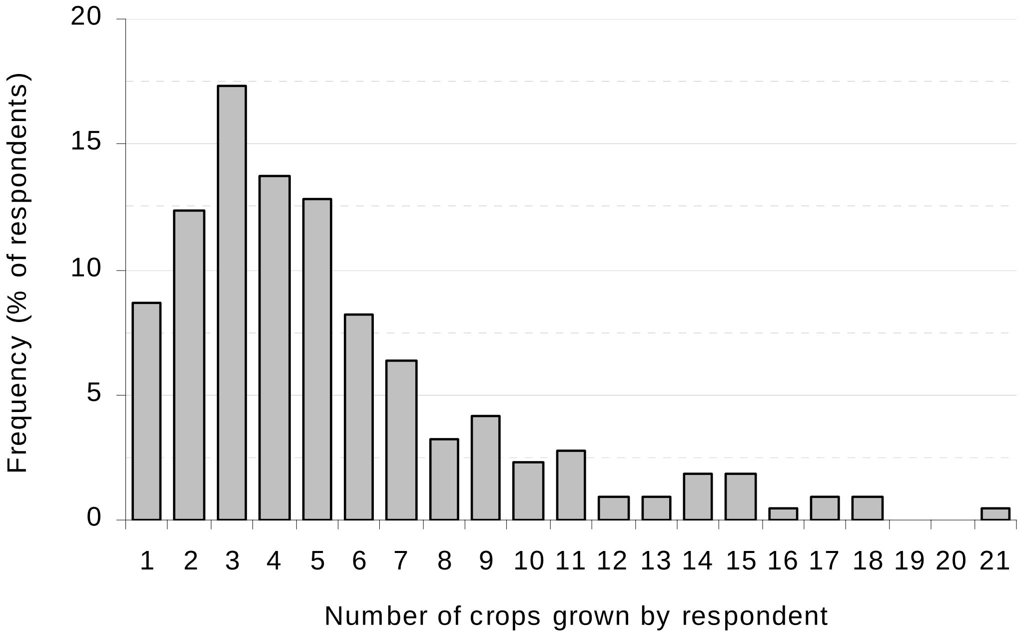


Figure 2.6 Percentage frequency of the reported number of crops grown by respondents.

Several comments were made in the open-ended responses in the OWM survey about the ecological and economic advantages of growing a diverse range of crops at any one time. For example, one grower stated that "growing a number of different crops provides some protection against pests and diseases" and that "this diversity also fits in with the optimum usage of drying facilities, and marketing requirements" (herb grower, 28 years, Tasmania). An FAO report on organic agriculture noted "that the diversification of crops typically found on organic farms, with their various planting and harvesting schedules" may help to even out the demand for labour (FAO 1999). It is probable that conventional herb and vegetable growers also grow several crops during a season, especially herb growers (Miller 1985) and market gardeners (Stivers-Young and Tucker 1999), although no reports quantifying this issue were identified.

Weeds

Common names were invariably cited by respondents rather than botanical names and, in some cases, some interpretation and assumptions have been made to ascertain the specific identity of the weeds. Often general names like "dock" and "clover" were used. Some respondents did not list any weeds (3%) whilst others gave very general information (10%) such as "summer weeds" and "woody weeds", although they may also have listed more precise weed names as well. The diversity of weeds reported included almost 250 species or groups (e.g. "thistles") from 48 families and 156 genera. The most frequently reported weeds are given in Table 2.9. Most of the weeds (90%) were mentioned by no more than 5% of respondents. Conversely, the top five weeds were each reported by 15% or more growers, with couch, capeweed, dock, Kikuyu and sorrel being the most frequent. Three families were predominant: they were Poaceae (30% of all weed instances), Asteraceae (22%) and Polygonaceae (10%). All other families were reported in less than 5% of instances. Four of the five most common weeds (i.e. couch, dock, Kikuyu, sorrel) have persistent underground parts that resist common forms of organic weed control such as cultivation and mulch.

Table 2.9 Percentage frequency of weeds reported by at least 10% of the respondents (n = 219).

Weeds	Family	% of respondents
Couch (*Cynodon dactylon*)	Poaceae	27.4
Capeweed (*Arctotheca calendula*)	Asteraceae	21.5
Dock (*Rumex* and *Acetosa* spp.)	Polygonaceae	17.8
Kikuyu (*Pennisetum clandestinum*)	Poaceae	17.8
Sorrel (*Acetosella vulgaris*)	Polygonaceae	17.8
Thistles (various species)	Asteraceae	16.9
Clover (*Trifolium* spp.)	Fabaceae	15.1
Cobbler's pegs/Farmer's friend (*Bidens pilosa*)	Asteraceae	12.8
Fat hen (*Chenopodium album*)	Chenopodiaceae	11.4
Chickweed (*Stellaria media*)	Caryophyllaceae	10.0
Ryegrass (*Lolium* spp.)	Poaceae	10.0

Aggregating reported weed taxa into more general botanical or functional categories provides another level of analysis. The predominant growth habit of the reported weeds was herbaceous (94%), a small proportion were shrubs (5%) and the remainder were either trees or vines. The growth of plants with woody structures and seed production that is delayed for several years is disadvantaged in the regularly changing environment of intensive row cropping (Baker 1974). Such conditions do not appear to disadvantage perennial weeds that are able to rapidly achieve vegetative reproductive capability.

A summary of the characteristics of perenniality and type (i.e. broadleaf or grass) of the reported weeds is presented in Figure 2.7. About 70% of the weeds were broadleaf weeds and the other 30% were grasses. Short-lived (annual and/or biennial) and long-lived (perennial) were equally common, at about 40% each. A smaller number of weeds (22%) of variable perenniality were reported. A Chi-square test of the relationship between the perenniality and weed type showed that the differences were highly significant ($P < 0.001$).

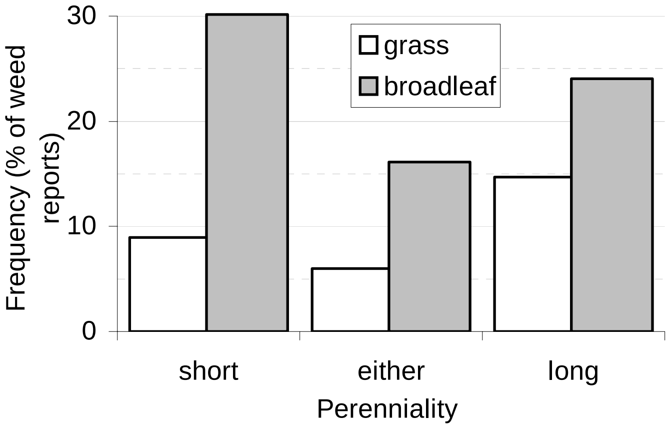


Figure 2.7 Frequency of weeds reported by survey respondents classified by (a) perenniality: short (annual and/or biennial), either (variable or uncertain perenniality) and long (perennial); and (b) weed type: grass (white bars) and broadleaf (grey bars) (n = 1097).

The most commonly reported weeds in the survey were members of similar botanical families to those listed for the weeds that are generally common throughout Australia (Groves 1991, Kloot 1991, Michael 1994, Lazarides *et al.* 1997). For example, Poaceae and Asteraceae are very large and diverse families and are likely to be well represented in most farming systems. Other families that are well represented amongst weedy genera are the Fabaceae, Brassicaceae, Liliaceae, Apiaceae and Polygonaceae (Michael 1994, Lazarides *et al.* 1997).

Short-lived broadleaf weeds were the most common type reported by survey respondents, however they were generally not the most problematic for growers as 90% of these weeds were reported by less than 10 growers. The most frequently reported short-lived broadleaf weeds were, in descending order, capeweed, cobblers pegs/farmer's friend, fat hen, chickweed, Paterson's curse, wireweed and Scotch thistle (possibly misidentified spear thistle [*Cirsium vulgare*]). Short-lived grasses were generally of localised importance to respondents, each being reported by only a few growers. However, ryegrasses (annual, perennial and unspecified), summer grass and barley grass were moderately common.

Longer-lived broadleaf weeds, the second most frequently reported group (24%), were also predominantly of minor importance (90% reported by less than 10 respondents). Six weeds, i.e. dock, sorrel, nutgrass, dandelion, blackberry and lantana, were commonly reported by growers. Longer-lived species of Poaceae were the most frequently reported grasses, with couch and Kikuyu being very common, paspalum less so, and about 25 infrequent species. Common weeds of variable or uncertain perenniality were thistles, clover, stinging nettles and unspecified grasses.

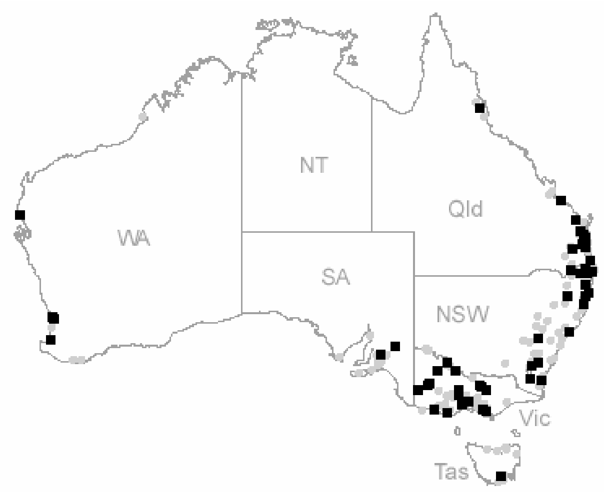
Conventional vegetable growers report a greater commercial impact from broadleaf weeds compared with grasses, possibly as a result of selection pressure against grassy weeds by the use of selective herbicides (Henderson and Bishop 2000). This selection pressure doesn't occur in organic production, yet broadleaf weeds were reported in the survey twice as much as grassy weeds. The dominance of broadleaf species as weeds on organic farms may be due to their diversity in the Australian and world flora generally (Groves 1991), rather than as a direct consequence of farm management practices.

Annual weeds that reproduce from seed are commonly found in conventional vegetable crops, although there are several notable exceptions such as couch and nutgrass (Henderson and Bishop 2000). Organic growers in the OWM survey reported similar numbers of annual and perennial weeds, with the most highly reported weeds being perennials displaying persistent underground reproductive parts such as stolons and rhizomes. Without systemic herbicides, organic growers may be less capable of controlling such herbaceous perennials. Comments by survey respondents requesting the development of organic sprays and thermal methods such as stream weeding were probably indicative of their frustration with managing such weeds. A weed's resistance to control in organic herb and vegetable production may be related to various biological and ecological factors such as seasonality, vegetative reproductive strategies, competitive ability and seed production, rather than perenniality *per sé* or the broadleaf/grass dichotomy.

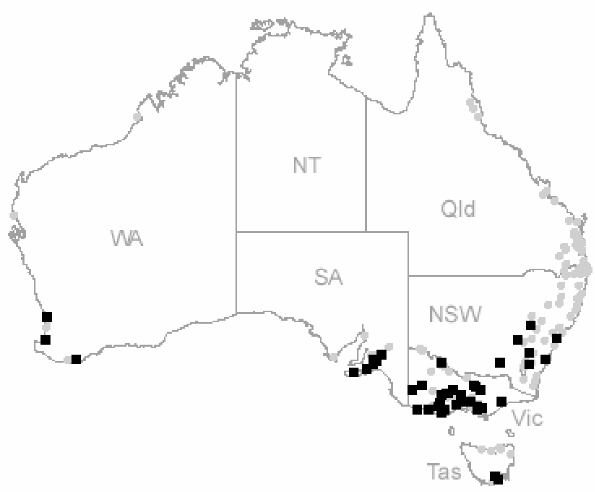
The locations of the five most commonly reported weeds are shown in Figure 2.8. These maps illustrate the geographical variation in reports of weeds. Couch is a fairly cosmopolitan weed (Lazarides *et al.* 1997) and is considered to be one of the world's ten hardest weeds to control (Hartmann *et al.* 1988). This weed species was the most widely dispersed of the common weeds reported, with about a third in the northern NSW – southern Queensland coastal region and another third scattered through central and western Victoria. These areas include semi-arid, Mediterranean, cool temperate, warm temperate and sub-tropical climatic zones. Extreme occurrences were reported from Huonville, Tasmania (latitude 43.0° south) to Malanda, Queensland (latitude 17.4° south).

On the other hand, the reported geographic distributions of capeweed, Kikuyu and sorrel suggest that these weeds have more specific climatic requirements. Capeweed was generally limited to cool and warm temperate areas in the south of the continent, with 60% of reports occurring in Victoria. Sorrel was also more common in cooler regions such as the southern States and up the sub-coastal Great Dividing Range, at higher elevations, to the Queensland border, but was also reported from several warmer locations near or on the coast, including Maleny (latitude 26.7° south) and Byron Bay (latitude 28.6° south). Kikuyu was limited to the warmer and higher rainfall areas, with 70% of the reports coming from coastal sub-tropical areas and the balance from warm temperate regions. Only one report was received from Queensland, i.e. Cooroy (latitude 26.4° south). It was unclear why there were no other reports of Kikuyu from survey respondents from Queensland.

Lazarides *et al.* (1997) list 11 species in two genera for "dock", with some wide distributions, including curled dock (*Rumex crispus*), swamp dock (*R. brownii*) and broadleaf dock (*R. obtusifolius*). Therefore, it was expected that reports of "dock" were likely to be from a wide range of locations. The reported farm distributions appear to be less contiguous than the other weeds in Figure 2.8, with some clustering in several regions such as south-eastern Victoria, Gippsland, southern Tasmania and the north coast of NSW. The clustering may have been due to different species or biotypes of dock, but that was uncertain.



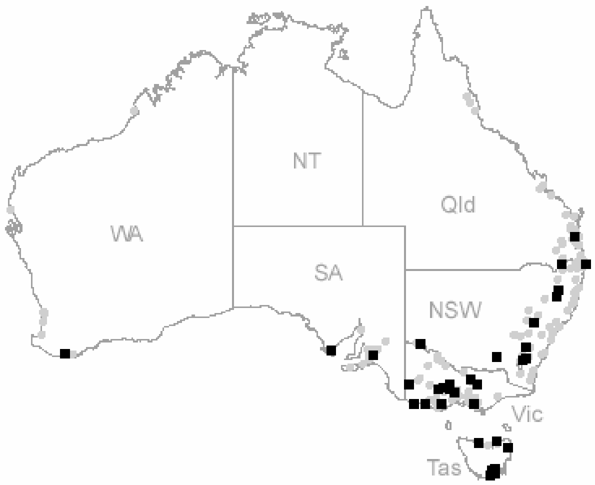
couch (*Cynodon dactylon*)



capeweed (*Arctotheca calendula*)

dock (*Rumex* and *Acetosa* spp.)

kikuyu (*Pennisetum clandestinum*)



sorrel (*Acetosella vulgaris*)

Figure 2.8 Locations of the five most commonly reported weeds; couch, capeweed, dock, Kikuyu and sorrel. The black squares represent the locations were each weed was reported and the grey dots represent the 219 farm locations reported in the survey.

About 240 weeds or weed groups were reported in the OFRF survey. The six most frequently cited weeds, i.e. those that were reported by at least 3% of respondents, are listed in Table 2.10. The botanical names were inferred by consulting the INVADERS database (http://invader.dbs.umt.edu/), HYPPA database (http://www.dijon.inra.fr/malherbo/hyppa/hyppa-a/hyppa_a.htm), the Weed Science Society of America's plant names database (http://www.wssa.net/weednames/) and University of California IPM Online (http://www.ipm.ucdavis.edu/). Pigweed was assumed to refer to species of *Amaranthus*, rather than *Portulaca oleracea* because purslane, the usual common name used in the USA, was also listed. The percentages are generally lower in the OFRF survey compared with the OWM survey (Table 2.9) possibly because respondents to the former study were not just herb and vegetable farmers, therefore the overall range of weeds reported may have been greater and the frequencies of individual weed species reduced as a consequence.

Table 2.10 The most frequently reported weeds in the OFRF survey, i.e. those reported by at least 3% of respondents (n = 1,192).

Weeds	Family	% of respondents
Foxtail (various genera possible?)	Poaceae	6.5
Pigweed, Amaranth (*Amaranthus* spp.)	Amaranthaceae	5.5
Quack grass (*Elytrigia repens*)	Poaceae	5.3
Lambsquarters, Fathen (*Chenopodium album*)	Chenopodiaceae	4.7
Canada thistle, Perennial thistle (*Cirsium arvense*)	Asteraceae	3.7
Bindweeds (*Convolvulus* and *Calystegia* spp.)	Convolvulaceae	3.6

Apart from foxtail, which could not be botanically distinguished below family using the available information, these weeds were either heavily seeding annuals or perennials with persistent rhizomes. Broadleaf weeds made up 63% of the weeds reported and grasses constituted the other 37%, a similar ratio to the weeds reported in the OWM survey. The most difficult weeds to control in the OFRF survey were Bermuda grass (couch, *Cynodon dactylon*), Johnson grass (*Sorghum halepense*) and bindweed (*Convolvulus* and *Calystegia* spp.), all rhizomatous weeds (Lazarides *et al.* 1997). Walz (1999) notes that "the reliance on mechanical and hand tillage for weed management is probably correlated to the high level of difficulty assigned to the management of rhizomotous [sic] weed species, which are easily spread rather than killed by tillage". Beveridge and Naylor's survey of organic farmers, in the United Kingdom (1999) noted a range of commonly reported weeds (e.g. docks [*Rumex* spp.], wild oats [*Avena fatua*], thistles [*Cirsium* spp.]), including both annuals and perennials, although frequencies were not given.

2.3.3 Attitudes to weeds

Are weeds a problem?
Approximately 80% of the herb and vegetable growers answered yes to the question "Do you consider weeds to be a problem in your organic crops?" This parameter is referred to below as "Problem". A more detailed picture emerged from the open-ended questions where attitudes to weeds ranged from active utilisation to passive acceptance, through to desperation. Growers' comments such as "weed management is the major cost associated with the growing of medicinal herbs and threatens the viability of the enterprise" (herb grower, 2 years, NSW) and "weed control would be the main limit to our production using organic methods" (vegetable grower, 9 years, NSW) clearly emphasise the general impact of weeds in organic horticultural production.

Several respondents (11%) considered weeds to be a normal part of the farming system that can have positive functions such as stock feed, capturing otherwise unavailable soil nutrients, raw material for liquid fertiliser, mulch, compost, habitat for spiders and insects, physical protection of crop, soil cover against erosion, and as an indicator of soil condition. Comments highlighting these positive perceptions of weeds included: "[they are] just a necessary part of the whole" (vegetable grower, 20 years, Victoria) and "they are an important part of the ecology " (vegetable grower, 12 years, Tasmania). Respondents citing the beneficial role of weeds were compared with those not citing benefits against several variables including weeding methods used and farm/farmer characteristics such as organic farming experience, certification status, farm size and geographic location. No significant differences were observed using the Chi-square test in GLM for all parameters ($P > 0.16$).

The question of whether farmers' attitudes to weeds change with the number of years of organic farming experience was of interest as it may indicate whether weed management is perceived to become easier with time. The effect of organic farming experience (Years) on concerns about weeds (Problem) was tested using the Chi-square test in GLM and a significant decrease in concern was detected with increasing experience (P = 0.052). The histograms in Figure 2.9 illustrate this variation in response, with the left graph showing a high frequency of respondents perceiving weeds as a problem in the first 10 years of organic farming and a rapid decline thereafter. The right graph shows a lower initial frequency of responses and higher levels from 10 years or more.

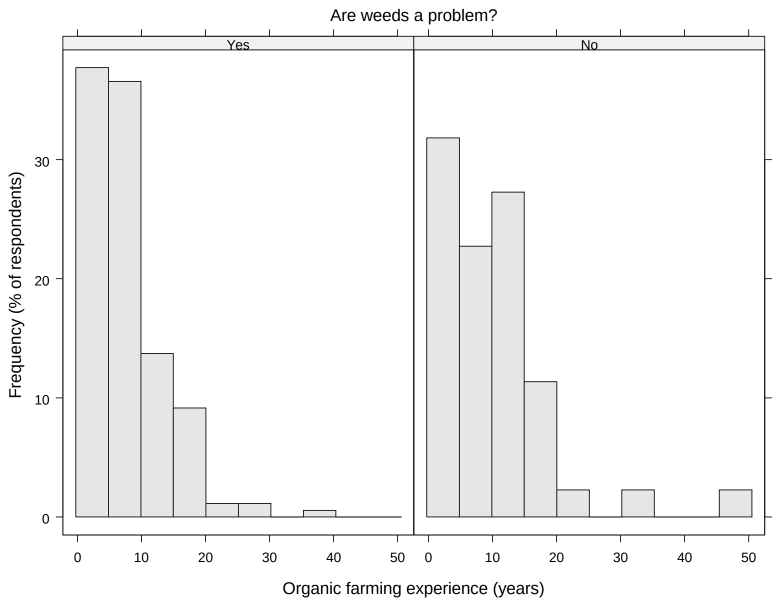


Figure 2.9 Frequency of respondents answering yes or no to the survey question "Do you consider weeds to be a problem in your organic crops?" in relation to their organic farming experience (years).

The finding that weeds were a significant problem for organic growers, was consistent with the results of Walz (1999) regarding the impact weeds have in organic production. Her report showed that weeds were ranked as the top research priority, the top category for desired production information, the top pest management concern and the top constraint to production during the conversion process.

Conventional growers also report that weeds were an significant problem in their farming systems. In a 1998 survey of Australian conventional wheat farmers, weeds were ranked as the most serious problem by 90% of respondents. A large percentage of farmers considered that the weed problems were worse or unchanged from five years ago (34 - 62% depending on bioregion, Jones *et al.* 2000), despite the considerable time and money spent on herbicide-dominated weed management strategies.

The ubiquity and general consistency of reports about the impact of weeds is compelling. However, growers may have a vested interest in reporting to researchers that weeds were a significant problem, or exaggerating the extent of the problem, if it will encourage further research on issues of direct benefit to them. The difference between visual thresholds for taking action against weeds observed by farmers and higher thresholds based on a quantitative assessment of weed levels (Cousens 1987) suggests that growers' perceptions of the impact of weeds may be overstated partly as a risk avoidance strategy. The use of data derived from on-farm monitoring of weed densities (Gavin *et al.* 1999) may provide a mechanism for verifying grower perceptions. A comparison of mail survey responses and a field survey of weed problems and management practices showed broad agreement between the two survey methods (Jones *et al.* 2000).

Why are weeds a problem?
The level of concern expressed by respondents about various weed impacts on organic herb and vegetable production is shown in Figure 2.10. The frequency of responses by all survey respondents was calculated from the number of growers reporting some level of concern (i.e. marking one, two or three on the scaled-choice question) about each impact (grey bars in Figure 2.10). The average responses for the various weed impacts, i.e. the mean of all responses on the 4-point scale, were strongly correlated with percentage frequency ($r^2 = 0.98$). Therefore the relative importance of the impacts was assumed to be the same.

The 44 open-ended responses recorded in the "Others" section were all reclassified into the existing categories, except for a single comment about "community responsibility" to control weeds (vegetable grower, 15 years, Victoria). The frequency of reporting weed impacts in the "Others" section is shown in Figure 2.10 (white bars).

The most important perceived impact of weeds was that they were difficult and time consuming to control (93% of respondents). About 80% of the growers expressed a moderate to high level concern about the effort required to manage weeds, emphasised by the comment "weed control is the single most time consuming activity connected with the running of my farm" (vegetable grower, eight years, Victoria), and "weed control is a huge problem on my property and takes up more time than any other activity" herb grower, 13 years, Victoria). More than half of the growers who recorded a comment in the "Others" sections (i.e. 11% of all respondents) mentioned the time consuming and costly nature of OWM.

Other very frequently reported weed impacts were reduced crop yields due to weed competition and interference with farming operations. Competition from weeds was also reported by over 20% of respondents in the "Others" section. Reasons of less concern, though still reported by more than 50% of respondents, were the harbouring of pests and diseases by weeds and contamination of crop or product with plant parts from weeds.

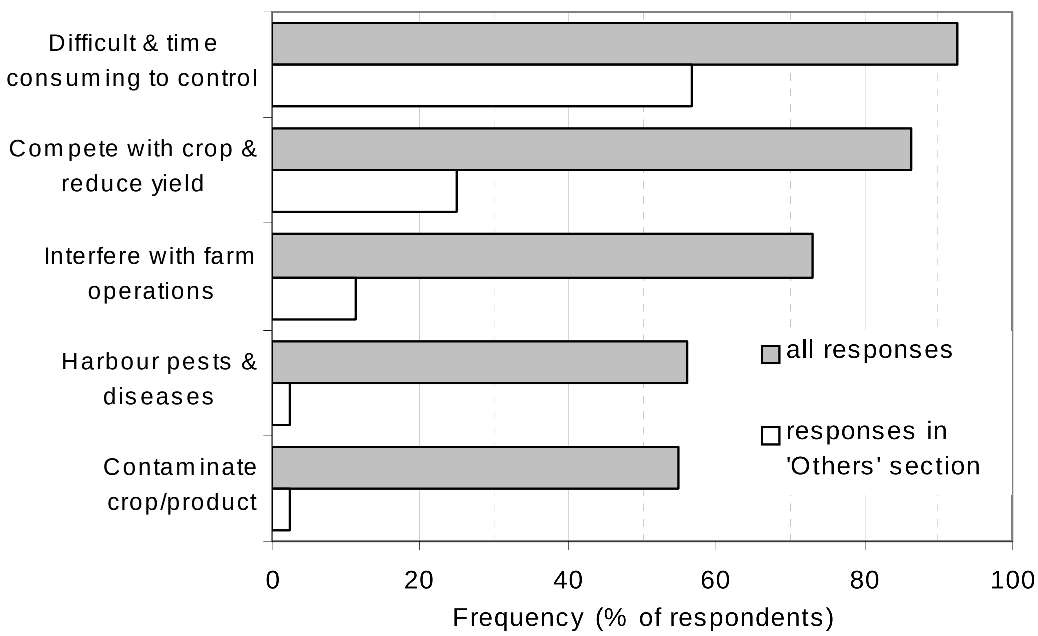


Figure 2.10 Level of concern about specific weed impacts on herb and vegetable production, expressed as the percentage frequency of respondents. The grey bars represent the frequency of responses by all survey respondents (n = 219) and the white bars represent the frequency of responses recorded in the "Others" section (n = 44).

A regression analysis of the level of concern about weed impacts against years of farming experience was carried out using the Chi-square test in GLM. A significant ($p \leq 0.05$) decrease was detected in levels of concern for most weed impacts as experience increased. The strongest response was observed for concern about weeds being difficult and time consuming to control and contamination of crops/products. Levels of concern dropped by more than one point on the three-point scale for these two parameters. Concerns about weeds interfering with farming operations and harbouring pests/diseases decreased by about 0.5 points. Concern about weed competition and reduced yields decreased with experience by about 0.4 points, but was not significant ($P = 0.35$) due to the variability in responses from more experienced growers.

A regression analysis of the level of concern about weed impacts and farm size (hectares) was also carried out. A significant ($P \leq 0.05$) decrease in concern was detected as farm size increased only for difficulty of control and interference in farming operations. Concern about the other impacts also decreased, but not significantly. As reported above, there was a strong relationship between farm size and farmer experience. Therefore, it is possible that reduced concern by managers of larger properties was due to greater experience.

To summarise the section on attitudes to weeds, although weeds were reported as a key production constraint, it appears that growers tend to become less concerned about weeds as they gain more experience in organic farming. In general, growers with about 10 years experience or more will be less concerned about weeds than their less experienced colleagues. The change in attitude may be due to an increase in the growers' skills, changes in their level of tolerance of weeds on their farm, a reduction in weed densities to more manageable levels, and changes to the weed flora toward fewer problematic species.

2.3.4 Organic weed management methods

Methods used: scaled-choice questions
The scaled-choice questions enabled respondents to indicate the regularity with which they used a number of listed weeding methods. A five-point scale was used, ranging from one ("never") to five ("always"). In addition to the 17 methods listed, respondents were able to add weeding methods that they used. Many of the methods added were variations of existing categories and were therefore reclassified into the appropriate existing category. However, seven new methods or categories were identified. These were, in descending order of frequency, underlying principles of OWM, farm hygiene, strategic fertilisation fallowing, bio-dynamic peppering, strategic irrigation and solarisation.

The responses were reclassified into 15 general categories consistent with those used for responses to the open-ended questions. The average response for each method was determined and those averages were ranked in descending order to indicate their relative importance to organic herb and vegetable growers. Figure 2.11 presents that data and the percentage frequency of respondents using each method at *any* level of regularity, i.e. those respondents who marked two, three, four or five on the five-point scale.

Manual weeding was very regularly used by a vast majority of respondents, with a mean score of 4.3 points (out of a maximum of five) for regularity, and 95% of growers reporting some usage of this method. Several methods were used with moderate regularity (mean ≈ three points), including organic mulch, tillage, rotations, bed preparation, slashing/mowing and timing of operation. The frequency of respondents using these methods was moderately high (> 50% of respondents) and generally consistent with regularity of use, except that slashing/mowing and timing of operations were more commonly used but with less regularity than rotations and bed preparations. Less regularly (mean ≈ two points) used methods were cover crops, grazing, inter-cropping and cultural methods. These techniques, and thermal methods, were used by at least 30% of growers.

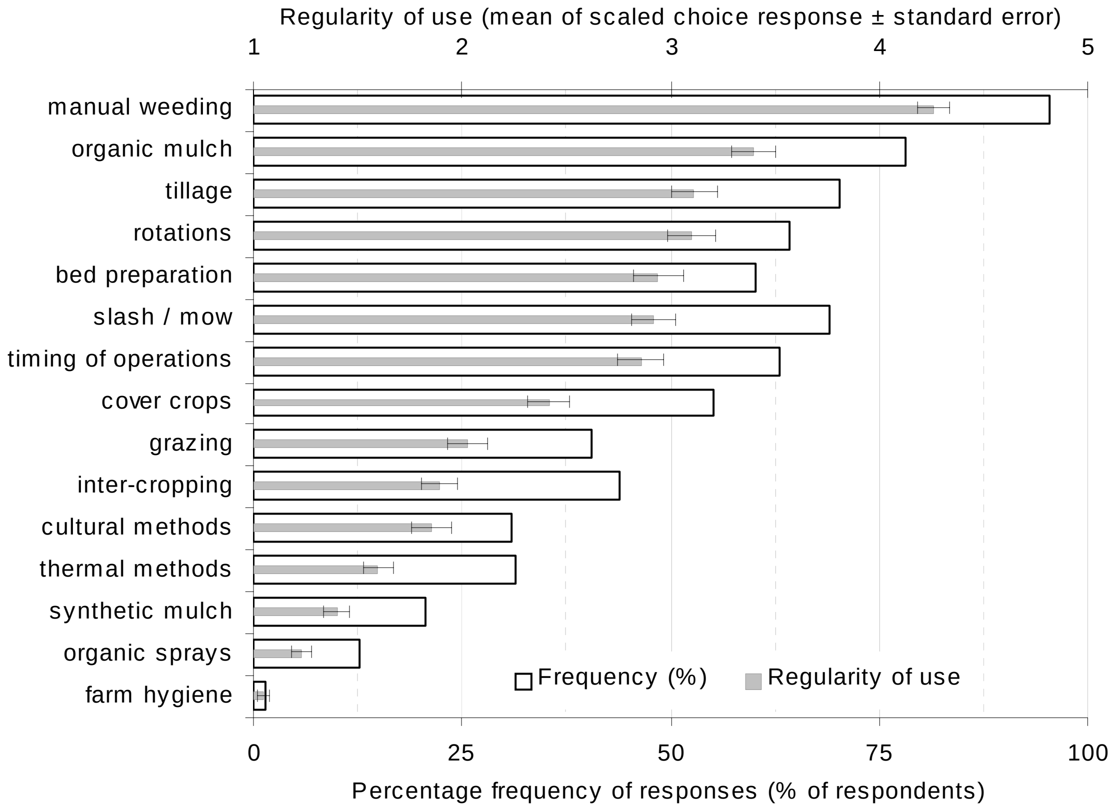


Figure 2.11 Regularity of use (mean ± standard error) and percentage frequency of responses (% of respondents) for weeding methods reported in the scaled-choice questions. The top axis depicts the regularity data, which are an average of responses on a five-point scale, i.e. one = "never" to five = "always" for each weeding method. The grey bars indicate the mean regularity of use, the error bars indicating the standard error of that mean. The bottom axis depicts the frequency data, which are the percentage frequency of respondents using each method at any level of regularity. The white bars indicate the frequency of responses (n = 219).

Respondents also provided information about the tillage implements they used for weed management. About 70% of all respondents reported using some form of mechanical cultivation and about a quarter of these used more than one implement. Figure 2.12 shows the percentage frequency of reported use of various categories of tillage implements. The most popular implement by a considerable margin was the rotary hoe. More than 40% of growers using tillage reported using a rotary hoe compared with 10 - 15% of growers using a tractor-drawn implement plough with tines, discs or mouldboards. Less than 5% reported using a harrow, ripper or scarifier, and a range of other implements such as hydraulic rotating tines, rolling blades and home-made devices were used by only a few growers.

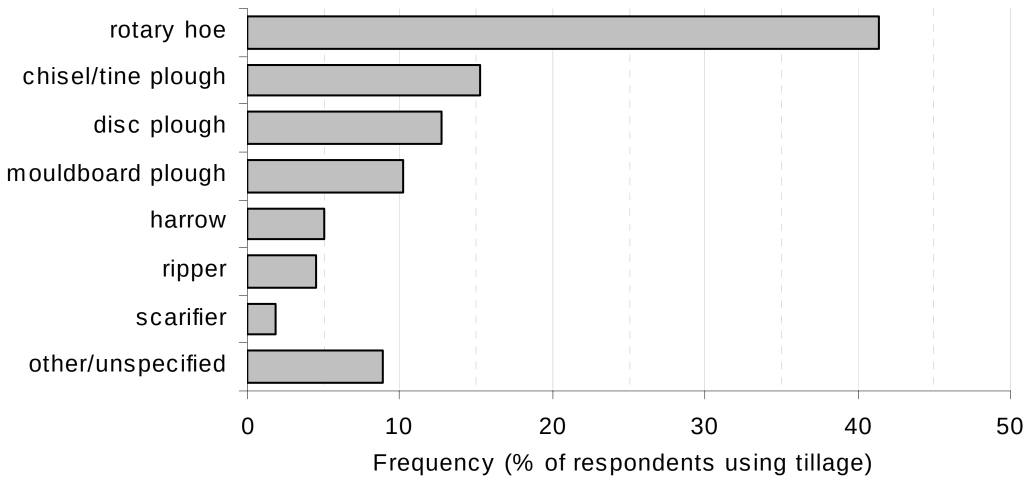


Figure 2.12 Percentage frequency of the use of various tillage implements (n = 157).

Despite some serious potential problems with the overuse or misuse of rotary hoes, such as damage to soil structure and pan formation, these implements can be a versatile and effective weed management tool (Bowman 1997, Whitten 1999), especially on smaller farms that were common amongst the herb and vegetable growers in the OWM survey. A Chi-square test confirmed that rotary hoe users have significantly smaller farms than non-users ($P = 0.05$), with mean farm sizes of 5 and 12 hectares respectively. Other variables such as organic farming experience, farm location, certification status, certification organisation and days to return questionnaire were not significant.

Methods used: open-ended questions

Responses to open-ended questions ranged from a few words (e.g. “hand weed, mow, mulch”) to a few pages explaining weed management strategies and the underlying principles in considerable detail. These responses highlight the diversity of practices in OWM across the industry (Table 2.11). Some of the categories in Table 2.11 overlap, for example, rotations are likely to include grazing and/or cover crops, and the integrated nature of organic production makes it difficult to clearly classify individual methods. Other weed researchers have categorised weeding methods in various ways and acknowledge that such schemes are imperfect (Watson 1992).

Table 2.11 Weeding methods reported in the open-ended questions and examples of specific techniques or equipment used.

Method	Example
manual weeding	hand pulling, rake, fork, mattock, wheel hoe and various chipping hoes
organic mulch	paper (pellets, sheets, rolls), hay, cardboard, straw, woodchip, sawdust, seaweed, wool, hessian
tillage	numerous plough types such as bed former/potato hiller, brush weeder, chisel/tine, deep ripper, disc, harrow, hydraulic rotating tines, mouldboard, rolling blades, rotary hoe, scarifier, scufflers, spring tine
slashing	brush-cutter, whipper-snipper, hand mower, ride-on mower, slasher
rotation	fallowing, green manure crops, grazing, cash crop sequence, competitive crops before uncompetitive ones
bed preparation	stale seed bed, raised beds
timing	sowing, tillage, hand weeding, slashing, applying inputs, weed and crop lifecycles, lunar cycle
cover crops	cereal and legume green manures, living mulch, weed-suppressive brassicas
inter-cropping	companion crops, under-sowing, hedges, barrier crops, wind breaks, inter-cropping, permaculture
grazing	cattle, chickens, ducks, geese, goats, horses, pigs, sheep,
thermal methods	burning, flame weeder (hand-held and tractor-mounted), steam weeder, solarisation
synthetic mulch	black plastic film, carpet, woven plastic weed mat
sprays/intervention	citrus and pine oils, salt, mustard powder, homeopathic potencies, bio-dynamic “peppers”
hygiene	prevent seed set and spread, composting, clean machinery, buy weed-free inputs
other cultural methods	crop selection, site selection, sowing/planting rate, fertiliser placement, irrigation and water monitoring, soil management, diligence, observation, weed seed bank reduction focus, integration

About 40 weeding methods or strategies were identified from a quantitative analysis of the open-ended questions. However, many of these methods were used by only a small number of growers. Half of the methods were used by less than 5% of the growers and another quarter were used by 5-10% of growers. Only 7 of these methods were reported by more than 20% of respondents. The responses were reclassified into 15 categories of weeding methods to provide a more general evaluation of the frequency with which various OWM methods were used by herb and vegetable growers (Figure 2.13).

The most frequently reported method was manual weeding, which was reported by about 80% of respondents. Manual weeding, usually performed as chipping with a hoe, was sometimes used as a central management technique or as a final “clean up” after relying on other methods such as tillage or mulch for the bulk of the weed control. Other commonly reported methods (> 40% of respondents) were mulching with organic materials such as hay, paper or compost; tillage using a wide range of implements including rotary hoes and various types of ploughs; and slashing, often to prevent seed set, using brush-cutters, mowers and tractor-mounted slashers.

Less frequently reported OWM methods (10-25%) were cover crops, thermal methods such as solarisation and flame weeding, adjusting the timing of farming operations including sowing, cultivation and slashing, and using rotations incorporating various cash crops, green manures, fallowing and grazing. A wide range of cultural weed management methods were reported with moderate frequency overall, although many were limited to only a few growers. Cultural techniques reported included crop and site selection to suit the existing weed burden, higher crop densities, strategic irrigation and fertilization, and the manipulation of various soil quality parameters such as pH, the calcium:magnesium ratio and drainage.

Infrequently reported methods (< 10%) included practising good farm hygiene by preventing the spread of weed seeds; bed preparation methods such as raised beds to ease between-row weed control and false seed beds to eliminate a final cohort of emerged weeds prior to sowing or planting; and various inter-cropping strategies that were designed to reduce weed impacts compared with growing a single crop species.

Synthetic mulches and organic sprays were also used by a small number of growers. These materials are approved for use by the Australian organic certification standards, but they are only recommended for limited use in weed management, not as substitutes for good organic farm management (OPAC 1998). Synthetic mulches reported in the survey included weed matting (woven black plastic) and polythene film. Growers mentioned a number of organic sprays such as essential oils, homeopathic potencies and bio-dynamic peppering. Peppering refers to burning the seeds of specific weeds, collecting the ash, mixing the ash with water in a particular process and then spraying the solution onto the paddock (Thun 1980).

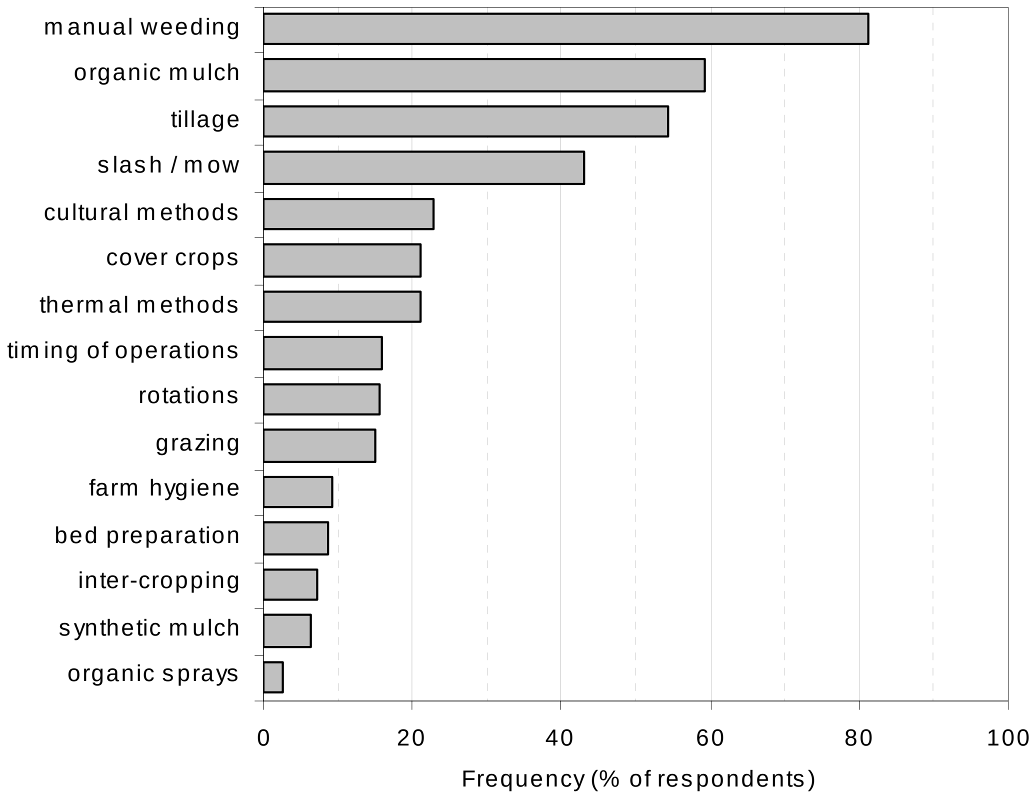


Figure 2.13 Frequency of weeding methods reported in the open-ended questions. The methods were classified into 15 categories and sorted in descending order by frequency (n = 219).

Summarising individual practices may neglect the importance of principles in OWM. An understanding of the role of weeds in the ecology of a farming system is emphasised by many authors of organic production publications (Marshall 1992, Walters 1996, Oien 1997, Merfield 2000). About 7% of the survey respondents specifically referred to underlying principles that guided their weed management practices.

Various responses to the open-ended questions reported principles and integrative strategies, including:
* observing weed lifecycles and succession,
* timing operations to maximize the impact on weeds,
* preventing weed seed set,
* paying attention to detail early to save extra effort later,
* planning operations in a logical sequence, and
* gearing all operations on the farm towards weed management.

Diversity of practices
The range of techniques listed in response to the open-ended questions about weeding indicates the diversity of weed management methods used amongst the surveyed population. Over 40 methods were reported, although many were used by a very small number of respondents. This diversity may be related to several factors such as farm size, farm location, years of experience, commodities grown and the various practical and philosophical backgrounds of the respondents. Duram's (1999) report on decision-making by organic farmers in Colorado, USA, found a high level of operational diversity that was tailored to suit specific local conditions and the farmer's expertise. A survey of conventional broadacre farmers in Australia (Alemseged *et al.* 2001) also reported distinct regional differences in weed management practices across the continent, although they noted that the small number of respondents for certain regions made comparisons unreliable.

The scaled-choice questions can provide a more comprehensive evaluation of the diversity of OWM practices on individual farms. The average number of weed control methods reported in the scaled-choice questions was 8.6 and the maximum number of methods was 17. About a quarter of the respondents reported using five methods or less. Surveys about weed management practices may report the frequency of each weeding method or category, but they generally do not report the frequency of methods used by individual respondents. Alemseged *et al*. (1999) reported that the conventional broadacre farmers responding to their survey routinely used an average of four to five different methods to control weeds in winter crops. Although that figure was about half of the average reported in the OWM survey, differences in cropping system, survey design, terminology and categorization of weed control methods may account for the differences in weed control practices between the two sampled populations.

A comparison of the frequency histograms of the number of methods used by individual respondents for the two types of questions (i.e. open-ended and scaled-choice), with two levels of method classification (i.e. uncategorised and categorised) is shown in Figure 2.14. The shape of the histograms for the open-ended responses (graphs A and B) show a rapid rise in the frequency, peaking at about four methods used. For the scaled-choice questions (graphs C and D), the rise was less steep, the peak was at a higher number of methods and the maximum number of methods was greater.

The differences in histogram shapes in Figure 2.14 suggest that the question types elicited different responses. This hypothesis was tested using the Chi-squared test in GLM. The number of methods reported in the open-ended (Graph A) and scaled-choice questions (Graph C) were significantly different ($P < 0.001$), with medians of four and nine respectively. After reclassifying the methods into 15 categories of weed control methods the question types (Graphs B and D) were still significantly different ($P < 0.001$), with medians of four and seven respectively. It may be concluded that scaled-choice questions did provide a more comprehensive evaluation of the diversity of OWM practices than did the open-ended questions. Foddy (1995) noted that answers to open questions tend to be less complete than answers to corresponding closed questions (such as the scaled-choice questions in the OWM survey), and that respondents find closed questions easier to answer because they are guided in the types of answers required and prompted to recall more information. He recommends, however, that a judicious mixture of both types of questions is generally desirable.

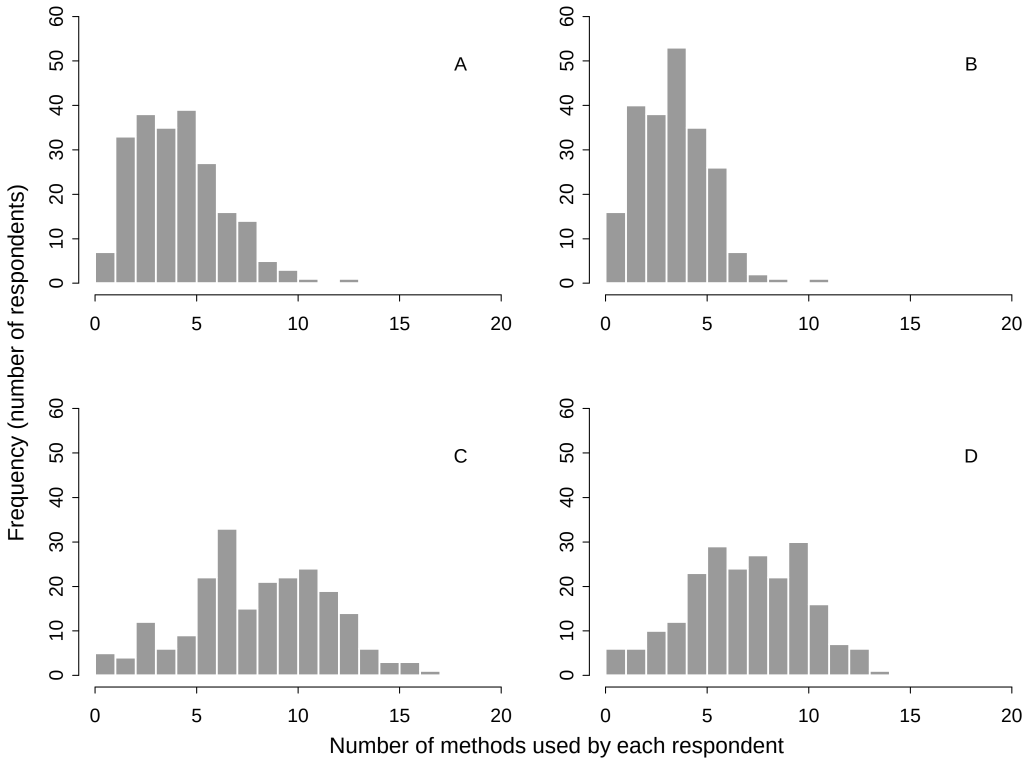


Figure 2.14 Frequency histograms (number of respondents) for the number of weeding methods reported in the open-ended questions (A: uncategorised, B: categorised) and scaled-choice questions (C: uncategorised, D: categorised) (n = 219).

Comparison with other organic surveys

The popularity of weed management methods reported in the OWM survey was compared with that reported in three other surveys of organic growers that presented data in a similar format (Beveridge and Naylor 1999, Walz 1999, Burnett 2001). The results from two of those surveys are shown in Figure 2.15, with the weeding control methods ranked in descending order of frequency. Graph A shows the results of the OFRF survey in the USA that included farmers producing a broad range of organic commodities. Horticultural crop producers made up 57% of the respondents, 52% produced broadacre field crops, 40% grew tree crops and 27% produced animal products (Walz 1999). The total was greater than 100% as some respondents operate mixed farming systems. Graph B depicts the results of a survey of Australian organic broadacre cropping and grazing enterprises (Burnett, pers. comm.). In Beveridge and Naylor's survey (1999) of UK organic farmers, grain production was the main cropping system of respondents, with a smaller number of potato growers and graziers responding.

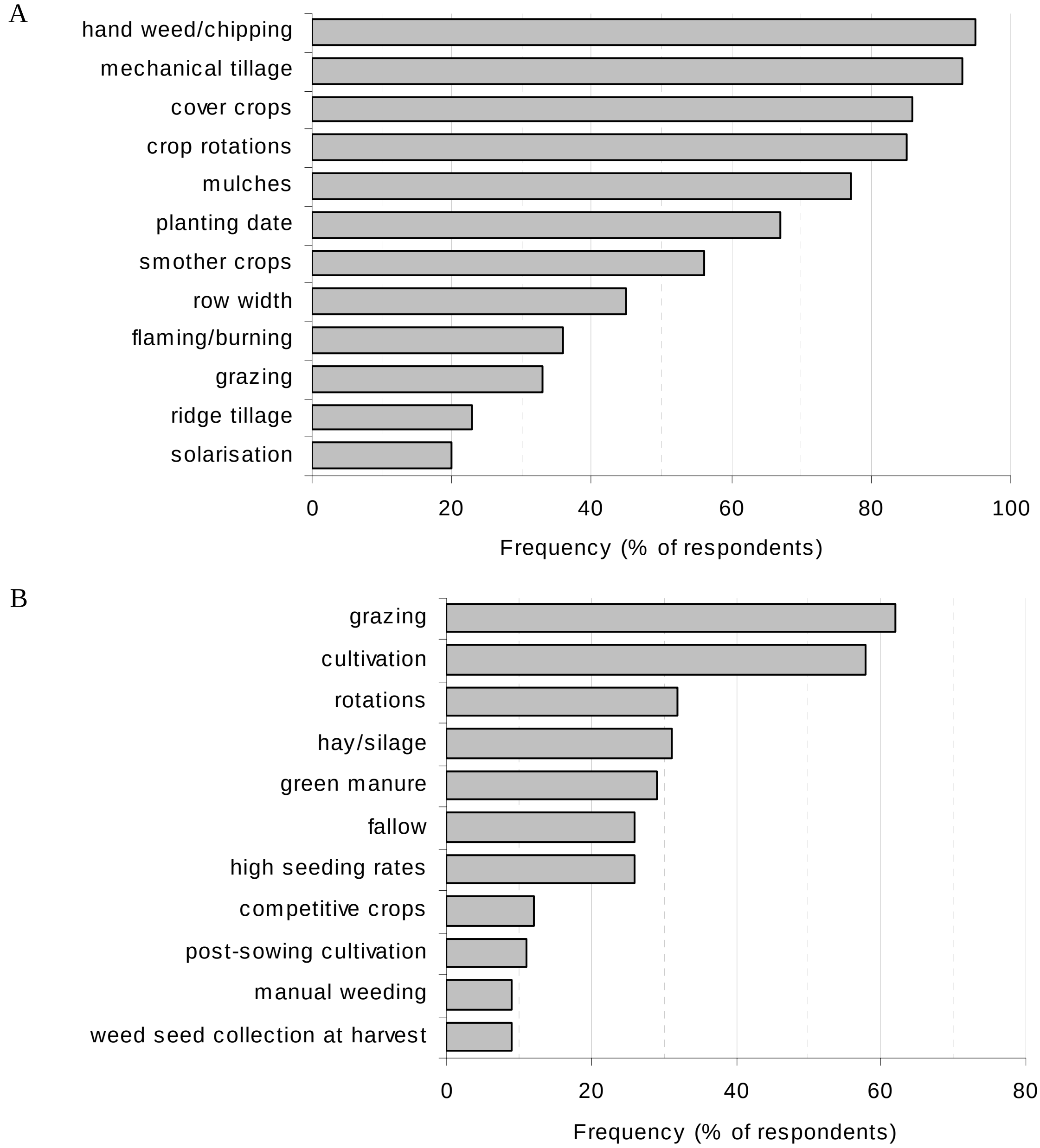


Figure 2.15 Percentage frequency of respondents reporting the use of various weed management method in A, a survey of US organic producers (n = 1,192) (Walz 1999), and B, a survey of broadacre organic farmers in Australia (n = 70) (Burnett 2001).

Comparing these surveys with the OWM survey was complicated by the different types of farming systems sampled, survey design characteristics, terminology used in the questionnaires and categorisation of methods during the analyses. Therefore, care should be taken in identifying differences in the ranking of methods. Nevertheless, some common trends were apparent between the weed control methods reported in the four surveys, particularly between the OFRF (Walz 1999) and OWM surveys. Tillage or cultivation was a very commonly used tool for weed management, being ranked second or third in all surveys. Rotations were also consistently highly ranked, and cover crops (or green manures) and timing of operations were considered to be at least moderately important techniques in weed control. "Slashing" (OWM survey), "topping/mowing" (Beveridge and Naylor 1999) and cutting "hay/silage" (Burnett 2001) were also moderately common. Thermal methods and cultural methods (e.g. crop selection, modified crop density) were generally used with low to moderate frequency in all surveys.

The lower ranking of mulches and ridge tillage (equated with "bed preparation" in the OWM) in the OFRF survey, compared with the OWM survey, may be related to the inclusion of farmers with broadacre and animal production systems where such practices are presumably less common or not relevant. Also, raised beds and ridge tillage are possibly not directly comparable. The very high ranking of grazing, and the low ranking of manual weeding and absence of mulches as a weed control method in Burnett's survey (2001) was probably due to the absence of horticultural enterprises and the large proportion of permanent-pasture grazing enterprises in the surveyed population (Burnett, pers. comm.). Two recent reviews of organic weed management failed to mention grazing as a weed control method (Rasmussen and Ascard 1995, Bond and Grundy 2001).

Success and expense of the methods used

This section presents the results from the scaled choice questions regarding the perceived success and expense of weeding methods used by growers (Figure 2.16). The results are averaged responses and only include data from growers using each weed control method (i.e. those reporting a regularity of use score of at least two). The scales ranged from one = "very poor" to five = "very good" for success, and one = "not expensive" to five = "very expensive" for expense, and the methods were ranked in descending order by regularity of usage. Excluding non-users of each method may bias the results against respondents who believe that certain weeding methods were not successful, have ceased using those methods and were therefore disinclined to respond, whether favourably or not. However, the "users only" sub-sample provides an overview of the perceptions of current users of each weed control method.

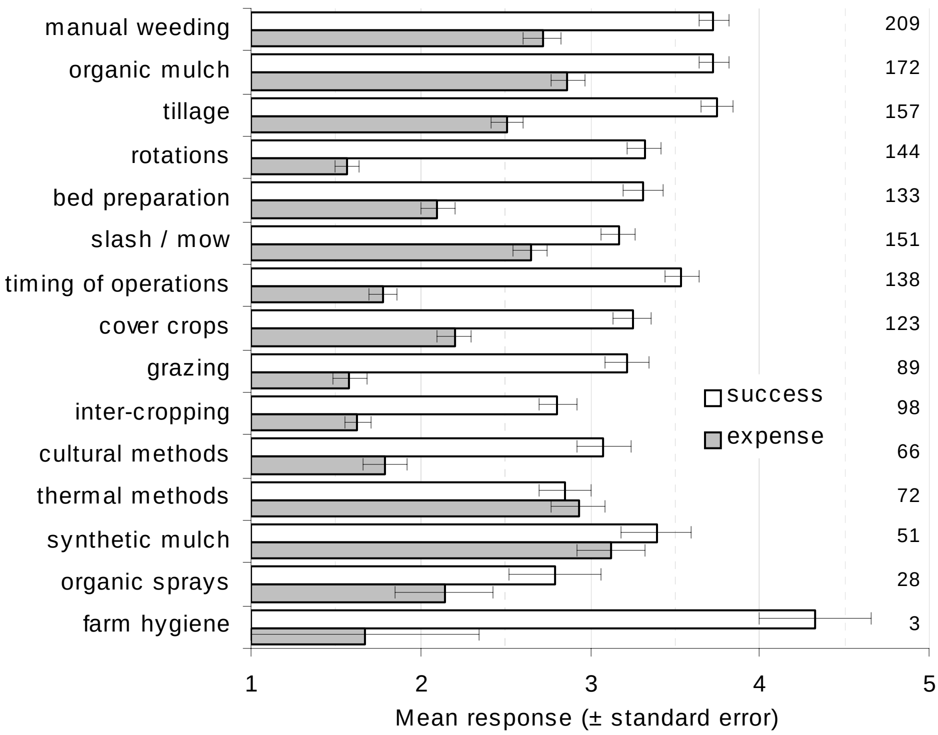


Figure 2.16 Mean response (± standard error) by all respondents to perceived success and expense of weeding methods. The data are an average of responses on a five-point scale from "very poor" to "very good" for success (white bars), and "not expensive" to "very expensive" for expense (grey bars). The methods are in descending order by regularity of use. The numbers down the right-hand side indicate the number of respondents using each method (n = 219).

Growers reported that the most successful methods of weed management were farm hygiene, tillage, organic mulches, manual weeding and timing of operations. The exceptionally high reported success of farm hygiene was possibly unreliable given the very low number of growers reporting that method (i.e. three). However, the other methods are used by at least 70% of the respondents, so those values are assumed to be more reliable. These methods were also the most frequently reported by the respondents.

Several moderately successful weed control methods were reported including, synthetic mulches, rotations, bed preparation, slashing/mowing, grazing and various cultural methods. Methods that were perceived to be less effective for controlling weeds were thermal methods, inter-cropping and organic sprays. The success of weeding methods showed relatively little variation between methods compared with regularity of use and expense. Apart from farm hygiene, all methods averaged between 2.7 and 3.7 points, suggesting that most of the reported methods were at least moderately successful at controlling weeds, and that none were dramatically effective or ineffective. This finding concurs with other studies of organic weed management, where individual weed control practices are neither "very effective" nor "poor" (Beveridge and Naylor 1999), and that reliance on several methods is important (Bond and Lennartsson 1999).

The most expensive OWM methods reported were synthetic mulches and thermal methods, with organic mulch, manual weeding, slashing/mowing and tillage also considered to be expensive. These methods generally rely on high levels of external-input requirements such as fabricated materials that are non-recyclable (limited to single-season usage) and dependence on fossil fuels and special machinery. Organic mulches are bulky materials with high purchases prices, transport costs and application costs. Several respondents reported using paper and cardboard which may offer a cheaper alternative to hay and straw mulches. Labour, whether for direct manual weed control or for operating tractors and other machinery used in weed control, is widely considered to be a major cost in organic and low-input weed management (Ascard and Mattsson 1994, Bastiaans *et al.* 2000, Leinonen and Närkki 2000). The high labour requirements were acknowledged by survey respondents with respect to why weeds are a problem (Section 0). The greatest problem posed by weeds was perceived to be the difficult and time consuming nature of OWM (92.6% of respondents). About 55% of the 44 responses recorded in the "Others" sections were related to the time and cost of managing weeds.

Methods that were reported to be moderately expensive included organic sprays, cover crops and bed preparation. These methods may be considered to be expensive because of the cost of materials used in organic sprays such as essential oils; the costs of producing a cover crop such as seed, inputs, labour and forgone income; and the labour and machinery costs incurred in preparing and maintaining raised beds. The least expensive methods were a range of cultural techniques or farm management operations including timing of operations, farm hygiene, inter-cropping, grazing and rotations. Many of those methods are likely to be undertaken for other reasons than weed management, so the full expense was not applied to weed control.

The linear correlations between regularity of use, success and expense are shown in Figure 2.17. A loose correlation (graph A, $r^2 = 0.63$) was detected between the mean responses for regularity of use and success and the slope was significant ($P < 0.001$). The moderately close relationship between regularity and success appears logical; respondents would not be expected to persist with weeding control methods that were not perceived to be successful, and the more successful a method is at controlling weeds, the more regularly it is likely to be used.

No correlation was found between regularity of use and expense (graph B, $r^2 = 0.06$) and success and expense (graph C, $r^2 = 0.002$) and the slopes were not significant ($P = 0.38$ and 0.89 respectively). The lack of relationship between these parameters implies that respondents generally do not base their choice of weeding method on cost, and that more expensive weeding management methods do not necessarily provide greater success.

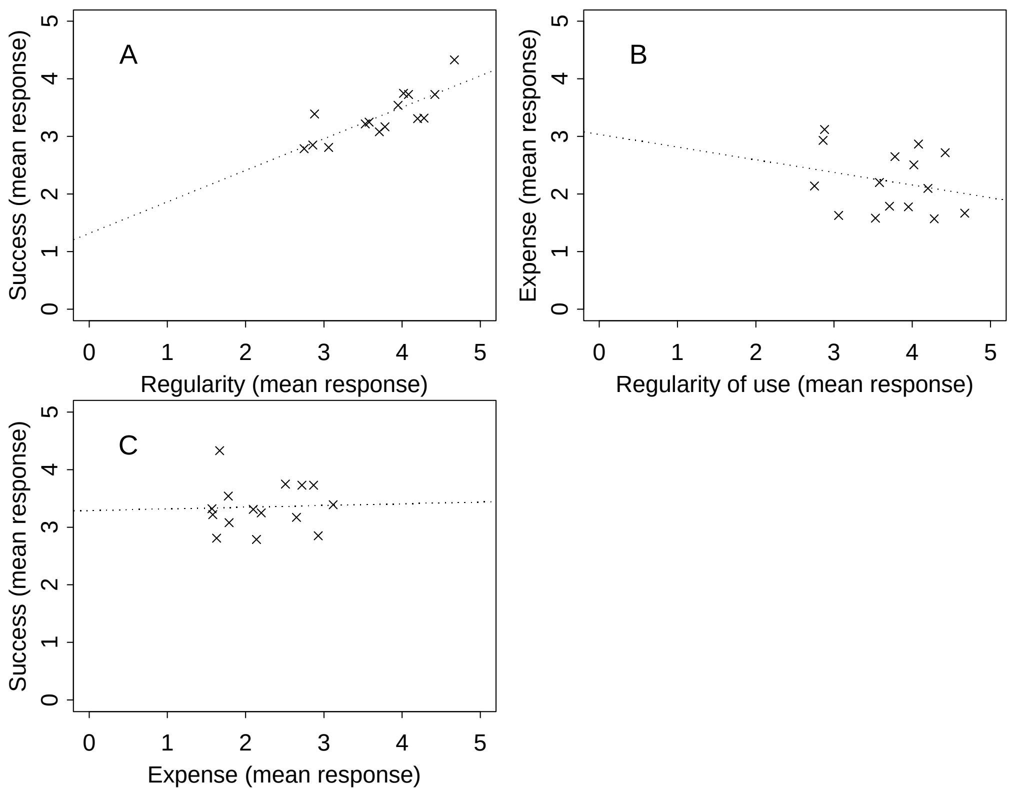


Figure 2.17 Correlations between the mean responses for the regularity of use, success and expense of weeding methods. The data are an average of responses on a five-point scale for each method. The linear regression is indicated by the dotted line.

Relationships between weed control methods and farm characteristics

The relationships between weeding methods and farm and farmer characteristics (explanatory variables) were analysed using the Chi-square test in GLM. Several relationships were found to be significant ($p \leq 0.05$) and these are shown in Table 2.12. The relationships were not necessarily causal, but may indicate associations between variables that provide a broader understanding of adoption and use of OWM practices reported in the survey. Only two weeding methods, organic sprays and farm hygiene, were not affected by any of the explanatory variables. These were the two least frequently reported weeding methods and it was possible that there were too few responses to detect significant trends.

Table 2.12 *P*-values for relationships between weeding methods reported and various farm and farmer characteristics (explanatory variables) that were identified in the bivariate analysis as being significantly different (p ≤ 0.05). The *P*-values generated using the Chi-square test in GLM.

	Weeding methods reported												
	manual weeding	organic mulch	tillage	rotations	bed preparation	slashing, mowing	timing of operations	cover crops	grazing	inter-cropping	cultural methods	thermal methods	synthetic mulch
Explanatory variables	*P*-values												
Geographic location		0.037	0.008				0.039	0.052				0.002	0.049
Organic farming experience	0.018			0.008		0.001	0.021	0.047	0.006		0.054		
Farm size									0.011			0.048	
Certification status			0.004	0.002		0.008		0.003				0.023	
Are weeds are a problem?	0.049		0.054			0.026			0.037		0.039	0.050	0.033
Benefits of weeds cited				0.042	0.011			0.043		0.022	0.002		

The frequency of use of weeding methods varied with geographic location (latitude and longitude). Organic mulches and cover crops were more commonly reported in the east and north of the continent, especially NSW and Queensland, whereas tillage, timing of operations, thermal methods and synthetic mulch were less common in the north and/or the east. This suggests a preference by respondents in the north and east for weed control methods that are organically derived and not necessarily reliant on off-farms inputs, rather than (a preference for) methods that require a higher level of external inputs such as fuel and specialised equipment or materials. Whether such preferences are based on organic farming experience, farming systems (e.g. types of crops grown), availability of resources, local historical factors such as availability of information and grower groups with specific interests, or attitudinal factors is unclear.

Several weeding methods were more likely to be used by respondents with greater experience, especially cultural methods such as rotations, timing of operations, cover crops and grazing that rely more heavily on a systems approach to weed management. The use of slashing/mowing was also found to increase with experience, perhaps in response to an increase in awareness of the importance of minimising weed seed production. The only method with a negative relationship between frequency of use and organic farming experience was manual weeding. It is probable that reliance on this method decreases over time as skills and confidence increase with using other weeding methods.

The amount of land under organic production significantly influenced grazing and thermal weeding only, despite reports that farm size is an important factor in the cost-effectiveness of weed management methods such as hand weeding and tillage (Melander 1998a, Alemán 2001). The use of grazing for weed control was greater by those with larger farms. The average farm size of growers reporting very high regularity of use of grazing (i.e. those selecting five on the scaled-choice question) was about 20 hectares, while the average for all other levels of use was about seven hectares. Grazing options, particularly with larger stock such as cattle and pigs, may be constrained physically and economically on smaller properties (Popay and Field 1992). Smaller animals, including poultry and goats, were reported in the OWM survey, however their use in weed management is not generally widespread (Popay and Field 1992). Thermal weeding methods, e.g. flame and steam weeding, were less frequently used as farm size increased, with regular users reporting average farm sizes no larger than four hectares and moderate users less than six hectares.

Thermal methods are perceived to be very expensive {Figure 2.16, and \Litterick, 1999 #2594}, and they may only be cost-effective on high value crops that are currently grown on smaller acreages.

A number of weeding methods were used more frequently as respondents progressed from uncertified status, through transition, to full organic certification status. These methods were rotations, cover crops, tillage, slashing/mowing and thermal methods. The trends in the use of cultural methods was similar to that found for organic farming experience. Tillage and thermal weeding were also adopted more by certified growers, although other factors than increased farming experience appear to be consistent with such a trend.

The answer to the question of whether weeds are perceived to be a problem by respondents was significantly correlated to the frequency of use of many weeding methods reported. Hand weeding/chipping, tillage, slashing/mowing, thermal weeding and synthetic mulch were positively correlated with the perception that weeds were a problem, while grazing and cultural methods were negatively correlated. The former group of methods are relatively intensive, direct or high input weeding methods, while the latter methods are less intensive and direct, implying that growers concerns about weed impacts are proportional to the intensity of the weeding methods used. In contrast to the perception of weeds as a problem in herb and vegetable production, weeds were also considered to be a beneficial component of the farming system. Respondents who cited some beneficial aspect of weeds in their response were more likely to use rotations, bed preparation, cover crops, inter-cropping and other cultural methods. This positive correlation may also imply that growers who are more accepting of weeds tend to report using less intensive and direct weed control methods.

Both increasing organic farming experience and decreasing concern about weeds were associated with weed control methods that tend to be more passive and indirect. Respondents with less experience and more concern about weeds were more likely to use active and direct weed control methods. These differences in practices may represent the development of a more ecological approach to weed management that was more reliant on cultural methods rather than physical or mechanical methods. Such a trend may be expected given the emphasis crop protection strategies that are based on a whole farming system approach, rather than reliance on external inputs and intervention, in the Australian national organic standards (AQIS 2001) and elsewhere (Lampkin 1990, Joint FAO-WHO Food Standards Programme 1999, UKROFS 2001).

2.4 Conclusions

The organic weed management survey was prompted by the numerous anecdotal and research reports that weeds were a key constraint in organic crop production and the general lack of information about OWM practices. It was considered that the existing knowledge base amongst Australian organic herb and vegetable growers could be accessed through a mail survey. The OWM survey was, therefore, conducted to provide information about the weed control methods used by growers, attitudes towards weeds, basic characteristics of the farms and farmers surveyed, and the relationships between parameters. The survey provides a quantitative analysis of current weed management practices used by organic herb and vegetable growers in Australia and also gives an insight into some of the factors that influence those practices.

A review of the literature pertaining to mail survey methodology identified several potential sources of error. These sources of error were addressed in the subsequent analyses of the results by comparing data within the survey and with other similar surveys. The findings were found to be generally free from significant sources of error and consistent with other surveys. Although efforts were made to sample from the widest possible grower base, incomplete sampling inevitably means that results from the survey should be seen as indicative rather than conclusive and as a basis for further research into OWM practices amongst Australian organic herb and vegetable growers.

A moderate response rate was achieved (43%), with the majority of respondents were within the sampling frame, i.e. organically certified producers of herbs and vegetables. The reported farm sizes were small (median = 2.4 hectares) and the respondents had relatively little experience with organic farming (median = 6 years). Producers grew a wide range of herb and vegetable crops (median = 3) and reported numerous types of weeds on their farms. The most common weeds were predominantly those with persistent underground parts that resist common forms of organic weed control such as cultivation (by hand or plough) and mulch. Heavily seeding annuals were also frequently reported. Respondents expressed strong concern about weed management, particularly regarding the difficult and time consuming nature of OWM and the impact of weed competition in reducing crop yields. About 10% of growers reported that weeds could play a beneficial role in the farming system.

The respondents reported using a diverse range of weed management techniques, with over 40 specific methods or strategies being mentioned. The most common method was manual weeding, which was sometimes used as a central management technique or as a final “clean up” after relying on other methods such as tillage or mulch for the bulk of the weed control. Other commonly reported methods were organic mulches; tillage (especially rotary hoes); cultural methods such as rotations, bed preparation, timing of operations, cover crops and inter-cropping; slashing and/or mowing; and grazing. Less frequently reported OWM methods included thermal methods, synthetic mulches, organic sprays and farm hygiene practices.

The results for perceived success of weeding methods used were loosely correlated with the regularity of use. Therefore, manual weeding, organic mulches and tillage were reported to be the most successful weeding methods. No relationship was found between the perceived expense of a weeding method and the regularity of use of that method. This suggests that growers were not primarily motivated by the cost of a weeding method; instead, they were more concerned that it was successful in controlling weeds. Synthetic mulches and thermal weeding were considered to be the most expensive weed control methods.

A change in OWM practices was found in relation to respondents' organic farming experience and level of concern about weeds. There was a decline in the use of direct, physical methods (e.g. manual weeding, tillage) and an increase in the use of indirect, cultural methods (e.g. rotations, cover crops) as growers became more experienced and less concerned about the negative impacts of weeds.

Results from the OWM survey and the OFRF survey (Walz 1999) highlight a number of possible research issues of concern to organic growers. Improved control of particularly problematic weeds, such as couch, sorrel and nutgrass, was a common area of concern. Studies on the biology and ecology of such weeds may identify lifecycle vulnerabilities that can be exploited by modified management practices. There also appeared to be some interest from respondents in novel techniques such as flame weeding, steam weeding, improved tillage implements and organic sprays, although these methods require further development too. Cultural strategies such as techniques for weed seed bank reduction and the development of weed suppressing cover crops that don't become weeds themselves were also of interest to respondents.

Given the failure of the questions about time and cost of weed management to elicit reliable data in this survey, and the general importance of economic factors in broader decision-making, another potential research area may be an economic analysis of OWM practices. A more focused study of the economic impact of weeds and the cost and efficiency of various key weed management methods may generate empirical data about the relative cost of weed management in organic production. Such information is not currently available in Australia.

The dominant weed control methods reported in the survey - manual weeding, organic mulches and tillage - provided the focus for the experimental work reported in the following chapter.

3. Agronomic and economic evaluation of organic weed management methods

3.1 Introduction

Whilst weed management in organic herb and vegetable production is widely reported to be a major constraint, a range of systems are have been developed by organic growers in Australia to manage weeds on their property. These organic weed management (OWM) systems vary in the types of methods used and how they are used depending on a variety of issues including the crops grown, existing weed populations, soil conditions, climate, availability of resources (e.g. local mulch source), farm financial situation, organic farming experience and the farmers' mind set. In the absence of the highly developed extension and production strategies that are available to conventional farmers (e.g. fertiliser and crop protection programs), farmers have devised OWM solutions based on their own needs and capabilities, support from grower groups and certification organisations, and information from published materials in Australia and overseas.

In Australia, some farming systems trials have been conducted that investigate the effect of organic and non-organic production systems on crop yield, weed levels, soil fertility, costs and other variables (Penfold *et al.* 1995, Wells 1996). These trials have not studied the comparative effects of different weeding methods within a given farming system. Some research has been conducted on specific non-chemical weeding methods in herb or vegetable systems, including mulches (Olsen and Gounder 2001), grazing (Penfold and Miyan 1996), thermal methods (Hewitt *et al.* 1998) and tillage (Dunn and Penfold 1996). However, very few comparative studies that consider the economics of weed management methods in annual horticultural cropping in Australia have been published, apart from that by Tyler (1999). There appears to be scant quantitative data on farm budgets or weed control costs for organic herb and vegetable growers available in Australia (Buntain 1999, Whitten 1999, Davidson 2000), although such data have been collected in Europe (Philipps *et al.* 1998, Geven 2000) and the United States (Sellen *et al.* 1995, Clark *et al.* 1999, Brumfield *et al.* 2000).

Several overseas studies have reported findings based on comparative trials of different weeding methods in vegetable production, including some that present an economic evaluation of the methods tested (Edwards *et al.* 1995, Melander 1998a, Litterick *et al.* 1999, Feldman *et al.* 2000, Alemán 2001). Factors that are considered to have an impact on the relative economic performance of weed control methods include the existing weed density, the cost of labour, size of the area to be treated, crop type, crop yield and the price received for the harvested crop.

Although Australian organic herb and vegetable growers report using a wide range of methods to control weeds, several key methods are frequently used by the majority of growers (as reported in the previous chapter). This chapter reports on a comparative evaluation of the agronomic and economic performance of some of those commonly used methods, i.e. hand weeding, organic mulches and tillage. Hand weeding was used by about 95% organic herb and vegetable growers in the OWM survey, organic mulches by about 80% of respondents, and tillage by about 70% of growers. These methods were also frequently reported in other surveys of organic growers (Walz 1999, Burnett 2001). In addition to hay mulch, which is a common type of mulch used by organic growers (Whitten 1999), a novel pelletised paper mulch was used in the experiments. Paper mulches have been reported to be effective for weed suppression (Smith *et al.* 1998, Olsen and Gounder 2001).

A series of experiments was conducted on two crops with differing growth patterns, lettuce (*Lactuca sativa* L.) and echinacea (*Echinacea purpurea* Moench. [L.]), with the objective of assessing the relative performance of various weed control treatments in terms of weed growth, crop growth and treatment cost.

3.2 Methods

3.2.1 Site descriptions

The field experiments reported in this chapter were carried at three sites over three consecutive summer growing seasons on properties situated on the Northern Tablelands of New South Wales (Figure 3.1). In the first year (1998-1999) field trials were conducted at Yarrowitch, located at latitude 31 14°S, longitude 152 00°E and elevation 970 m. This property was owned by Subiaco Herbs Pty Ltd, the industry partner initially associated with the project. The withdrawal of Subiaco Herbs from the project during the first growing season meant that further trials could not be conducted at that site. The Yarrowitch site had been operated organically for the previous two seasons, before which it was a conventional wool growing property. Echinacea had been grown in the previous year. It had full organic certification from the accredited certifying body Organic Herb Growers Australia.

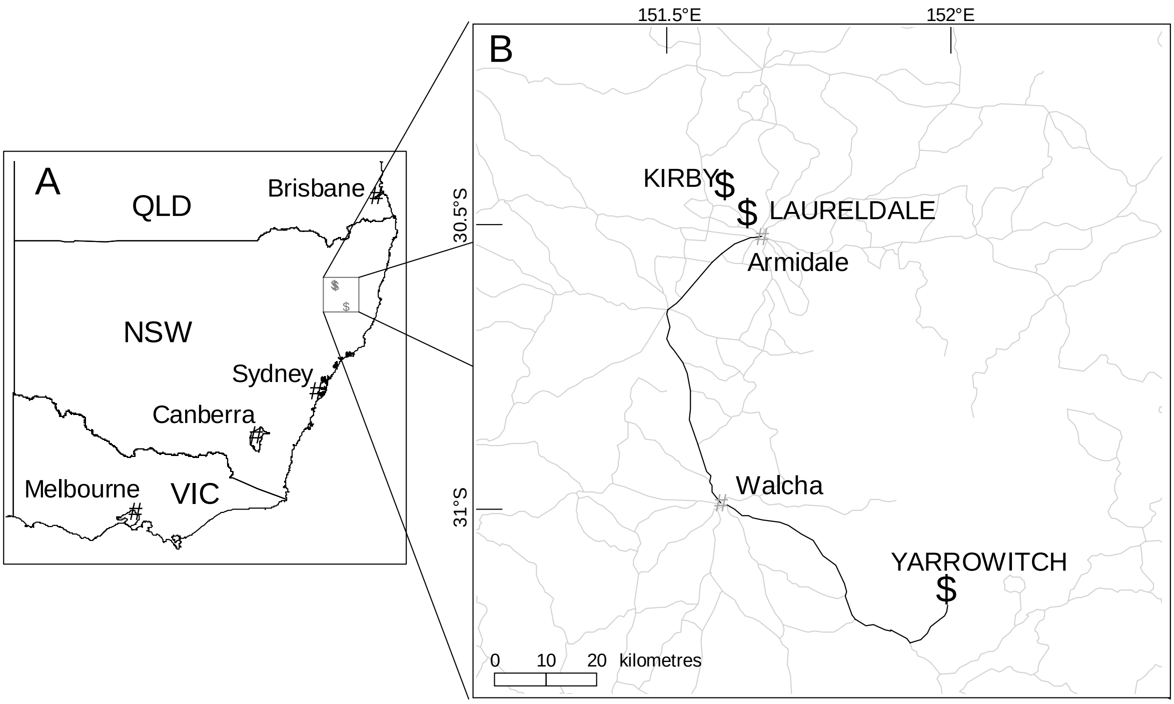


Figure 3.1 Map of south-eastern Australia (A) and detailed map (B) showing the location of the three sites used for the field trials reported in this chapter. In map B, the field sites are represented by ▲ , the gray lines indicate roads and the black line indicates the road from Armidale to Yarrowitch.

In the second year (1999-2000) field trials were undertaken on two of the University of New England's research farms (Figure 3.1). Kirby Research Station, located at latitude 30.43°S, longitude 151.61°E and elevation 1135 m, is principally a wool growing farm and the paddock in which the trials were conducted had been sown to pasture and grazed by sheep and cattle for at least the previous seven years. No herbicides or fertilisers had been used during that time. Laureldale Research Station, located at latitude 30.48°S, longitude 151.65°E and elevation 1063 m, is used for small-plot field trials and has a very complicated land-use history based on a range of cereal and legume crops and a diverse mixture of fertliser and biocide usage patterns. The area used in the field trial reported here had been used for a buckwheat variety experiment in the previous season. In the third year (2000-2001) field trials were undertaken at Kirby Research Station only. Experiments were not continued at Laureldale due to the poor growth of lettuce in the second season, heterogeneity of the site (e.g. high spatial variability of weeds and soil drainage), and the difficulty of access after rain.

Soil descriptions
The soil at Yarrowitch was a granite-derived fine sandy loam, Dg 3.42 (Northcote 1984). The soil at Kirby was a granite-derived sandy loam, Dy 4.42 (Northcote 1984). The Laureldale soil was a basalt-derived heavy chocolate clay, Ug 5.14 (Northcote 1984). Soil analyses were carried out at the beginning of each season at each field site. The soil was sampled by collecting 20 cores (100 mm diameter x 200 mm deep) in an X-shaped pattern across the trial area, bulking the cores, mixing thoroughly and randomly selecting a sub-sample of approximately 500 ml of soil. The sub-sample was oven dried at 40°C for 48 hours, hammer milled through a 2 mm sieve and placed in air-tight plastic specimen jars. Approximately 40 g of prepared soil was sent to Incitec (Paringa Road, Murarrie, QLD 4170) for analysis and the results are shown in Table 3.1.

Table 3.1 Results of soil analyses for the four field trials.

Parameter (method of analysis*) [units]	Trial			
	Yarrowitch 1999	Laureldale 2000	Kirby 2000	Kirby 2001
date sampled	5/11/1999	23/9/2000	23/9/2000	14/9/2001
soil colour (Munsell)	greyish brown	brown	greyish brown	dark grey
soil texture	fine sandy loam	medium clay	sandy loam	sandy loam
ph (1:5 water)	6.0	5.4	5.3	5.4
ph (1:5 $CaCl_2$)	5.4	4.9	4.7	4.8
nitrate nitrogen [mg/kg]	35.8	24.8	37.6	76.2
phosphorus (Colwell) [mg/kg]	22	73	18	29
potassium (AmAc) [meq/100g]	0.86	1.06	0.18	0.22
carbon, organic [%]	2.0	1.8	1.7	1.7
sulfur [mg/kg]	28	70	9	15
calcium (AmAc) [meq/100g]	6.6	19.6	2.6	2.5
magnesium (AmAc) [meq/100g]	3.2	14.6	0.84	0.76
sodium (AmAc) [meq/100g]	0.17	0.2	0.07	0.08
chloride [mg/kg]	100	20	10	10
manganese (DTPA) [mg/kg]	41	68	31	40
iron (DTPA) [mg/kg]	105	90	135	154
zinc (DTPA) [mg/kg]	1.4	6.7	7.7	1.5
copper (DTPA) [mg/kg]	0.8	2.9	0.3	0.5
aluminium (KCl) [meq/100g]	0.07	0.09	0.07	0.08
EC# (dS/m)	0.18	0.14	0.94	0.15
EC# (saturated extract) (dS/m)	1.6	1.4	9.7	1.5

* abbreviations: AmAc = ammonium acetate, DTPA = diethylenetriaminepentaacetic acid, KCl = potassium chloride
# EC = electrical conductivity

Climate
The long-term climatic averages for the Yarrowitch district are 19.2°C for daily maximum temperature, 5.2°C for daily minimum temperature (Bureau of Meteorology 2001) and 1300 mm for annual rainfall (H. Mason, pers. comm.). The long-term averages for the Armidale district, in which the two UNE research stations were located, are 20.3°C for daily maximum temperature, 7.1°C for daily minimum temperature and 790.1 mm for annual rainfall (Bureau of Meteorology 2001). A summary of the climatic data in Yarrowitch and Armidale during the duration of the trials is shown in Figure 3.2. This figure gives the average monthly maximum and minimum temperatures (°C) and the monthly rainfall (mm). Daily rainfall data for Yarrowitch were supplied by Helen Mason of Yarrowitch based on a rain gauge located 15 km south of the field site, and temperature data were

based on the nearest known recording station at the Walcha office of NSW State Forests. Weekly rainfall data for Kirby and Laureldale were obtained from rain gauges within 20 metres of the experimental sites and temperature data were obtained from the Armidale weather station (Bureau of Meteorology 2001).

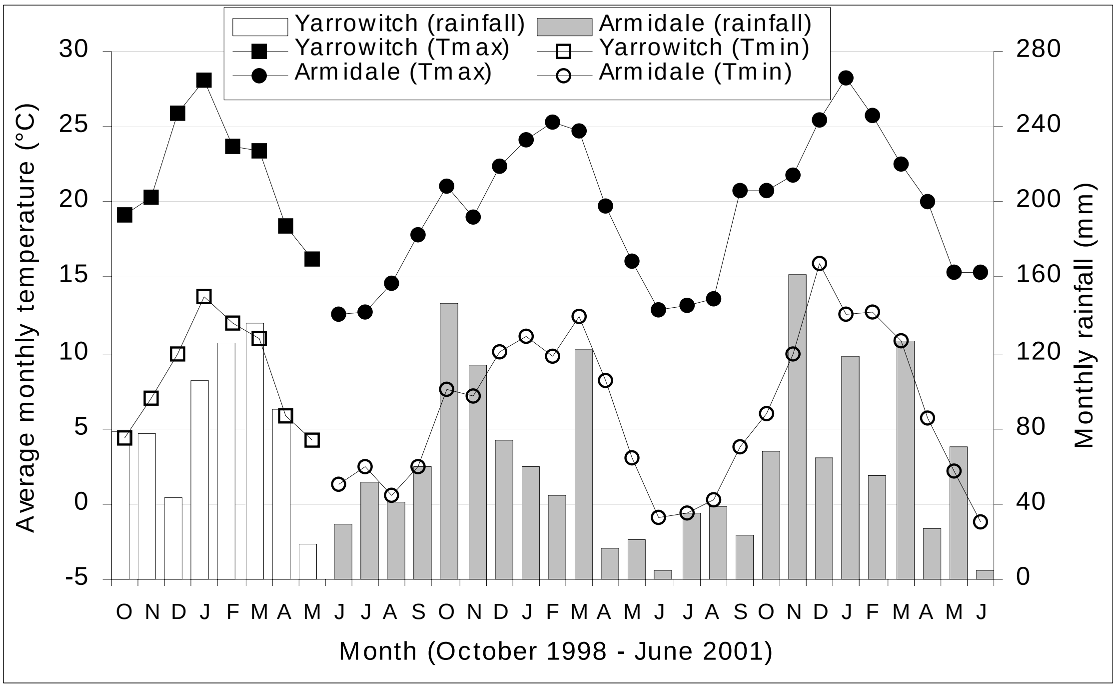


Figure 3.2 Monthly summaries of average maximum and minimum temperatures (°C) and rainfall (mm) at Yarrowitch and Armidale for the period in which the field trials were conducted. The solid lines indicate temperature, black squares (■) = maximum temperature (Tmax) at Yarrowitch, white squares (□) = minimum temperature (Tmin) at Yarrowitch, black circles (●) = maximum temperature (Tmax) at Armidale, white circles (O) = minimum temperature (Tmin) at Armidale. The white columns represent rainfall at Yarrowitch and the grey columns represent rainfall at Armidale.

For each field trial, cumulative rainfall, the amount of precipitation since the trial was planted, was calculated. Degree day estimates, based on the cumulative product of temperature and time (UC-IPM 2001), were also calculated. The single sine method, which has been reported to produce relatively low errors during the warmer months of the year and in inland areas (Roltsch *et al.* 1999), was used. A base temperature of 4.4°C was used for lettuce and 5°C was used for echinacea (Ash *et al.* 1999). A summary of the cumulative rainfall (mm) and accumulated degree days (°Cd) during each field trial is given in Figure 3.3. In the lettuce trials, the cumulative rainfall was greater at Yarrowitch in 1999 compared with the Armidale sites in 2000 ($P = 0.046$) and Kirby in 2001 ($P = 0.104$). The difference in cumulative rainfall between the Armidale site in 2000 and 2001 was small prior to harvest, with the latter year being slightly wetter overall ($P = 0.124$). In the echinacea trials, the rainfall was considerably greater at Yarrowitch in 1999 compared with Kirby in 2001 ($P = 0.032$). There were no significant differences ($P > 0.30$) in accumulated degree days observed between the field sites for lettuce or echinacea.

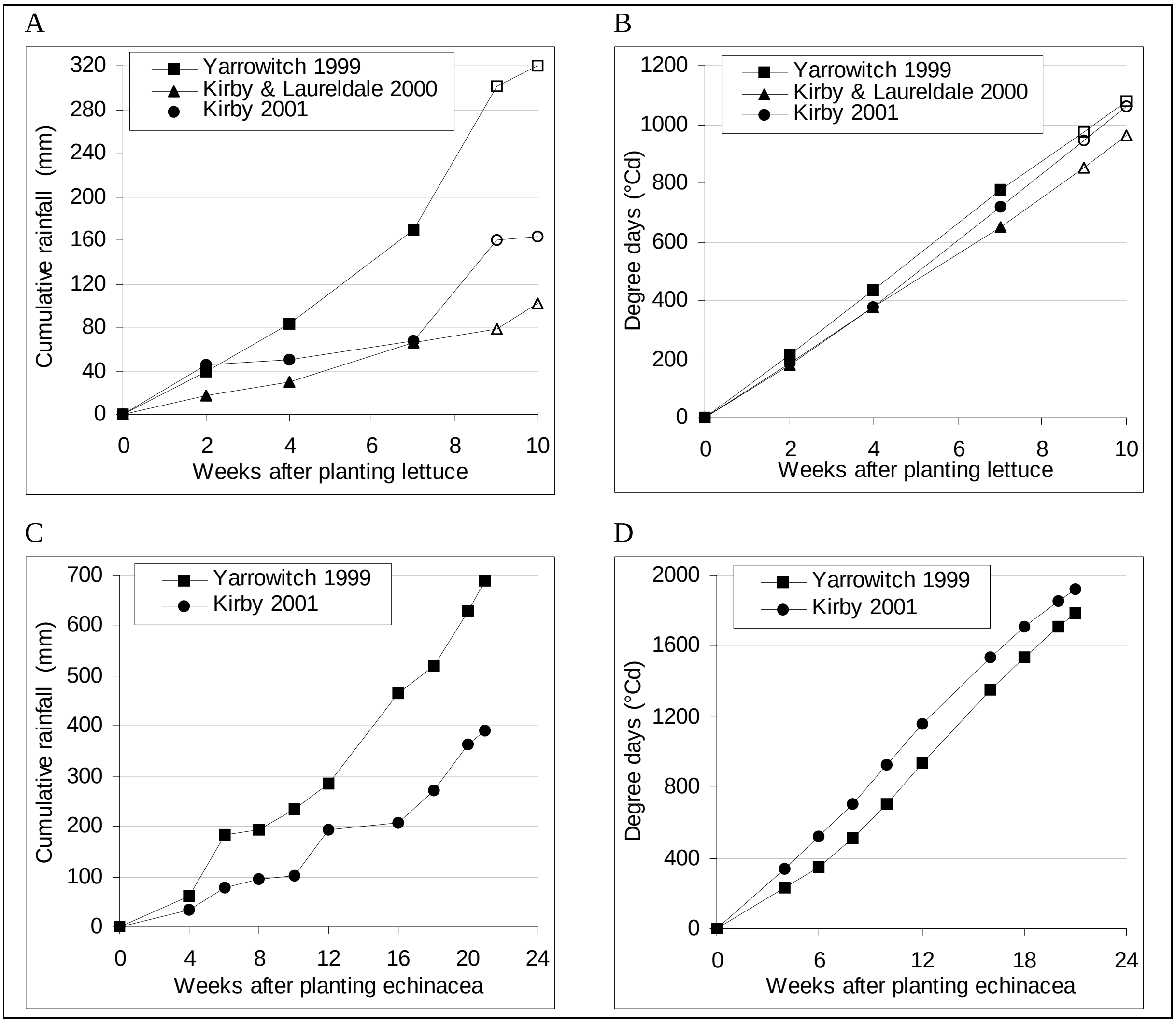


Figure 3.3 Cumulative rainfall (mm) and accumulated degree days (°Cd) during each field trial at Yarrowitch (1998-1999 [■]), Laureldale (1999-2000 [▲]) and Kirby (1999-2000 [▲] and 2000-2001 [●]) for lettuce (graphs A and B) and echinacea (graphs C and D). In graphs A and B, the closed symbols (■, ▲, ●) represent measurements taken up to harvest time, while the open symbols (□, △, O) represent measurements after the lettuce was harvested, but while bolting was still being recorded for the remaining plants.

3.2.2 Plant species

The test crops used in the experiments reported in this chapter were the medicinal herb echinacea, *Echinacea purpurea* Moench (L.), and the salad vegetable lettuce, *Lactuca sativa* L. 'Imperial Triumph', a crisphead variety. Echinacea seeds were supplied by Subiaco Herbs (Yarrowitch, NSW) in the first year and by Peter Green (Corindi Beach, NSW) in later years. Lettuce seeds were obtained from Purkiss Seeds, (Armidale, NSW).

All experiments were conducted using seedlings rather than direct seeding. Echinacea and lettuce seedlings used in the Yarrowitch experiments were grown at the on-farm nursery using organic methods. Lettuce seedlings used in 1999-2000 and 2000-2001 were grown by Withcott Seedlings (PO Box 9145, Withcott, Queensland, 4352) without the use of synthetic pesticides. The echinacea seedlings used in the Kirby experiment in 2000-2001 were grown by Peter Green (Corindi Beach, NSW) using organic methods.

3.2.3 Preparation and maintenance of the field plots

The experimental area at Yarrowitch was prepared using two passes with a chisel plough to a depth of 250 mm and one pass with a bed-former to create raised beds. The row width was 2 m and the top of the raised bed was 1.5 m wide and 120 mm high. The sides of the beds and the inter-row area were hand weeded in all treatments. Echinacea seedlings, aged approximately 8 weeks, were transplanted from 25 mm cell trays on 20/10/98. They were planted in two rows 600 mm apart with a 300 mm spacing between plants along the rows. Lettuce seedlings, aged approximately 3 weeks were planted in a similar configuration, but with a 300 mm spacing between plants along the rows, on 11/12/98. The plants were fertilised after planting using organically certified 'Long Life' Dynamic Lifter®, a pelletised poultry manure formulation, at a rate of 70 g per plant. The fertiliser was spread by hand in a circular area around each plant to a radius of 100 mm. The nutrient analysis was nitrogen 4%, phosphorus 3.1%, potassium 1%, calcium 7%, magnesium 0.3%, zinc 0.02 mg/kg and manganese 0.02%. Immediately after planting, the seedlings were watered-in using approximately 5 litres of water for each plant. No further irrigation was applied. The lettuce crop was harvested on 5/2/99 and the echinacea was harvested on 22/3/99.

At the Kirby and Laureldale sites, the experimental areas were prepared using two passes with a chisel plough to a depth of 250 mm and two passes with tractor-mounted rotary hoe to a depth of 100 mm. The rows were 2 m wide and the bed width (not including the tractor wheel paths) was 1.75 m wide. The inter-row area was mown in all treatments. The echinacea and lettuce planting configuration and fertilisation regime were the same as that used at Yarrowitch. The lettuce seedlings were planted on 7/1/00 and 8/1/01, and the echinacea seedlings were planted on 15/11/00. Immediately after planting, the seedlings were watered-in using approximately 5 litres of water for each plant. Watering was repeated three further times at 2-day intervals after the first irrigation. No further irrigation was applied. The lettuce crops were harvested on 26/2/00 and 28/2/01, and the echinacea was harvested on 4/4/01.

The plots used in all experiments were laid out along adjacent prepared and planted beds. The whole area used in each trial was as close to square as possible in order to maximise the area:perimeter ratio. The plots were 10 m long and 2 m wide for lettuce, and 7 m long and 2 m wide for echinacea.

3.2.4 Treatments applied

Five weed control treatments were used in the lettuce and echinacea trials. A summary of the treatments used in each trial is presented in Table 3.2. Supplementary hand weeding was used in the tillage and mulch treatments because it was intended that the treatments should have practical relevance to growers. The paper mulch was not used in the 1999-2000 trials due to lack of availability. Four replicates were used for each treatment at Yarrowitch and Laureldale and eight replicates were used at Kirby in 2000 and 2001. The replicates were allocated to plots in a completely randomised design and randomisation was achieved using a list of random numbers generated by the `rand()` function in Excel.

Table 3.2 Summary of experiments reported in this chapter, and treatments applied in each experiment.

Site	Year	Crop	Control	Hand weeding	Tillage	Hay mulch	Paper mulch
Yarrowitch	1998 - 1999	echinacea	✓	✓	✓	✓	✓
		lettuce	✓	✓	✓	✓	✓
Laureldale & Kirby	1999 - 2000	lettuce	✓	✓	✓	✓	
			✓	✓	✓	✓	
Kirby	2000 - 2001	echinacea	✓	✓	✓	✓	✓
		lettuce	✓	✓	✓	✓	✓

A control treatment, in which weeds were allowed to grow unchecked, was used to determine the background weed load and the comparative effect on crop yield of doing nothing to control weeds. A hand weeding treatment was used to both test its efficacy and cost effectiveness in controlling weeds, and to act as a weeded pseudo-control for determining crop yield in a situation with minimal competition from weeds (Donald 2000). Hand weeding was carried out at 4 WAP (weeks after planting) lettuce and at 4, 8, 12 WAP echinacea, and consisted of manually removing weeds using a wheel-mounted stirrup hoe (Figure 3.4) for weeding along the rows and a chipping hoe for removing weeds between crop plants in the planting row. The wheel hoe blade was 230 mm across and 30 mm wide and was used at a depth of 50 mm, with some deeper tilling required for larger individual weeds. The chipping hoe had a 100 mm wide blade and was used to a depth of about 100 mm.

Figure 3.4 Wheel-mounted stirrup hoe used for the hand weeding treatment. The stirrup hoe attachment is circled.

The tillage treatment, carried out at 4 WAP lettuce and at 4, 8, 12 WAP echinacea, consisted of mechanically removing weeds using a tractor-mounted rigid tine chisel plough (Figure 3.5). The plough had seven 50 mm wide tines operating at a depth of 130 mm. The tines were arranged so that two tines ran outside each of the crop rows, and three tines ran between the two crop rows along the middle of the bed. The operating speed was about 5 km/hour. Immediately after each tillage operation, a chipping hoe was used to remove weeds growing in the planting row between the crop plants, but no attempt was made to remove all weeds in close proximity to the crop plants.

Figure 3.5 Chisel plough used in the tillage treatment at Laureldale and Kirby.

Two mulch treatments were used (Figure 3.6). A hay mulch, predominantly ryegrass (*Lolium* sp.) and oats (*Avena sativa*), was applied to a thickness of 150 mm (9.5 tonnes/hectare) after the crop seedlings were planted, and at 4 WAP weeds immediately around the crop plants were manually removed by hand pulling and a further 0.5 tonnes/hectare of hay was added. A paper mulch, composed of pelletised and dried waste paper slurry, was applied to a thickness of 50 mm (42 tonnes/hectare) after the crop seedlings were planted. At 4 WAP, weeds immediately around the crop plants were manually removed by hand pulling.

Figure 3.6 Example of the hay mulch (left) and paper mulch (right) treatments used in the trials. (The scale bars are graduated in 1 cm intervals.)

3.2.5 Assessment

Assessments of various weed and crop parameters were carried out during the trials. These measurements were not taken within 1 m of the ends of each plot, nor within 250 mm of the sides of each plot.

Weeds

Weeds were defined as any non-crop plant growing in the experimental plots. The spatial distribution of weed species across the field trials was highly variable and, in some cases, limited to distinct patches. The distributions were not related to the treatments used in the experiment, but were based on the pre-existing weed seed bank. The predominant weed species at each site were noted, but no attempt was made to quantify the growth of weeds by taxon or type (e.g. broad-leaved vs. grass, perenniality).

The following measurements of weed growth were made in the lettuce trials. Weed density (weeds/m^2) was measured using a 0.5 m x 1 m quadrat placed lengthwise in the middle of the plot and counting all emerged weeds manually. In the first year's trial, weed density was recorded at harvest only, i.e. seven weeks after planting (WAP) lettuce. In the second and third years, weed density was recorded at two, four (prior to carrying out the scheduled weed control treatments) and seven WAP. Weed biomass was measured at crop harvest by placing a 0.5 m x 1 m quadrat randomly within the plots, cutting all weeds at ground level, drying the cut weeds at 80°C for 72 hours and weighing the dried weeds.

Measurements of weed growth in the echinacea trials included weed density and biomass, both recorded at harvest, i.e. 21 WAP. Similar methods were used to those used for weed measurements in the lettuce trials.

The relative cover of weeds was also measured in all trials, as described in section 0 below.

Crops

The height and diameter of lettuce were recorded at 2, 4 and 7 WAP. Five plants were sampled in each plot, using the 5th, 10th, 15th, 20th and 25th plant from the northern or eastern end of the plots, depending on the orientation of the rows. Height measurements were taken from the ground immediately adjacent to the plant base up to the tip of the highest leaf and diameter measurements were taken across the longest leaf tip-to-leaf tip distance. The relative cover of the lettuce plants was also recorded at the same time as the height and diameter measurements using the method described in section 0 below.

At harvest, eight lettuces were cut at ground level, roughly chopped, dried at 80°C for 72 hours and weighed. At 7, 9 and 10 WAP, the number of bolting lettuces were counted in each plot and those counts were converted to a percentage of total number of plants in each plot. A lettuce was considered to have bolted if the flower stalk had begun to form.

The height, diameter and number of flowers (capitula) of echinacea were recorded at 4, 8, 12, 16, 18 and 21 WAP. Height and diameter measurements were assessed in the same way as for lettuce. Flower counts were based on the number of capitula per sampled plant with a diameter of ≥ 20 mm. Flowering is used by echinacea growers as an indicator of crop maturity and readiness for harvest (P. Green, pers. comm.). The relative cover of the echinacea plants was recorded at 4, 6, 8, 10, 12, 16, 18, 20 and 21 WAP using the method described in section 0 below.

Crop biomass at harvest (21 WAP) was determined by sampling 10 plants in the centre of the plot. The soil was loosened around the plants using a garden fork and the plants were pulled up and separated into shoots (i.e. all above-ground plant parts) and roots sub-samples by cutting plants at the base of the main stem. The roots were roughly chopped to aid drying. Both sub-samples were dried at 80°C for 72 hours and weighed.

Relative cover

The proportion of ground cover occupied by weeds, crops or bare ground (neither crop nor weeds present), referred to here as relative cover, was determined periodically during the growing seasons using 100 ASA Kodak® film stock and a Nikon® FG 35 mm camera with a zoom lens set at a focal length of 35 mm. The aperture setting was adjusted according to the prevailing light conditions and the shutter speed was maintained at $^{1}/_{125}$ second. The camera was held above the centre of the plot in a horizontal position at a height of 1.5 m and the bottom edge of the view in the camera's view finder was kept perpendicular to the crop rows. The area captured in the photographs was 0.87 m^2 (1.11 m long and 0.78 m wide). The field of view included both rows of lettuce or echinacea in each plot, a ~600 mm wide strip between the two crop rows, and a ~250 mm wide strip on the outside of the crop rows. The photographs were 176 mm long x 126 mm wide.

Relative cover was assessed by placing a 28 x 20 cell grid over the photographs and manually counting the cells according to the predominant ground cover category, either weed, crop or bare ground (or mulch). The grid consisted of a pane of glass that was slightly larger than the photographs, with lines etched and painted at 6.3 mm intervals. The counts were converted from a proportion of the total number of grid cells to a percentage.

In the lettuce trials, relative cover was assessed at 2, 4 and 7 WAP. In the echinacea trials, relative cover was assessed at 4, 6, 8, 10, 12, 16, 18, 20 and 21 WAP.

Cost of treatments
A cost-benefit analysis was used to determine the effect of weed control treatments on the net return on a $/hectare basis. The analysis only considered the changes in costs due to the various treatments. The cost of each weed control treatment was based on the amount of materials used, the labour required and machinery usage. All other variable and fixed costs associated with the production of the crop, such as irrigating and fertilising, depreciation and interest on credit, were considered to be equal between treatments and were not included in calculating costs.

The cost for the hand weeding treatment consisted of labour only, while the tillage treatment costs included tractor/implement usage, driver's labour, and supplementary chipping along the planting rows. The costs of the two mulching treatments were based on the price of the mulch, labour to apply the mulch and labour for supplementary hand weeding at 4 WAP. The costs for machinery and implement usage were obtained from the farm manager at Subiaco Herbs (P. Brown, pers. comm.) and at Kirby Research Station (N. Thomas, pers. comm.). There were no costs associated with the control treatment. Labour was assumed to cost $15/hour, including 20% on-costs and the mulches cost $110/tonne and $200/tonne for hay and paper respectively, not including transport. The amount of mulch required was 8 tonnes/hectare of hay mulch and 42 tonnes/hectare of paper mulch. The cost of the tillage treatment, including tractor, ploughing implement and the driver's labour, was $48.82/hectare at Yarrowitch and $56.76/hectare at Laureldale and Kirby.

Weed control treatment costs were converted to $/hectare so that comparisons could be made with crop value. Crop value in $/hectare was calculated by multiplying the wholesale price ($/kg) by the crop yield (kg/hectare). The prevailing wholesale prices in 1999 were $0.58/kg for lettuce (Heisswolf *et al.* 1999), $20.00/kg for echinacea roots and $4.00/kg for echinacea shoots (P. Green, pers. comm.). Adjusted crop values (ACV) were derived by subtracting the cost of each treatment at each site from the gross crop values. The adjusted values provided a measure of the relative cost effectiveness of the treatments in each trial.

3.2.6 Statistical analysis
Data analyses were carried out using the statistical functions available in S-Plus 2000 (MathSoft 1999a, MathSoft 1999b, MathSoft 1999c) and a number of extra functions written for use in S-Plus 2000. In most cases, the Generalized Linear Models (GLMs) were used, via the `glm` function, as they allow for dependence of the variance on the mean (McCullagh and Nelder 1989). GLMs provide the ability to specify the type of distribution of the response variable through the use of family functions that define the link and variance functions (MathSoft 1999a). This overcomes the need to perform *ad-hoc* transformations that attempt to stabilize the mean-variance relationship for variables that are non-normal in distribution (Venables and Ripley 1999). The technique also allows the response variables to be analysed on their original scale (Smyth and Verbyla 1999).

The Tweedie family was used to define the response distribution for variables which could not be satisfactorily modelled using the common distributions available in S-Plus 2000 such as gaussian (normal), binomial, and poisson (Jørgensen 1997, Smyth 2001). The Tweedie family function is used in the GLM to allow the power variance function and power link to be specified. A power variance, p, of zero signifies a gaussian distribution, $p = 1$ signifies a poisson distribution, $p = 2$ a Gamma distribution, $p = 3$ and $p = 4$ an inverse gaussian distribution. The appropriate power variances were derived by computing the sample mean and sample variance for each treatment and then regressing logarithms of the variances against the logarithms of means. The resulting slope coefficient was used as an estimate of p (Smyth and Verbyla 1999).

The GLM function produces an Analysis of Deviance table with a Chi-square test for significance of the explanatory variables. The P-value is presented to indicate the level of significance, with a value of 0.05 or less regarded as significant. A goodness of fit test was conducted to ensure that the data conformed to the assumed underlying distribution by comparing the residual deviance with the underlying Chi-square distribution. When the goodness of fit test reported a significant value, i.e. ≤

0.05, the model was considered unsuitable and the results from that GLM were not used. The dispersion was also estimated in order to protect against erroneous results from over- or under-dispersed data that did not fit the assumed distribution. Dispersion was calculated by dividing the residual Chi-square statistic by the residual degrees of freedom (MathSoft 1999c).

Linear regressions were performed using the linear regression modelling function in S-Plus. This function calculates several values of interest including an Analysis of Variance (AOV) table, an r^2 value, the regression coefficients (and their standard errors and *P*-values) (MathSoft 1999a). Diagnostic plots were generated and assessed to confirm that the data fulfilled the assumptions of the model, particularly homogenous variance and normality of distribution.

Separation of the treatment means was achieved using treatment contrasts, rather than multiple comparison methods. Contrasts are suitable for factorial experiments, including unbalanced layouts and may be used with GLMs. They enable straightforward interpretation and provide superior error protection (Pearce 1993, Venables and Ripley 1999, Riley 2001).

Results from measurements repeated over a period of time cannot be assumed to be independent of each other (Webster and Payne 2002), therefore they were analysed as generalised linear mixed models (GLMMs) using the SAMM suite of functions in S-Plus (Butler *et al.* 2000). The SAMM functions allow for non-normally distributed data and use the ASReml program to evaluate fixed and random effects using restricted maximum likelihood (Butler *et al.* 2000, Gilmour *et al.* 2002). Time was expressed as accumulated degree days (°Cd). The effects of degree days, trial, weed control treatment and their interactions were evaluated as fixed effects and the effects of plot location within the field trials (and its interaction with time) were evaluated as random effects. The response variables weed relative cover and crop relative cover were analysed using the binomial family function. The suitability of the models was assessed by inspecting the plot of residuals versus fitted values and by observing which random terms increased the log residual likelihood. The heterogeneity of the variance (deviance divided by the degrees of freedom) was also checked to ensure that it was close to one, signifying that the chosen distribution was satisfactory. An AOV table with *P*-values based on the Chi-squared test was generated to evaluate the significance of the fixed effects.

Standard errors of the means were used to show the variability of the mean values for categorical data (e.g. weed control treatments) and confidence intervals are used to represent the variability of continuous data (e.g. over time). The correlation between two variables is reported as an r^2 value, and only values of about 0.8 or above are considered to express a strong relationship (Riley 2001).

The Student's *t*-test was used to determine whether the cumulative rainfall and degree days differed between the field sites. A standard two-sample *t*-test was performed, with checks on the assumption of normality and the presence of outliers carried out (MathSoft 1999a).

3.3 Results

3.3.1 Weeds

Weed species
The most abundant weeds at the three field sites are listed in Table 3.3. The list is based on observations made during each trial. The weed flora at Yarrowitch was heavily dominated by the three grasses *Digitaria sanguinalis*, *Paspalum dilatatum* and *Setaria pumila*, with almost no individuals of broad-leaved weeds achieving canopy dominance. At Laureldale, the weed flora was predominantly composed of *Fagopyrum esculentum* and *Polygonum aviculare* early in the growing season and *Echinochloa crus-galli* later in the season. The trials at Kirby were mostly infested with *Acetosella vulgaris* and *Polygonum aviculare* in both growing seasons (2000 and 2001), with the grasses *Festuca arundinacea* and *Vulpia myuros* becoming more common in the second season.

Table 3.3 Weeds that were most abundant at the three field sites, based on observations made during the growing seasons at each trial.

Field site	Weed
Yarrowitch 1999	*Amaranthus* sp. (Amaranth)
	Digitaria sanguinalis (Summer grass)
	Echinochloa colona (Awnless barnyard grass)
	Paspalum dilatatum (Paspalum)
	Setaria pumila (Pigeon grass)
Laureldale 2000	*Amaranthus* sp. (Amaranth)
	Digitaria sanguinalis (Summer grass)
	Echinochloa crus-galli (Barnyard grass)
	Fagopyrum esculentum (Buckwheat)
	Polygonum aviculare (Wireweed)
Kirby 2000 and 2001	*Acetosella vulgaris* (Sorrel)
	Festuca arundinacea (Tall fescue)
	Juncus bufonius (Spiny rush)
	Polygonum aviculare (Wireweed)
	Vulpia myuros (Rat's tail fescue)

Weeds in lettuce

Weed growth during trials
The response of weed relative cover to the weed control treatments during the lettuce trials at Yarrowitch in 1999, Laureldale and Kirby in 2000 and Kirby in 2001 is shown in Figure 3.7. An analysis of the response using GLMMs was carried out with time (degree days), trial, treatment and their interactions as fixed effects. All fixed effects were highly significant ($P < 0.001$), except the trial by time interaction term which was not strongly significant ($P = 0.031$). The relationship between weed relative cover and time (weeks after planting [WAP]) fitted a quadratic function ($r^2 \geq 0.80$) for all treatment by trial combinations except the tillage treatment at Yarrowitch ($r^2 \geq 0.72$) and Kirby in 2001 ($r^2 \geq 0.63$). Weed relative cover in the tillage treatment in these trials showed greater variability than the other trials, especially at harvest (7 WAP). While the control treatment was the most variable (average standard error = 2.7% weed relative cover), tillage was also relatively variable (1.4%) and hand weeding, hay mulch and paper mulch were less variable (0.7, 0.5 and 0.9% respectively).

Weed relative cover increased most rapidly over time in the control treatment. Averaged across all trials, the mean relative cover in that treatment was 1.6%, 18.0% and 43.1% at 2,4 and 7 WAP respectively. A moderate increase was observed for the tillage treatment, rising from a mean relative cover of 1.9% at 2 WAP, to 10.4% at 4 WAP and 12.9 at 7 WAP. The weeding operation at 4 WAP in the hand weeding and tillage treatments appeared to effectively limit further weed growth up to 7 WAP. Weed relative cover in the hand weeding, hay mulch and paper mulch treatments not rise significantly during the trials. At Yarrowitch, the emerged weeds in the hay mulch plots were mainly from the existing weed population (e.g. paspalum, pigeon grass) while at the other sites weed seeds contained in the mulch were the dominant source of weeds.

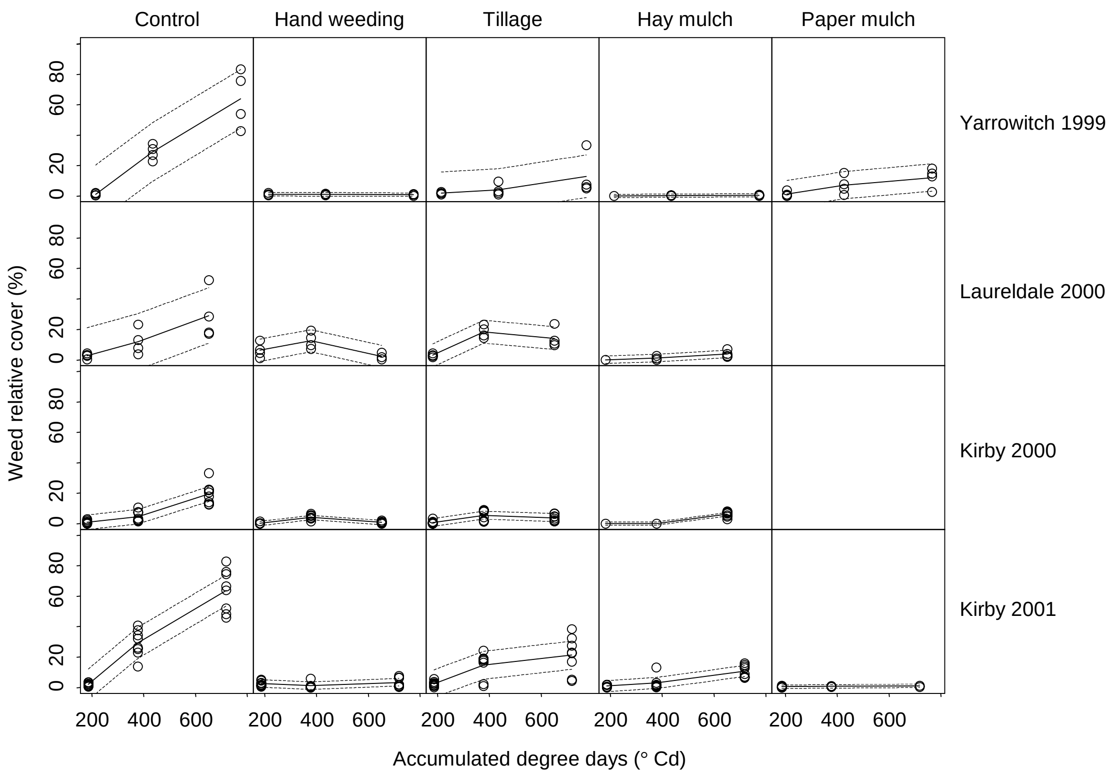


Figure 3.7 Effect of weed control treatments applied in the lettuce trials on weed relative cover (%) over time (accumulated degree days [°Cd]). The circles show the data points, the solid lines are the quadratic regression curves and the dashed lines are the 95% confidence intervals. The paper mulch treatment was not used in 2000.

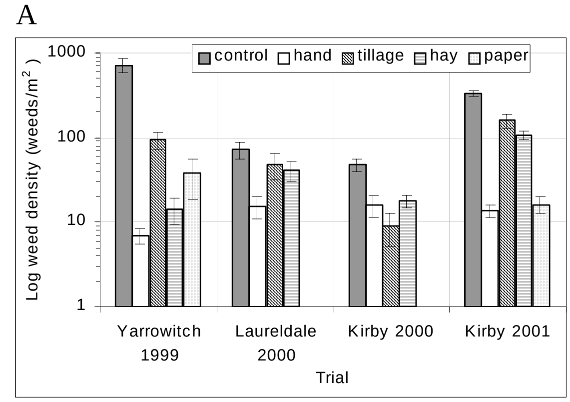
Weed density, biomass and relative cover at harvest

The response of weed density, biomass and relative cover at lettuce harvest is shown in Figure 3.8. Weed density differed significantly ($P < 0.001$) between the trials, treatments and in the interaction of trials and treatments (Figure 3.8A). The weed density of the control treatments gave an indication of the size of the existing weed populations in the absence of any weed control effort. Weed density was highest at Yarrowitch, with 715 weeds/m^2, which was more than double the density at Kirby in 2001 and about ten times more than that at Laureldale and Kirby in 2000.

The weed density in the controls were usually greater than the other treatments, except at Laureldale where it was equivalent to tillage and hay mulch. The tillage treatments showed higher weed densities compared with the non-control treatments at Yarrowitch and Kirby in 2001. In general, the lowest weed densities were observed in the hand weeded plots, however at Kirby in 2000 the non-control treatments were equivalent ($P = 0.664$) and in 2001 the paper mulch produced a similarly low weed density compared with hand weeding ($P = 0.724$). Averaging the treatments for each trial, the control yielded 259 weeds/m^2, tillage produced 80 weeds/m^2, hay mulch 53 weeds/m^2, paper mulch 27 weeds/m^2 and hand weeding 14 weeds/m^2. The difference in weed density of the control treatments between the two seasons at Kirby was very large, i.e. about 50 weeds/m^2 in 2000 and 335 weeds/m^2 in 2001. Staff at Yarrowitch also reported that weeds levels had increased in the three years of annual cropping, prior to using the land for sheep grazing (P. Brown, pers. comm.).

Weed biomass followed a similar pattern to weed density in response to the weed control treatments applied in each lettuce trial, and the differences between trials, treatments and in the interaction of trials and treatments were significant ($P < 0.001$) (Figure 3.8C). Averaged across all trials, the unweeded control produced the greatest weed biomass (1,450 kg/hectare), followed by tillage (498 kg/hectare) and then hay mulch (268 kg/hectare). The weed biomass accumulation in the hay mulch plots was due to the germination and growth of grass seeds, predominantly ryegrass (*Lolium* sp.) and oats (*Avena sativa*), in the hay, rather than pre-existing weeds. Paper mulch and hand weeding produced similar weed biomasses (both about 59 kg/hectare). Expressed as a percentage of the weed biomass for the control treatment (i.e. as a proportion of the background weed levels), this represents an average reduction of weeds by 96% for hand weeding and paper mulch, 80% for hay mulch and 66% for tillage.

The results for weed relative cover (Figure 3.8B) followed a similar pattern as for weed biomass and, to a lesser extent, weed density, with all terms showing significant differences ($P < 0.001$). When the data were averaged across all trials, the unweeded control produced the highest relative cover (43%), followed by tillage (13%), hay mulch (6%), paper mulch (7%) and hand weeding (2%). Weed relative cover for the control treatment was highest at Yarrowitch and Kirby in 2001 and significantly lower at Laureldale and Kirby in 2000.



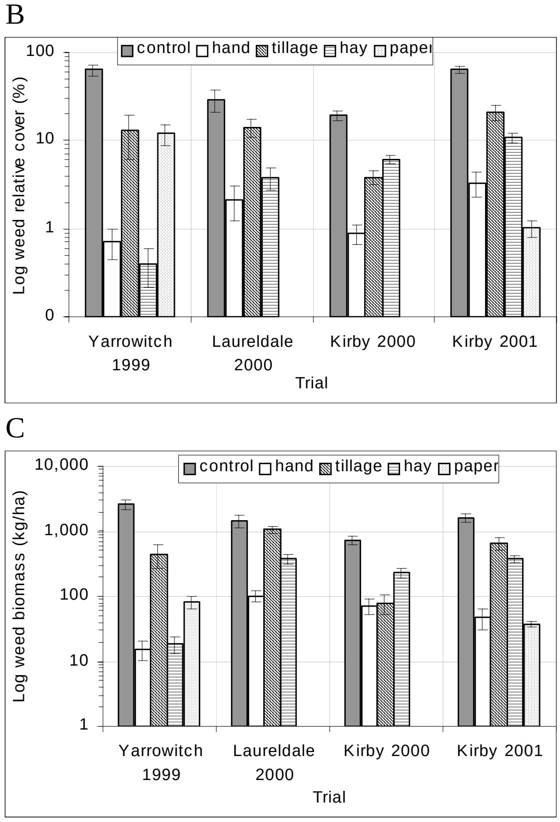


Figure 3.8 Response of (A) weed density (log[weeds/m^2]), (B) weed relative cover (log[%]) and (C) weed biomass (log[kg/hectare]) at lettuce harvest to the weed control treatments applied in the field trials. The columns show the mean of each treatment at each site and the error bars show the standard error of the means. The legends refer to the weed control treatments.

A comparison of the relationships between the three weed variables indicated that weed relative cover was well correlated with weed biomass in all lettuce and echinacea trials ($r^2 \geq 0.826$). The relationships between weed biomass and relative cover in the trials are shown in Figure 3.9. The weed density-relative cover and weed density-biomass relationships were also closely correlated in the trials at Yarrowitch and Kirby in 2001 ($r^2 \geq 0.896$), but not at Laureldale and Kirby in 2000 ($r^2 \leq 0.582$).

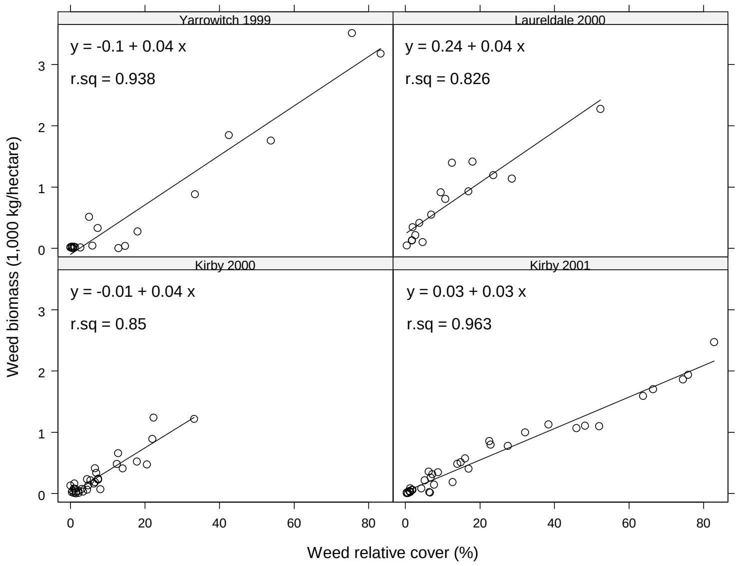


Figure 3.9 The relationship between weed biomass (1,000 kg/hectare) and weed relative cover (%) at harvest for the lettuce trials. The circles represent the data points and the solid lines are the linear regression curves defined by the equation on each graph. The "r.sq" value refers to the correlation coefficient, r^2.

The relationship between weed variables (density, biomass and relative cover) and lettuce yield variables (relative cover and crop value) at harvest was assessed using linear regression. The three weed variables had poor correlations with crop value ($r^2 \leq 0.170$) and crop relative cover ($r^2 \leq 0.388$). The regression slopes were not significant for crop value ($P \geq 0.059$), and were only significant for crop relative cover at Yarrowitch ($P \leq 0.013$, b = -0.01 to -0.44). Treatments with low weed relative cover may also have had lower crop yields (e.g. paper mulch), whilst treatments with moderate weed levels may have had reasonable crop yields (e.g. tillage).

Weeds in echinacea

Weed growth during trials

The response of weed relative cover to the weed control treatments during the echinacea trials at Yarrowitch in 1999 and Kirby in 2001 is shown in Figure 3.10. An analysis of the response using GLMMs was carried out with time (degree days), trial, weed control treatment and their interactions as fixed effects and all terms were highly significant ($P \leq 0.003$). The relationship between weed relative cover and time fitted a quadratic function for all treatment by trial combinations ($r^2 \geq 0.80$) except the tillage treatment at Yarrowitch ($r^2 \geq 0.57$) and Kirby ($r^2 \geq 0.77$). Tillage had an average standard error during the trials of 4.3% relative cover, the control treatment's averaged standard error was 1.8% and the other treatments were between 0.5% and 0.7%. These differences indicate that the tillage treatment was more variability than the other treatments.

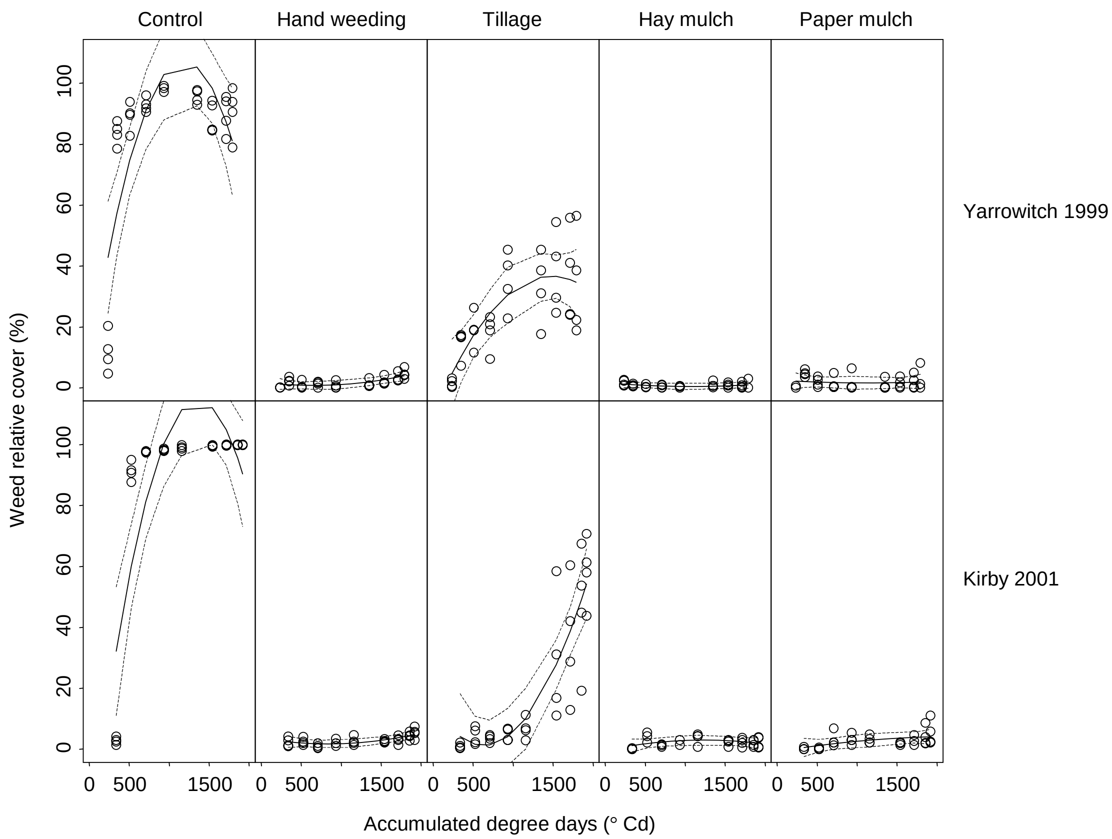


Figure 3.10 Effect of weed control treatments applied in the echinacea trials on weed relative cover (%) over time (accumulated degree days [°Cd]). The circles show the data points, the solid lines are the quadratic regression curves and the dashed lines are the 95% confidence intervals.

Weed relative cover increased rapidly early in the trials for the control treatment, rising from an average of the two trials of 7.3% at 4 WAP (~ 285 °Cd) to 87.4% at 6 WAP (~ 440 °Cd), and then rising only slightly to an average of about 96% for the rest of the experiments. The weed cover at Yarrowitch was more variable in the final weeks of the experiment, ie. 18 - 21 WAP (~ 1,630 - 1,850 °Cd), as the tall grass weeds began to lodge, revealing the stunted echinacea plants lower down in the canopy.

The tillage treatment reduced weed relative cover significantly compared with the control ($P >$ 0.001), however, the response of weed cover over time differed in the two trials. At Yarrowitch, weed cover increased more rapidly during the early weeks of the trial, i.e. from 1.6% at 4 WAP (235 °Cd) to 35.2% at 12 WAP (933 °Cd), and then maintained a similar level for the rest of the trial. At Kirby, the weed cover increased slowly early in the trial, i.e. from 1.0% at 4 WAP (355 °Cd) to 6.8% at 12 WAP (1160 °Cd), but rose quickly in the later weeks to a final coverage of about 58%. Weed relative cover in the hand weeding, hay mulch and paper mulch treatments did not rise significantly during the trials. Averaged across the two trials, these treatments produced significantly lower weed relative covers than tillage from 6 WAP (~ 440 °Cd) onwards, but they were not significantly different from each other at any time. At Yarrowitch, the emerged weeds in the hay mulch plots were mainly from the existing weed population (e.g. paspalum, pigeon grass) while at the other sites weed seeds contained in the mulch were the dominant source of weeds.

Weed density, biomass and relative cover at harvest

The response of weed density, biomass and relative cover at echinacea harvest is shown in Figure 3.11. The effect of the weed control treatments on weed density at echinacea harvest was similar in both trials (Figure 3.11A), although the weed densities of the control and tillage treatments at Kirby were lower (P = 0.018 and 0.031 respectively) than at Yarrowitch. There was a large difference in the underlying weed load, as indicated by the weed densities of the control treatments, with 930 weeds/m^2 at Yarrowitch and 560 weeds/m^2 at Kirby. The interaction between trial and treatment was not significant (P = 0.72).

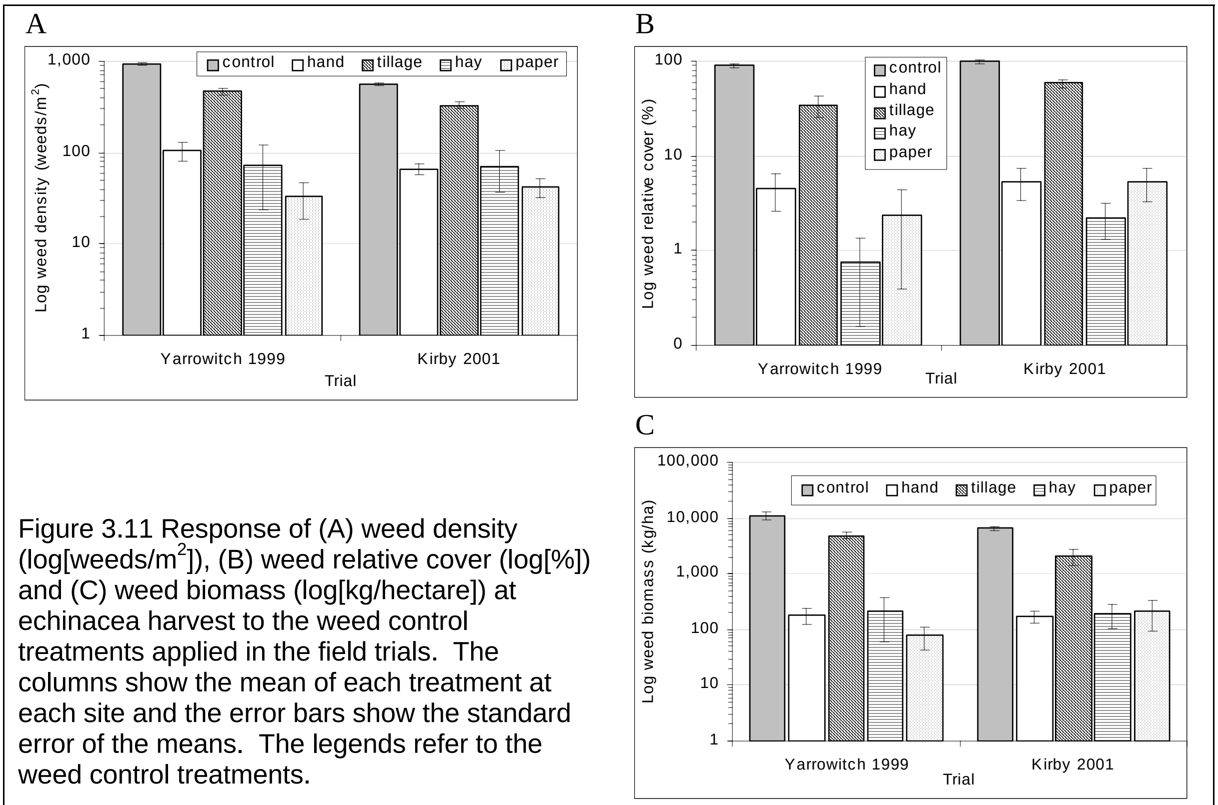


Figure 3.11 Response of (A) weed density (log[weeds/m^2]), (B) weed relative cover (log[%]) and (C) weed biomass (log[kg/hectare]) at echinacea harvest to the weed control treatments applied in the field trials. The columns show the mean of each treatment at each site and the error bars show the standard error of the means. The legends refer to the weed control treatments.

The treatment effect on weed density was highly significant ($P < 0.001$). The highest densities, averaged for both trials, were recorded for the unweeded control (745 weeds/m^2) and the tillage treatment (401 weeds/m^2). The hand weeding (85 weeds/m^2), hay mulch (72 weeds/m^2) and paper mulch (38 weeds/m^2) produced similar weed densities ($P > 0.68$). Tillage reduced the density of weeds present (compared with the control treatment) by about 46%, whilst the other non-control weeding methods reduced weed densities by between 89% and 94%.

The treatment and site effects on weed biomass at the echinacea harvest (Figure 3.11C) showed the same trends as for weed density. Again, the effects of trial and treatment were significant ($P = 0.006$ and $P < 0.001$ respectively), but the interaction was not significant ($P = 0.1234$). Weed biomass was greatest in the control treatment (11,200 kg/hectare at Yarrowitch and 3,500 kg/hectare at Kirby) and moderately high in the tillage plots (average of 3500 kg/hectare for both sites). The final weed biomass of the other treatments, ranging from 150 to 200 kg/hectare, did not differ significantly ($P > 0.88$). A 60% reduction in weed biomass by tillage, compared with unweeded plots, was observed. Hand weeding, hay mulch and paper mulch reduced weed biomass by an average of 98%.

The relative cover of weeds (Figure 3.11B) also showed a similar pattern to the density and biomass measurements in response to the treatment and site effects and their interaction. The weed relative cover for the tillage treatment differed between the two trials ($P = 0.017$), but the other treatments did not ($P \geq 0.130$), and the interaction term was non-significant ($P = 0.098$). Averaging the data for the two sites, weeds almost completely covered the control plots (95%), half covered the tillage plots (46%) and were a very small proportion of the ground cover in the hand weeded, paper mulched and hay mulched plots (5%, 4% and 1% respectively). The treatment differences were significant ($P < 0.001$).

A comparison of the relationships between the three weed variables indicated that weed relative cover was well correlated with weed biomass in both echinacea trials ($r^2 \geq 0.878$). The relationships between weed biomass and relative cover in the trials are shown in Figure 3.12. The weed density-relative cover and weed density-biomass relationships were also closely correlated in the echinacea trials ($r^2 \geq 0.920$).

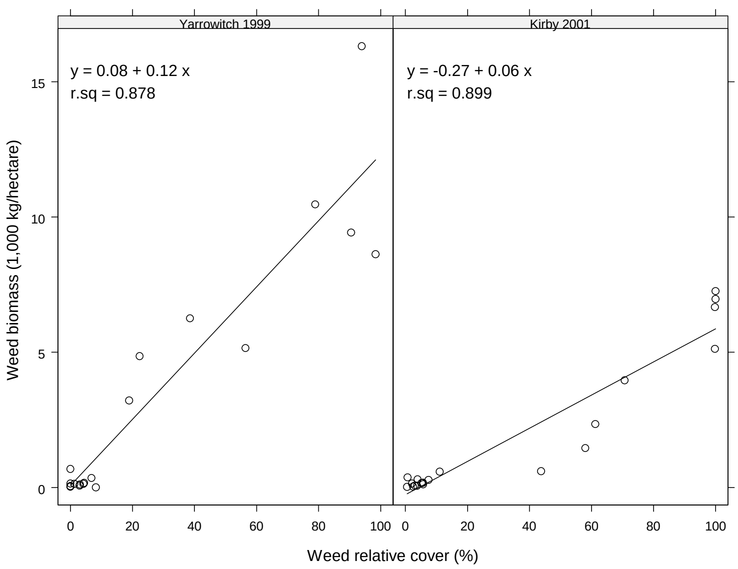


Figure 3.12 The relationship between weed biomass (1,000 kg/hectare) and weed relative cover (%) at harvest for the echinacea trials. The circles represent the data points and the solid lines are the linear regression curves defined by the equation on each graph. The "r.sq" value refers to the correlation coefficient, r^2.

The relationship between weed variables (density, biomass and relative cover) and echinacea yield variables (relative cover and crop value) at harvest was assessed using linear regression. Of the three weed variables, relative cover had the highest correlation with both crop value and crop relative cover in all trials and the slopes were all negative and significant ($P \leq 0.002$). The correlation of weed relative cover was stronger with crop relative cover ($r^2 = 0.985$ and 0.570 at Yarrowitch and Kirby respectively) than with crop value ($r^2 = 0.750$ and 0.423 at Yarrowitch and Kirby respectively). The paper mulch had low weed levels but also had lower crop yields, so excluding the paper mulch treatment improved the correlations ($r^2 \geq 0.80$). However, in general, higher weed relative cover was clearly associated with lower yields of echinacea.

3.3.2 Lettuce

Crop relative cover during trials
The response of crop relative cover to the weed control treatments during the lettuce trials at Yarrowitch in 1999, Laureldale and Kirby in 2000 and Kirby in 2001 is shown in Figure 3.13. Time was expressed as accumulated degree days (°Cd). The relationship between weed relative cover and time was linear, with $r^2 \geq 0.80$ for all treatment by trial combinations. An analysis of the response using GLMMs was carried out with time, trial, weed control treatment and their interactions as fixed effects. All fixed effects were highly significant ($P < 0.001$) except the trial by time interaction, which was slightly non-significant ($P = 0.067$).

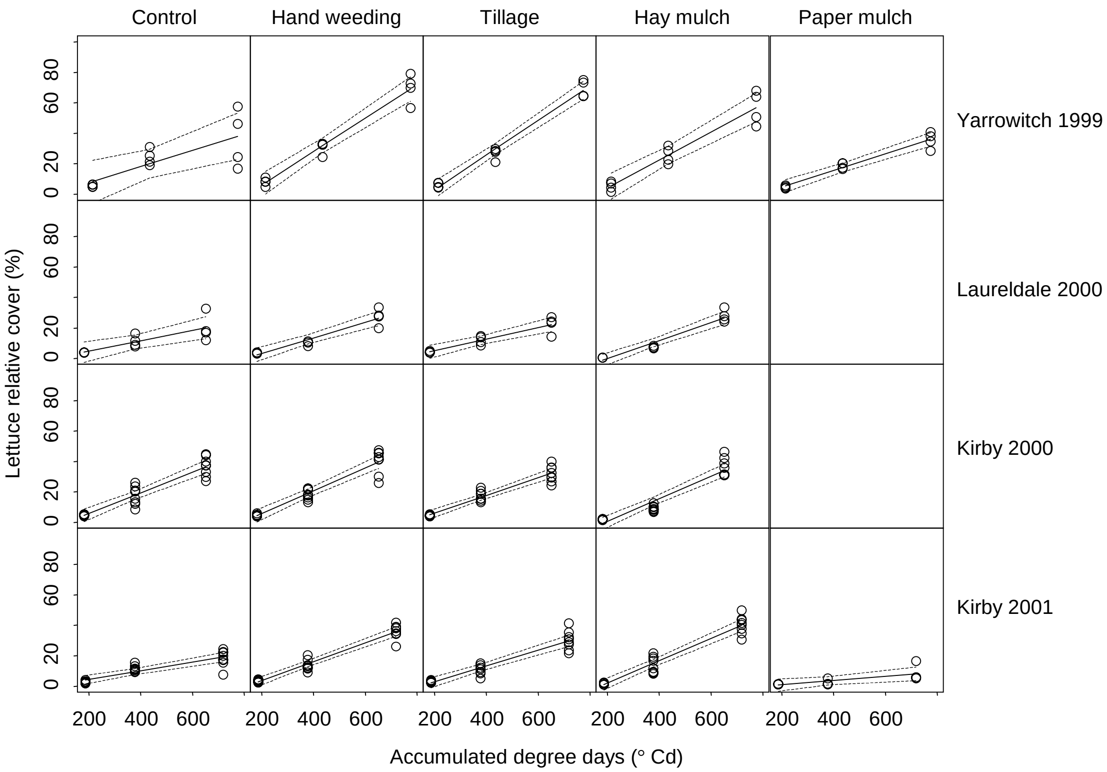


Figure 3.13 Effect of weed control treatments applied in the lettuce trials on crop relative cover (%) over time (accumulated degree days [°Cd]). The circles show the data points, the solid lines are the linear regression curves and the dashed lines are the 95% confidence intervals. The paper mulch treatment was not used in 2000.

The effect of cumulative rainfall on crop relative cover was also tested, and the results were similar to the effect of time (degree days). The linear correlations were high, i.e. $r^2 = 0.81 - 0.98$, except the control treatments where $r^2 \geq 0.57$, and the fixed effects were all highly significant ($P \leq 0.001$). This indicates that lettuce growth was closely related to the amount of rainfall received.

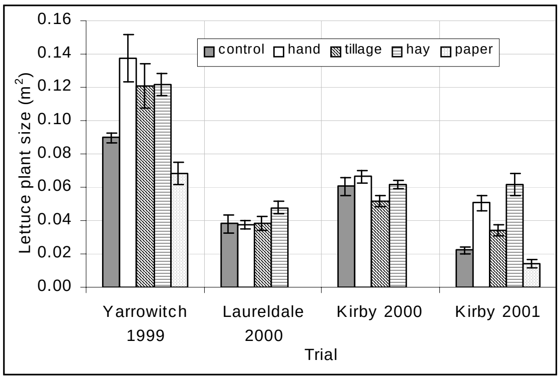
The slope coefficient from the regression may be used as an indicator of the growth rate of the crop. In the lettuce trials, degree day accumulation in a one week period was approximately 100°Cd. Therefore, a *b* value of 0.05 would be equivalent to about 5% increase in relative cover per week. At

Yarrowitch, *b* was about 0.05 for the control and paper mulch treatments and double that for the hand weeding, tillage and hay mulch treatments (*b* ≈ 0.11). At Laureldale in 2000, hand weeding and hay mulch had similar slopes (*b* = 0.05 and 0.06 respectively), while the control and tillage (*b* = 0.03 and 0.04 respectively) were less steep ($P = 0.016$). At Kirby in 2000, the treatments had equivalent slopes of crop relative cover (*b* ≈ 0.07), but in 2001, all treatments at Kirby yielded significantly different slopes ($P \leq 0.025$). Hand weeding and hay mulch had the highest coefficients (*b* = 0.06 and 0.07 respectively), tillage produced an intermediate slope (*b* = 0.05) and the control and paper mulch had smallest coefficients (*b* = 0.03 and 0.01 respectively).

Plant size, relative cover and yield at harvest

The parameters lettuce plant size (height x diameter), relative cover and yield (expressed as fresh weight biomass, tonnes/hectare) were measured at harvest (7 WAP) and analysis using GLMs found that their response was significantly different between trials and treatments ($P < 0.001$). Each of these parameters showed a generally similar pattern in response to the treatments and between trials (Figure 3.14). The highest growth and yields were recorded at Yarrowitch, with plants averaging 0.11 m^2 in size, 53% relative cover and about 25 tonnes/hectare in crop yield. The lettuce growth at Kirby in 2000 was significantly lower than at Yarrowitch ($P \leq 0.002$) by about 40% for plant size, 30% for relative cover, and about 10% for yield. The lowest growth was observed in the trials at Laureldale in 2000 and Kirby in 2001, both significantly lower than Kirby in 2000 ($P \leq 0.05$).

A



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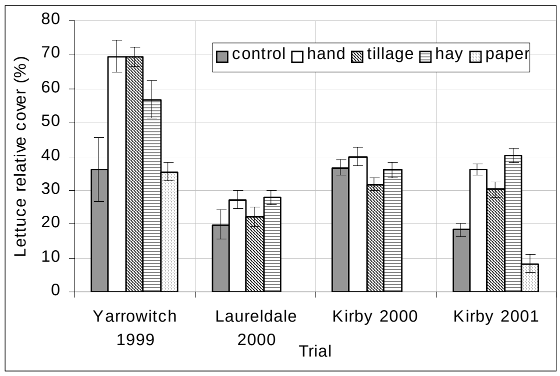

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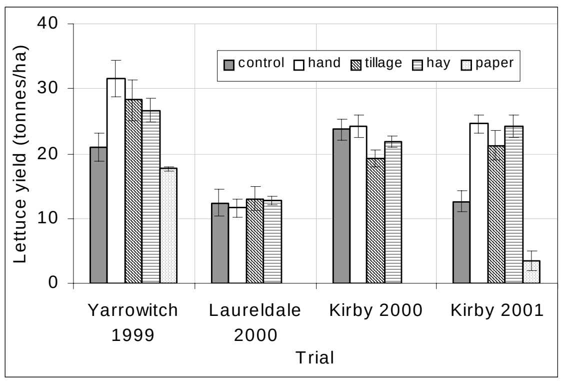


Figure 3.14 Response of lettuce (A) plant size (height x diameter, m^2), (B), relative cover (%) and (C) crop yield (tonnes/hectare) at harvest to the weed control treatments applied in the field trials. The columns show the mean of each treatment at each site and the error bars show the standard error of the means. The legends refer to the weed control treatments.

The weed control treatments produced the same ranking for each parameter measured when averaged across the four trials. Hand weeding and hay mulch gave the highest growth and yield, with lettuce plants averaging 0.07 m^2 in size, 40% relative cover and about 23 tonnes/hectare crop yield. The results for tillage were slightly less (~10-19%) than hand weeding and hay mulch, though not significantly ($P \geq 0.089$). In the control treatment, plant size was reduced by 28% compared with the hand weeding treatments, relative cover was reduced by one third and yield was down by one quarter. Paper mulch produced the lowest growth and yields, with lettuce plant size reduced by 40%, and relative cover and yield by about 50% compared with hand weeding.

The relative performance of the treatments differed between trials, as indicated by the highly significant interaction of trial and treatment in the analysis ($P < 0.001$). Larger differences were observed at Yarrowitch and Kirby in 2001, while responses to treatments at the other two sites were mostly not significantly different. At Yarrowitch and Kirby in 2001, the rankings generally followed the pattern found for the across-site averages referred to above, i.e. hand weeding = hay mulch = tillage > control > paper mulch. The treatment effects at Kirby in 2000 were smaller, with the only significant differences occurring between hand weeding and tillage ($P \sim 0.034$). At Laureldale, the treatments produced similar results ($P \geq 0.142$).

Bolting
The proportion of lettuces that were bolting at harvest time is shown in Figure 3.15. At 7 WAP, the lettuces in the hand weeding and tillage treatments showed significantly higher rates of bolting (25% and 8% of plants per plot, respectively) compared with the other treatments ($P < 0.001$). In plots in which the soil was covered by either weeds (i.e. the control treatment) or mulch, only 1-2% of the lettuces were bolting. An analysis of the effect of soil relative cover on bolting using GLMs indicated that there was a significant relationship ($P < 0.001$).

The extent of bolting was similar in 1999 and 2000 (2.8 - 4.2%), however, bolting at Kirby in 2001 was significant greater ($P < 0.001$) than the other trials, with about 18% bolting averaged across treatments. In particular, lettuces in the hand weeded treatment at Kirby in 2001 had bolted excessively (60%) by harvest time.

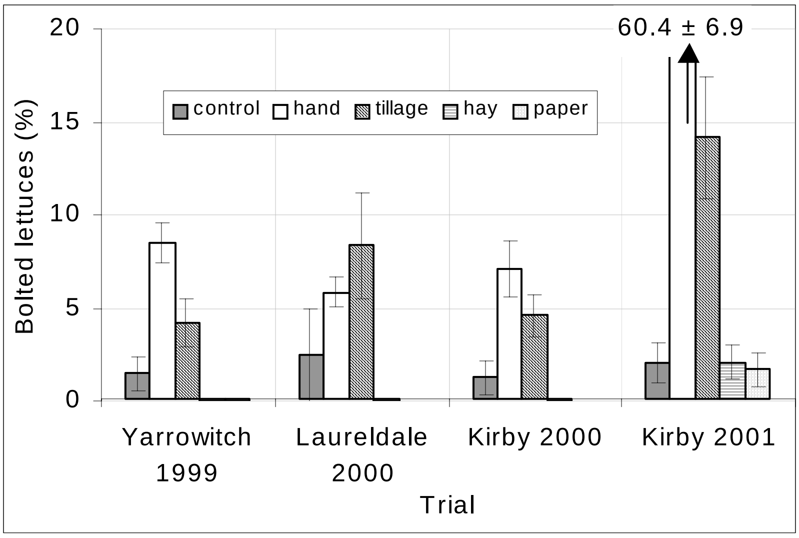


Figure 3.15 Proportion of bolted lettuces (% of plants per plot, n = 48) at harvest in response to the weed control treatments applied in the field trials. The columns show the mean of each treatment at each site and the error bars show the standard error of the means. The legend refers to the weed control treatments.

Economic analysis
The direct cost of carrying out each weed control treatment in the four trials is given in Figure 3.16. Paper mulch was the most expensive treatment, costing about $12,100/hectare for the initial purchase of the mulch, laying and minor follow-up hand weeding at 4 WAP. About 70% of the cost was related to the purchase of the mulch and 29% to laying the mulch, and 1% for the follow-up hand weeding. The hay mulch was the next most expensive treatment, costing about $7,600/hectare. However, the purchase cost of the mulch was considerably less (14% of total cost) than the cost of labour for laying the hay mulch (50%) and subsequent hand weeding (36%). The cost of the hand weeding was approximately $4,400/hectare, consisting entirely of labour. The tillage treatment was relatively cheap, about $985, and was made up of 5% for machinery costs and 95% for labour

(tractor driving and supplementary hand weeding). No direct financial costs were incurred in the control treatment.

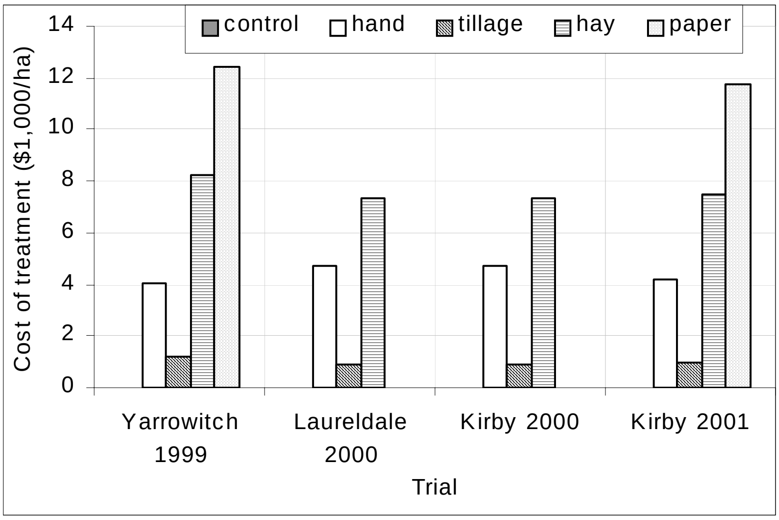


Figure 3.16 The cost of weed control treatments applied in the field trials. The columns show the mean of each treatment at each site (n = 4). The legends refer to the weed control treatments.

The gross crop value and the adjusted crop value (ACV), i.e. the gross crop value minus the cost of the treatment, are given in Figure 3.17. Graph A shows that the highest gross crop value was recorded at Yarrowitch ($19,000/hectare), followed by Kirby in 2000 ($17,000/hectare). The lowest crop values were observed in the trials at Laureldale in 2000 and Kirby in 2001, $9,400 and $14,200 per hectare respectively, both significantly lower than Kirby in 2000 ($P \leq 0.05$). Averaged across the trials, the treatments with the highest gross crop value were hand weeding, hay mulch and tillage, with values for the control treatment slightly lower ($P = 0.014$), and considerably lower for paper mulch ($P < 0.001$). These differences were distinct at Yarrowitch in 1999 and Kirby in 2001, but in the 2000 trials the treatment differences were generally not significant, except hand weeding and tillage at Kirby (P = 0.051). The income reported in the gross margin budget for lettuce production in NSW in 2001 was $17,600/hectare (NSW Agriculture 2001).

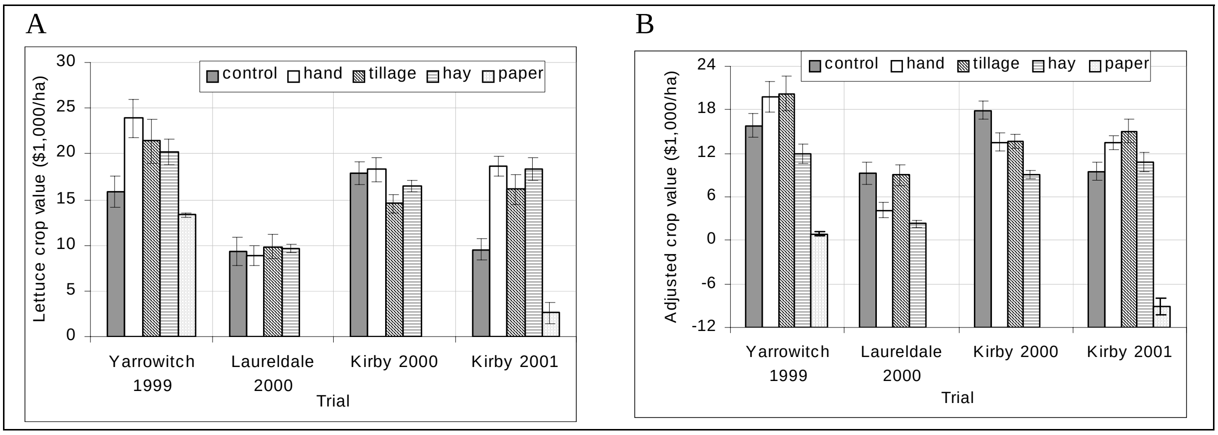


Figure 3.17 The (A) gross crop value and (B) adjusted crop value ($1,000/hectare) of lettuce for each treatment applied in the field trials. The columns show the mean of each treatment at each site and the error bars show the standard error of the means. The legends refer to the weed control treatments.

The ACV provides a measure of the relative cost effectiveness of the weed control treatments under the experimental conditions imposed (Figure 3.17B). Averaged across all trials, the tillage, control and hand weeding treatments resulted in the highest ACVs ($14,600/hectare, $13,300/hectare and $11,700/hectare respectively). Hay mulch, with an ACV of $8,700/hectare, was significantly lower than tillage and the control ($P \leq 0.015$), but not hand weeding ($P = 0.114$). Paper mulch yielded a very low ACV, giving a mean loss of $4,100/hectare.

The ACV showed a similar pattern amongst treatments at Yarrowitch and Kirby in 2001. Tillage, hand weeding, the control and hay mulch gave the highest values and paper mulch the lowest. In those trials, the top four treatments were generally not significantly different. At Laureldale, the ACVs for the control and tillage treatments were equivalent ($P = 0.902$), as were the ACVs for hand weeding and hay mulch ($P = 0.913$). Those two pairs of treatments were significantly different from each other ($P < 0.001$). The response of the ACV at Kirby in 2000 was unique amongst the trials in that the control treatment was significantly higher than the other treatments ($P \leq 0.048$). Tillage, hand weeding and hay mulch were equivalent, but tillage was slightly higher than hay mulch ($P = 0.032$).

3.3.3 Echinacea

Crop relative cover during trials
The response of crop relative cover to the weed control treatments during the echinacea trials at Yarrowitch in 1999, Laureldale and Kirby in 2000 and Kirby in 2001 is shown in Figure 3.18. A cubic function was used to describe the change in echinacea relative cover over time (expressed as degree days) and all treatment by trial combinations had high correlations ($r^2 \geq 0.80$), except the tillage treatment ($r^2 \geq 0.79$) and paper mulch at Kirby ($r^2 \geq 0.66$). One replicate in the latter treatment showed significantly higher growth towards the end of the trial than the other replicates ($P = 0.029$) and temporarily excluding this replicate from the regression analysis yielded an r^2 of 0.88. An analysis of the response using a GLMM was carried out with time, trial, weed control treatment and their interactions as fixed effects. All fixed effects were highly significant ($P < 0.001$).

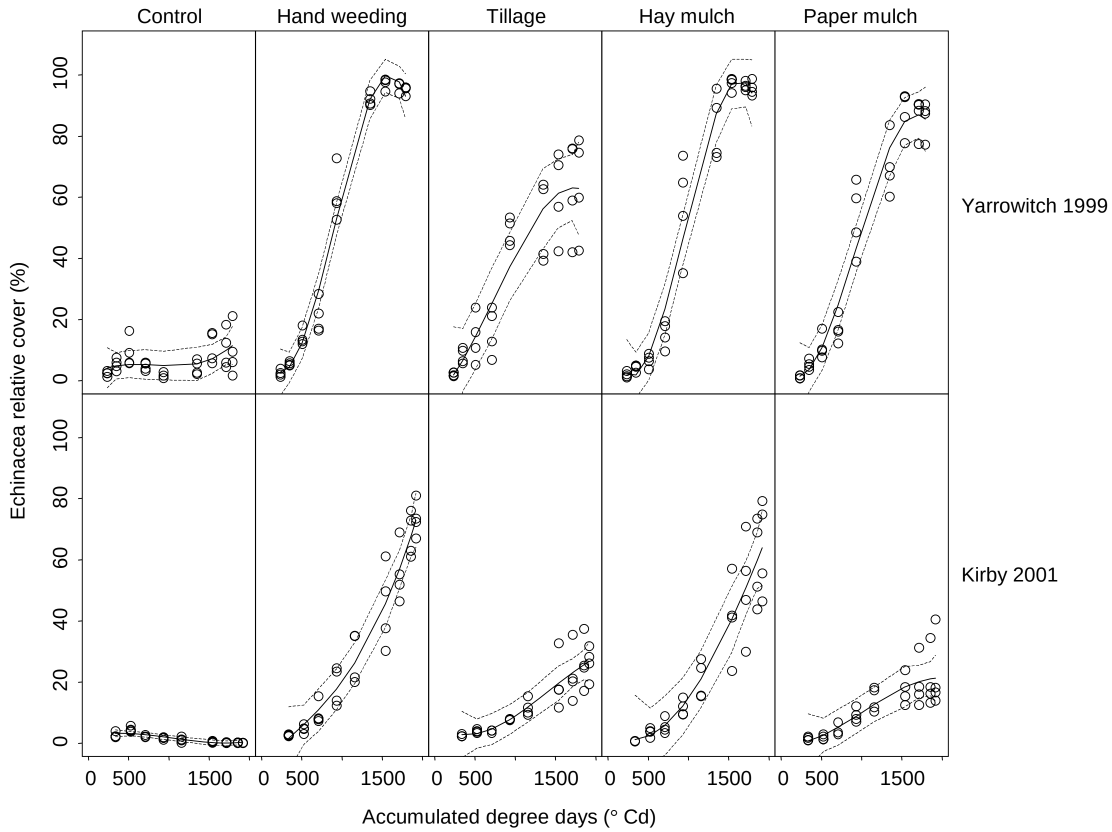


Figure 3.18 Effect of weed control treatments applied in the echinacea trials on crop relative cover (%) over time (accumulated degree days [°Cd]). The circles show the data points, the solid lines are the cubic regression curves and the dashed lines are the 95% confidence intervals.

An analysis of the effect of cumulative rainfall on crop relative cover was also carried out. The results were similar to the effect of time (degree days). The cubic correlations were relatively high, i.e. $r^2 = 0.76 - 0.95$ (except the control treatments where $r^2 = 0.19$ at Yarrowitch and 0.67 at Kirby) and the effects were all highly significant ($P \leq 0.001$), apart from the trial by rainfall interaction ($P = 0.029$). This suggests that echinacea growth was closely related to the amount of rainfall received, except in very weedy plots.

The control treatment in both trials produced very little increase in echinacea relative cover over time, with the plants at Kirby slightly decreasing ($P < 0.001$). At Yarrowitch, the greatest increase in relative cover occurred in the hand weeding and hay mulch treatments ($b \approx 0.07$), with both treatments reaching about 96% coverage. The paper mulch at Yarrowitch also produced a strong growth response ($b = 0.06$) but with a lower asymptote of 86% relative cover. In the tillage treatment, the crop plants had an moderate growth rate($b = 0.04$), achieving a maximum relative cover of about 64%.

At Kirby, hand weeding and hay mulch treatments gave the greatest increase in crop growth ($b \approx 0.05$), with a relative cover at harvest of about 66%. The paper mulch treatment produced a notably smaller growth rate ($b = 0.01$) compared with paper mulch at Yarrowitch ($P < 0.001$), causing it to be ranked below tillage ($b = 0.02$), though not significantly ($P = 0.02$).

The non-control treatments appear to have reached their asymptote of maximum relative cover at Yarrowitch but not at Kirby. The crops were grown for the same length of time at each site and accumulated the same number of degree days, but Kirby received 43% less rainfall. Some differences in the soil nutrient status between the sites were detected. The possible reasons for the different growth responses between trials are considered in the discussion below.

Plant size, relative cover and yield at harvest
The effect of the weed control treatments applied at Yarrowitch in 1999 and Kirby in 2001 on final echinacea plant size (height x diameter), relative cover and yield (expressed as dry weight biomass, tonnes/hectare) is shown in Figure 3.19. Analysis of plant size, relative cover and crop yield using GLMs found significant differences between the two trials ($P = 0.001$), the weed control treatments ($P \leq 0.007$), and in the interaction of trials and treatments ($P \leq 0.002$). The possible reasons for the large differences in the growth of echinacea recorded at Yarrowitch and Kirby are evaluated in the discussion (0 below). An analysis of the effect of cumulative rainfall and various leaf tissue nutrient concentrations (unpublished data) on crop yield was carried out using GLMs. The nutrients tested were nitrogen (N), potassium (K), calcium (Ca), magnesium (Mg) and aluminium (Al), all of which differed between the soil tests at each trial (Table 3.1), and which may have had an effect on echinacea yield. The analysis showed that rainfall was highly significant ($P \leq 0.003$) but leaf nutrient concentrations were not ($P \geq 0.062$).

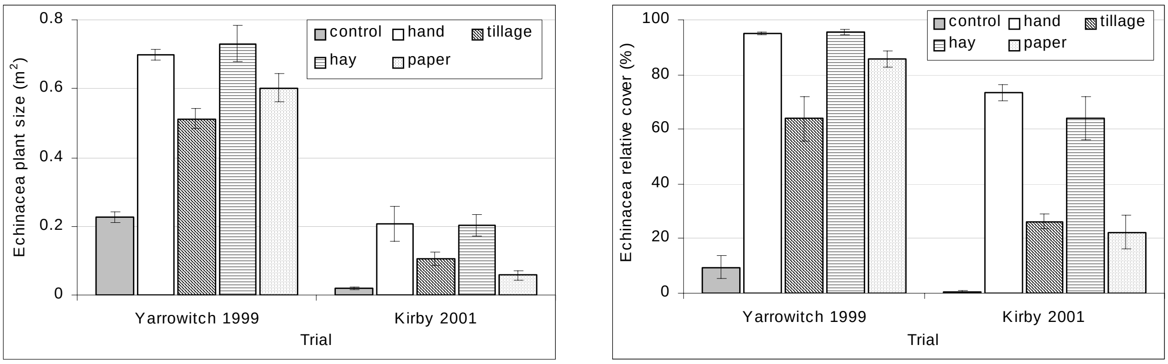
Averaging the results in each trial, plant size was 0.55 m^2 and 0.12 m^2 at Yarrowitch and Kirby respectively, relative cover was 70% and 37%, and crop yield was 5.1 tonnes/hectare and 1.1 tonnes/hectare. Despite the different scales of growth response in the two trials, the treatment effects showed a generally similar pattern, with the exception of paper mulch. Additionally, the treatment rankings were similar for the three growth parameters plant size, relative cover and crop yield.

Echinacea growth was highest in the hand weeding and hay mulch plots. These treatments were not different statistically ($P \geq 0.230$) from each other. The average plant size in the hand weeded and hay mulched plots was 0.71 m^2 and 0.20 m^2 at Yarrowitch and Kirby respectively, average relative cover was 95% and 69%, and mean crop yields were 7.8 tonnes/hectare and 2.2 tonnes/hectare.

At Yarrowitch, paper mulch had the next highest growth after hand weeding and hay mulch ($P \leq 0.032$), with mean plant size reduced by 15%, relative cover by 10% and crop yield by 33%. Tillage produced slightly lower echinacea growth than the paper mulch, with the difference being significant for relative cover ($P = 0.035$) but not for plant size and crop yield ($P \geq 0.148$). The tillage treatment reduced plant size and relative cover by about one third compared with hand weeding and hay mulch, while yield was about half that in the hand weeding and hay mulch treatments. The lowest echinacea growth was recorded for the unweeded control treatments, a result that was significantly lower than the other treatments ($P < 0.007$). Plant size was reduced by about 70% of the hand weeded and hay mulched plots, and relative cover and crop yield were reduced by about 90%.

At Kirby, paper mulch produced lower yields than tillage, although the difference was not significant ($P \geq 0.132$). The responses of the tillage and paper mulch treatments were lower than hand weeding and hay mulch ($P \leq 0.012$), and were generally higher than the control treatment. The lower ranking of paper mulch was related to the large decline in echinacea growth under paper mulch, rather than a change in the performance of the tillage treatment. A moderate decrease in the crop growth of the tillage treatment at Kirby was recorded. Plant size in the tillage treatment was 72% (relative to hand weeding and hay mulching) at Yarrowitch compared with 52% at Kirby, crop relative cover was 67% at Yarrowitch compared with 38% at Kirby, and crop yield was 46% at Yarrowitch compared with 41% at Kirby. However, a comparison of paper mulch with hand weeding and hay mulch showed larger reductions in crop growth between Yarrowitch and Kirby. Relative performance decreased from 84% at Yarrowitch to 28% at Kirby for plant size, 90% to 32% for relative cover and 66% to 27% for crop yield. The control treatment gave the lowest growth in echinacea at Kirby. Compared with hand weeding and hay mulch, the unweeded control reduced plant size by 90%, relative cover by 99% and crop yield by 95%.

A	B



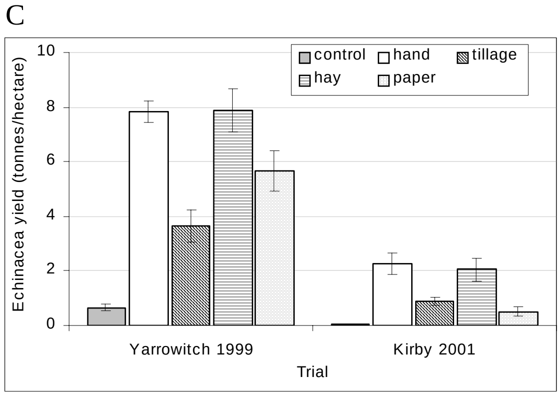


Figure 3.19 Echinacea (A) plant size (height x diameter, m^2), (B) relative cover (%), and (C) crop yield (tonnes/hectare) at harvest in response to the weed control treatments applied in the field trials. The columns show the mean of each treatment at each site and the error bars show the standard error of the means. The legends refer to the weed control treatments.

The echinacea yield was measured by determining the biomass of both the above-ground plant parts, called shoots, and the below-ground parts, called roots. The responses of the shoots and roots biomass to the treatments at each trial closely followed the pattern reported for crop yield (Figure 3.19C) and have, therefore, not been reported separately. However, the proportional contribution of shoots and roots biomass to total biomass (crop yield) is of interest (Figure 3.20), as echinacea roots have a higher economic value than the shoots. Therefore, weed control treatments that maximise the proportion of roots in total plant biomass, while not penalising overall yield, may have economic advantages.

An analysis of the ratio of shoot biomass to root biomass using GLMs indicated that the effects of trials, treatment and their interaction were significant ($P < 0.001$). The proportion of root biomass was greater at Kirby (average = 31%) than at Yarrowitch (average = 15%). At Yarrowitch, the ratio of shoot biomass to root biomass was the same for all non-control weed treatments ($P \geq 0.102$), an average of 86:14, but the control treatment had a lower ratio (80:20) of shoot to root ($P < 0.001$). At Kirby, the response pattern was similar, with the control having the lowest shoot:root ratio (48:52) ($P \leq 0.003$), and the other treatments having equivalent proportions of shoot to root biomass ($P \geq 0.197$) ranging from 70:30 in the tillage treatment to 81:19 in the hay mulch treatment. The tillage treatment did not appear to reduce the proportion of roots, an outcome that may have been expected given the higher level of soil disturbance compared with the other non-control treatments.

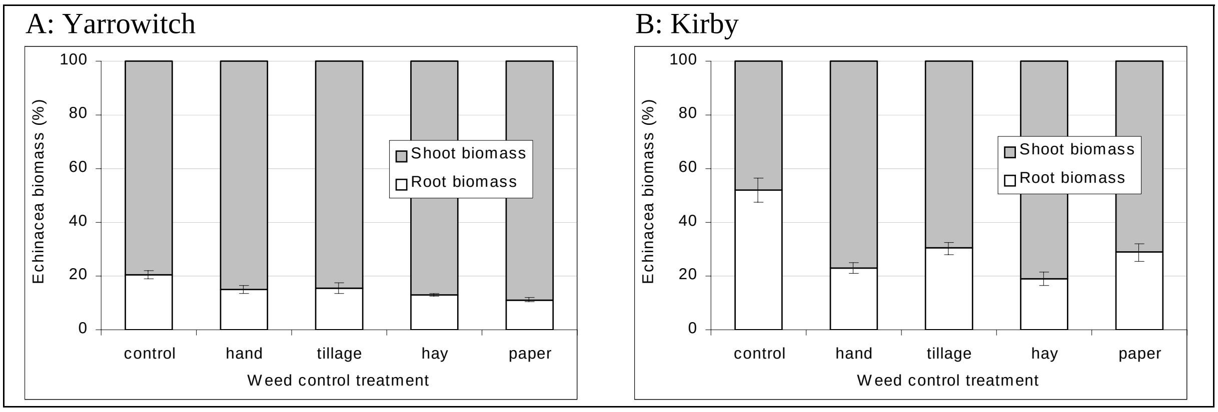


Figure 3.20 Proportional contribution (%) of shoot biomass and root biomass to total echinacea biomass at harvest in response to the weed control treatments applied at (A) Yarrowitch and (B) Kirby. The columns show the mean of each treatment (n = 4) and the error bars show the standard error of the means.

Flowering

The effect of the weed control treatments on echinacea flowering over time is presented in Figure 3.21. An analysis of the response using a GLMM was carried out with time, trial, weed control treatment and their interactions as fixed effects. All fixed effects were highly significant ($P < 0.008$) except the treatment by time interaction ($P = 0.110$).

The number of flowers in the control treatments was significantly lower than in the other treatments ($P < 0.001$) and did not increase during the sampling period ($P_{slope} \geq 0.327$). The other treatments at Yarrowitch fitted a quadratic function ($r^2 \leq 0.80$), with almost no flowering up to 12 WAP (~ 1050 °Cd) as the plants continued to grow vegetatively. Hand weeding had the greatest increase in flower numbers (about 2 flowers/plant/week), followed by paper and hay mulch (about 1.5 flowers/plant/week), then tillage (0.7 flowers/plant/week). The non-control treatments at Kirby were more variable in their flowering over time ($r^2 \leq 0.69$), particularly hand weeding and hay mulch, the two treatments with the highest rate of flowering (about 2.3 flowers/plant/week). Tillage and paper mulch had flowering rates of about 0.8 flowers/plant/week.

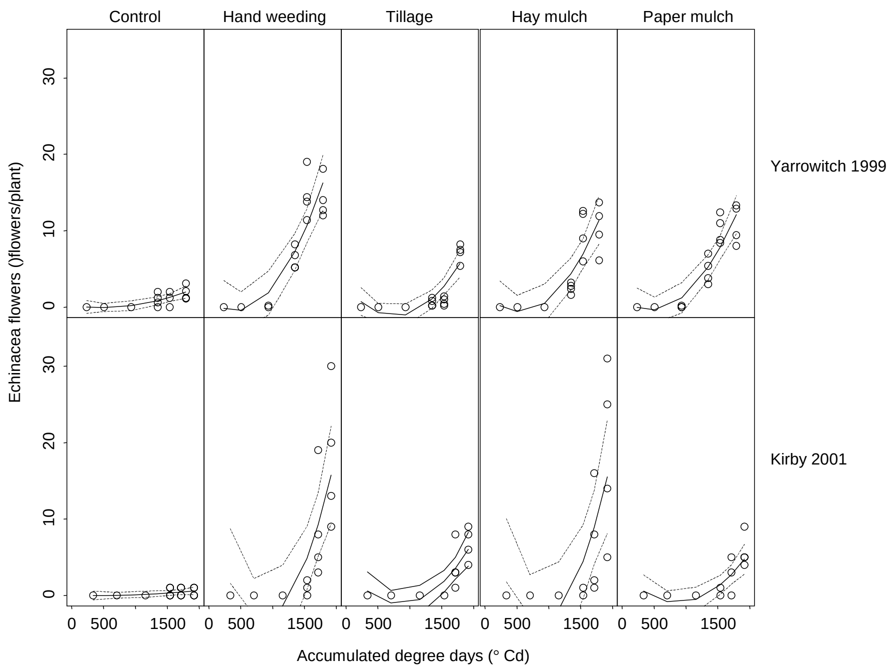


Figure 3.21 The number of flowers per echinacea plant over time (accumulated degree days [°Cd]) in response to the weed control treatments applied at Yarrowitch and Kirby. The circles show the data points, the solid lines are the quadratic regression curves and the dashed lines are the 95% confidence intervals.

The number of flowers occurring on echinacea plants at harvest is shown in Figure 3.22. Analysis using GLMs indicated that flowering varied significantly by treatment ($P < 0.001$), and that the difference in flowering between the two trials was not significant ($P = 0.319$) although the trial-treatment interaction was significant ($P \leq 0.002$). The most abundant flowering at Yarrowitch was observed in the hand weeding treatment, followed by the paper and hay mulches. These treatments were not significantly different ($P \geq 0.232$). The tillage treatment had about half as many flowers as the hand weeding treatment ($P = 0.029$), but only slightly less than the mulched plots ($P \leq 0.269$). Flowering in the control treatment was about 13% of the hand weeding plots, and significantly lower than the other treatments ($P < 0.001$). At Kirby, hand weeding and hay mulch flowered to an similar extent and had the highest number of flowers of the weed control treatments ($P \leq 0.023$). Tillage and paper mulch also had similar levels of flowering, having about one third the number of flowers of the hand weeding and hay mulch treatments. The control treatment had very few flowers (3% of the hand weeding and hay mulch plots) and was significantly lower than the other treatments ($P < 0.001$). A linear regression analysis indicated that the number of flowers was reasonably well correlated with the total crop biomass at harvest, with an r^2 of 0.77 at Yarrowitch and 0.90 at Kirby.

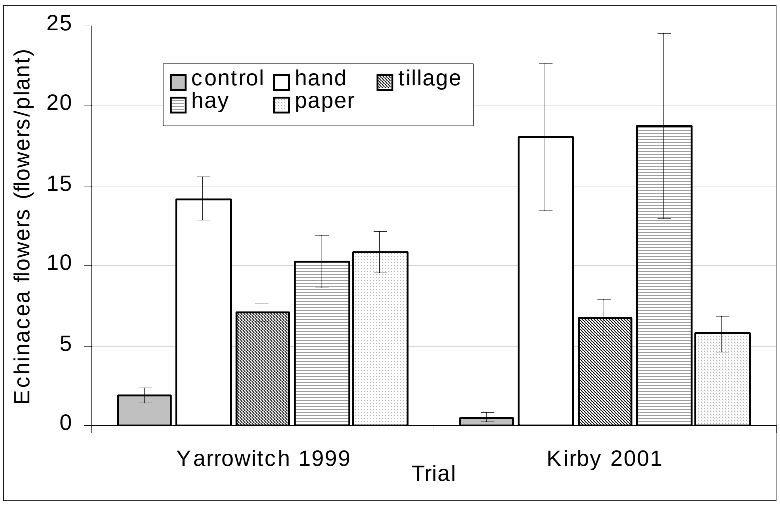


Figure 3.22 The number of flowers per echinacea plant at harvest in response to the weed control treatments applied at Yarrowitch and Kirby. The columns show the mean of each treatment at each site and the error bars show the standard error of the means. The legend refers to the weed control treatments.

Economic analysis

The direct cost of carrying out each weed control treatment in the four trials is shown in Figure 3.23. Paper mulch was the most expensive treatment at a cost of about $13,000/hectare, of which 65% was due to purchase costs, 30% to laying and 5% to minor follow-up hand weeding. Hand weeding was the next most expensive treatment ($9,600/hectare) followed by hay mulch ($8,900/hectare). The hay mulch costs were based on purchase costs (14%), laying the mulch (50%) and supplementary hand weeding (36%). Tillage was the least expensive treatment ($4,000/hectare), made up of machinery costs (4%) and labour (95%). No costs were associated with the control treatment.

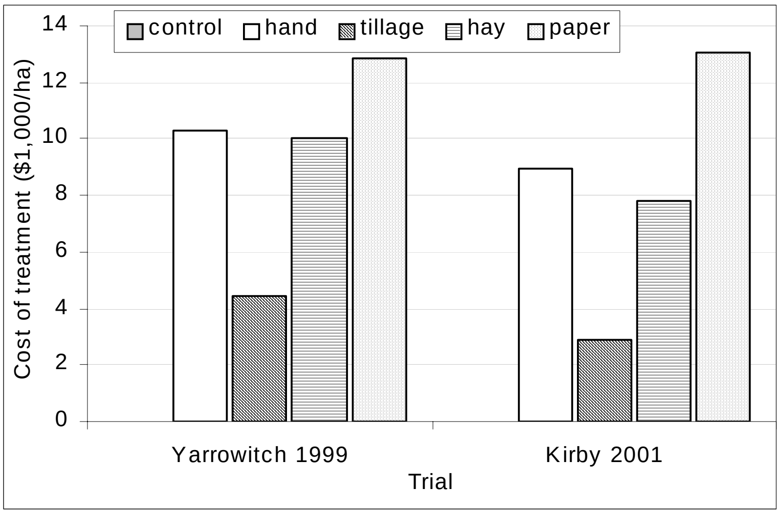


Figure 3.23 The cost of weed control treatments applied in the field trials. The columns show the mean of each treatment at each site (n = 4). The legend refers to the weed control treatments.

The gross crop value and the adjusted crop value (ACV) of the weed control treatments are shown in Figure 3.24. In graph A, the response pattern for gross crop value follows that reported for crop yield (Figure 3.19C), with large differences observed between trials and treatments ($P < 0.001$). Hand weeding and hay mulch produced similarly high crop values, averaged at $49,000/hectare and $15,500/hectare at Yarrowitch and Kirby respectively, whilst the crop value for tillage was about half those figures and the control treatment about 10% of the value of hand weeding and hay mulch.

Paper mulch performed moderately well at Yarrowitch, with a crop value about one third less than hand weeding and hay mulch, but performed poorly at Kirby, with a crop value about 70% less than hand weeding and hay mulch.

The ACVs for the treatments in Figure 3.24B indicated that the treatment rankings changed, compared with gross crop value, at Kirby but not at Yarrowitch. In the former trial, the higher cost of implementing hand weeding and hay mulch, in combination with the lower overall yields, reduced the yield advantages observed at Yarrowitch. The ACV for hand weeding and hay mulch became equivalent to the cheaper tillage treatment ($P \geq 0.526$) and control slightly more cost effective than the control treatment ($P = 0.013$ and 0.052 respectively). The relatively high cost of the paper mulch treatment and its poor crop yield at Kirby meant that a loss of about $9,000/hectare was incurred.

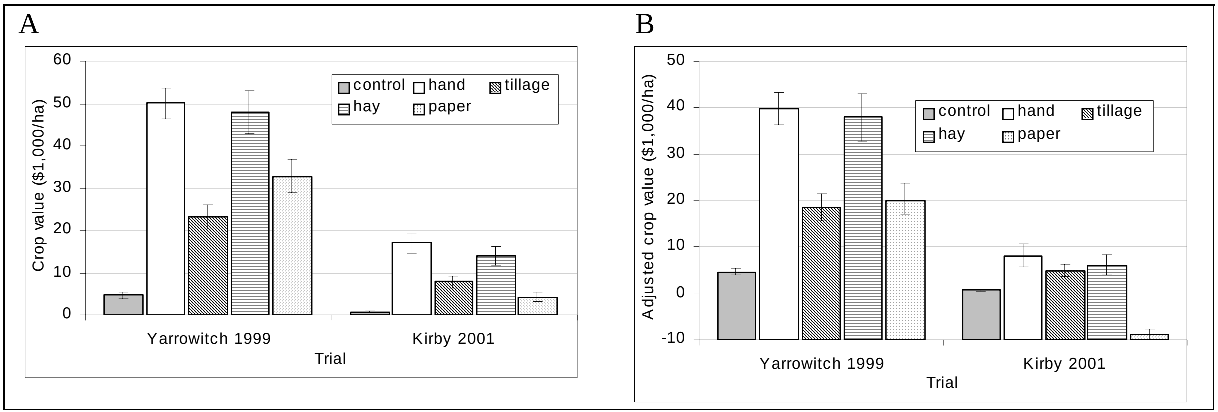


Figure 3.24 The (A) gross crop value and (B) adjusted crop value ($1,000/hectare) of echinacea for each treatment applied in the field trials. The columns show the mean of each treatment at each site and the error bars show the standard error of the means. The legends refer to the weed control treatments.

Although the ranking of the treatments by their cost was similar for both lettuce and echinacea, expressing the costs as a percentage of the hand weeding treatment cost indicated that the different weeding requirements of the two crops altered the relative costs of the treatments (Table 3.4). The cost of tillage doubled relative to hand weeding, while the cost of mulching halved. An evaluation of weed control strategies for large-scale organic potato production in the UK found a similar ranking of treatments to that found in the study reported here. However, the actual and relative values were different, partly due to the non-equivalence of the treatments.

Table 3.4 Relative costs of weed control treatments, expressed as a percentage of the hand weeding treatment cost, with the actual cost of the hand weeding treatment is given in brackets. The values for lettuce and echinacea are across-trial averages from the experiments reported in this chapter. The values for potatoes are from an experiment in the UK (Litterick *et al.* 1999) and are included for comparison.

Weed control treatment	Relative cost of weed control treatment (% of hand weeding treatment)		
	Lettuce	Echinacea	Potatoes
Hand weeding	100 ($4,390/hectare)	100 ($9,600/hectare)	100 ($1,600/hectare)
Control	0	0	-
Tillage	22	41	6
Hay mulch	173	93	13 *
Paper mulch	276	135	125

* Mulch grown *in-situ* as a cover crop preceding the potato crop

3.4 Discussion

3.4.1 Weed variation between trials

Weed levels varied between the trials in terms of the species that were dominant, the background weed levels observed in the control treatments, and the different responses due to the weed control treatments. Weed species differed between sites, apart from wireweed (*Polygonum aviculare*) which was common at both Laureldale and Kirby. The most abundant weed growth in lettuce and echinacea trials occurred at Yarrowitch in 1999, followed by Kirby in 2001 and then Laureldale and Kirby in 2000. No assessment of the soil seed banks in each trial was attempted, so the extent to which variations in weed emergence were simply due to variations in the existing number of weed seeds is uncertain.

Factors that may have affected weed emergence and growth include recent land use history, climatic variables, soil conditions and the method of bed preparation (Cousens and Mortimer 1995, Bond *et al.* 1998b, Buntain 1999). These factors varied considerably between the field sites used in the trials. For example, the land use histories included land that had been subject to organic annual cropping for two years after being used for conventional sheep grazing for many years (Yarrowitch), land that had been continuously cropped as research plots (Laureldale) and land that had only been grazed by sheep and cattle for the previous seven years (Kirby). The observed increase in weed density at Kirby (50 to 335 weeds/m^2 in 2000 and 2001 respectively) parallels comments by staff at Yarrowitch who reported that weeds levels had increased since converting from grazing to annual cropping (P. Brown, pers. comm.). An increase in the abundance of annual weeds may be expected after a fallow (Sjursen 2001), and increased weed density and biomass has been reported in other organic cropping studies (Samuel and Guest 1990, Belde *et al.* 2000, Sadowski and Tyburski 2000).

The method of bed preparation was the same at Kirby and Laureldale, but different at Yarrowitch due to the use of a different bed forming implement. The heavy clay soil at Laureldale caused the planting beds to have more and larger clods than in the finer structured soil at Kirby. Large soil clods can reduce weed seedling emergence, but may also protect emerged weeds against damage by direct weeding methods (Bond and Lennartsson 1999). Therefore, the initial conditions for weed seed germination and seedling emergence will have varied between trials, including soil texture, soil moisture and weed seed depth (Cussans *et al.* 1996, Grundy *et al.* 1999b).

After the experiments were established, climatic factors are likely to have had an impact on the growth of emerged weed seedlings and on further emergence. Cumulative rainfall was significantly higher at Yarrowitch, while the 2001 trial had slightly more rainfall than the 2000 trials. The timing of the rainfall events, particularly in relation to the timing of the weeding operations, may also have influenced weed emergence, growth. The differences in weed levels between trials may also have been related to the differing ability of the dominant weed species to accumulate aboveground biomass or cover the ground quicker. Wireweed had a low spreading habit and would be expected to achieve greater relative cover with lower biomass, while buckwheat (*Fagopyrum esculentum*) grew with an upright and sparse canopy and may contribute less to both weed relative cover and biomass.

The three variables used to measure the weed response to the treatments generally had a high correlations in all trials for both lettuce and echinacea, particularly the relationship between weed relative cover and biomass. However, at Laureldale and Kirby 2000 the correlations were low for weed density and relative cover, and for density and biomass. The weed densities at these sites were relatively low while the relative cover and biomass were not, suggesting that fewer individual weeds produced relatively more growth, but with greater variability.

While the inter-trial variations in weed levels are of interest and had a statistically significant effect on the performance of the weed control treatments, the effects due to trials may be considered to be a random selection of the possible range of effects that may be observed at different field sites over different growing seasons. Of greater interest in these experiments were the effects of the weed control treatments, the fixed effects from deliberately applied treatments. The general trends observed for the effect of treatments on weed growth were generally similar between trials and a reasonably clear set of conclusions can be made from those trends.

3.4.2 Weed response to treatments

The weed control treatments varied significantly in their ability to control weeds effectively in a lettuce or echinacea crop. In both crops, the ranking of treatments by weed biomass accumulation at harvest was similar: hand weeding ≈ paper mulch < hay mulch < tillage < control. Weed growth was very effectively controlled by hand weeding and paper mulch, with a 96% reduction in weed biomass in the lettuce trials compared to the control, and a 98% reduction in the echinacea trials. The hay mulch was equally as effective in reducing weed biomass in the echinacea trials, but less effective in the lettuce trials (80% reduction) due to weed seeds contained in the mulch. The tillage treatment reduced weed biomass by about 60% in both lettuce and echinacea. Weeds in the control treatment were allowed to grow unchecked.

Hand weeding

The low weed populations at the end of the lettuce and echinacea trials indicate that the hand weeding regime was adequate for each crop. The high level of weed control achieved by the hand weeding treatment was deliberate, so that the crop yields in a relatively weed-free situation could be determined, but it was also intended to emulate organic weed management practices of a grower reliant on hand weeding. Hand weeding is very commonly used by organic growers (Walz 1999, Kristiansen *et al.* 2001), and its efficacy in controlling weeds, either as a central method of weed management or as a supplement to other methods has been widely reported in both organic (Melander 1998a) and conventional production systems (Lewthwaite and Triggs 2000).

Lettuce is a short-season crop, particularly when transplanted rather than sown, and one thorough hand weeding at 4 WAP was sufficient to prevent almost all weed growth up to 7 WAP. The competitive ability of lettuce against weeds is poor due to its low stature and high nutrient and water requirements and inadequate weed control is likely to reduce crop yields (Grundy *et al.* 1999a, Napier 2001b). Echinacea has a longer growing season, with limited growth in the first 10 WAP when the crop is susceptible to weed competition (Buntain 1999). Crop relative cover had only reached 20% by 10 WAP in both trials. However, once shoot extension and leaf expansion begin (about 8-10 WAP in these trials), echinacea becomes more competitive against weeds and can develop a dominant canopy by about 12-16 WAP. The three weeding operations at 4, 8 and 12 WAP in the echinacea trials were sufficient to maintain a minimal level of weed growth up to 21 WAP. It is possible alternative regimes (e.g. hand weed at 4 and 10 WAP, or smaller operations at 2, 4, 6, 8 WAP) may have also sufficed. The emphasis should be on maintaining a high level of weed control up to about 10 WAP.

Paper mulch

The paper mulch treatment was used in the experiment as an alternative to the hay and straw mulches that are commonly used in organic herb and vegetable production. A very high level of weed control was achieved due to the thick, continuous layer that prevented most weeds from emerging. Once the mulch had been wet from irrigation or rainfall, the pellets swelled and partly coalesced to formed a dense, compact layer. This layer completely prevented light penetration through to the soil where the mulch was maintained at the required thickness of 50 mm. Thinner patches with < 10 mm of mulch were the most common point where weeds emerged. Paper mulch likely to have provided a formidable physical barrier against emergence by germinated weed seeds and. Weed control benefits have been reported for pelletised paper mulch in the nursery industry (Senesac 1998, Smith *et al.* 1998); paper sheeting has been effective in capsicum (Olsen and Gounder 2001), potatoes (Cui *et al.* 2000) and rice (Umezaki and Tsuno 1998); and shredded newspaper (Munn 1992, Monks *et al.* 1997). Several of these reports noted better weed control by a newspaper mulch than a mulches composed of crop residues (Munn 1992, Monks *et al.* 1997, Olsen and Gounder 2001).

Hay mulch
The hay mulch treatment was quite effective in reducing weed levels, an observation commonly reported in the literature (e.g. Wade and Sanchez 1983, Yih 1989, Schonbeck 1998, Alemán 2001, Olsen and Gounder 2001), but extra labour was required to maintain those low levels. About 36% ($3,000/hectare) of hay mulch treatment costs were due to supplementary weeding but only 1% ($120/hectare) of paper mulch treatment costs. The supplementary hand weeding was carried out in order to maintain the practical relevance of the hay mulch treatment. Follow-up weeding was also conducted in the tillage and paper mulch treatments for the same reason.

Hay mulch did not form a layer that was as dense as the paper mulch, although the mulch became moderately compact after wetting and settling. Light penetration through the mulch is unlikely to have been completely prevented. Ryegrass mulch biomasses of 8 and 16 tonnes/hectares have been reported to reduce light transmission to 10% and 5% respectively (9.5 tonnes/hectare of hay mulch was used in the lettuce and echinacea trials), and that was considered sufficient to stimulate germination in weed seeds that are dependent on a phytochrome response (Teasdale and Mohler 1993).

In a study of the effect of various mulch properties on weed emergence (Teasdale and Mohler 2000), the surface area of a mulch was found to be more useful for describing weed emergence than the biomass or height of the mulch, and the available space within the mulch was also an important parameter. The pelletised paper mulch used in the trials being reported here is likely to have had a high surface area and very little space between particles, especially after wetting, compared with the hay mulch. Tyler noted that shredded newspaper provided poor weed control in a trial of mulches in *Echinacea purpurea*, possibly due to the open nature of the mulch, whereas a finer, milled newspaper mulch provided better weed control (2000)

Other factors that may have reduced weed germination and growth in the paper and hay mulch treatments include leaching of phytotoxins that reduce weed germination and emergence, nitrogen immobilisation causing a reduction in growth of germinated weed seeds, unfavourable soil physical conditions (e.g. moisture, temperature, aeration), or the presence of herbivorous fauna such as gastropods.

Tillage
Tillage tended to be the least effective method of managing weeds, apart from the control treatment. It was also the most variable of the non-control treatments. Satisfactory weed control was usually achieved away from the crop rows, but poor weed control was achieved in the rows. The supplementary hand weeding was intended to remove weeds in the crop row with a chipping hoe but not those weeds immediately adjacent to the crop, where the competitive effects of weeds would be greatest. The observed weed growth was, therefore, an expression of the effectiveness and variability of the tillage and chipping operations.

The ploughs used in the trials were simple chisel ploughs with limited ability to accurately control weeds close to the crop plants without damaging crop plants. While this type of implement is commonly used by organic herb and vegetable growers in Australia (see Figure 2.12 in the previous chapter), its effectiveness is variable (Oriade and Forcella 1999, Welsh *et al.* 1999). Another source of variability in the trials was the skill of the tractor driver. The driver was inexperienced at cultivating between crop rows. With a more experienced operator, it may have been possible to set the tines closer to the planting rows and, thus, control more weeds with each tillage pass (Litterick *et al.* 1999). The 50% reduction in weed density due to inter-row hoeing in an organic cereal crop reported by Welsh *et al*. (1999) is similar to the 46% reduction in weed density in echinacea by the tillage treatment in these trials, but weed density was reduced by 69% in the shorter duration lettuce crop.

The quadratic response of weed relative cover during the echinacea trials varied between sites (Figure 3.10). Weed cover at Yarrowitch rose quickly and levelled off, whereas weed cover at Kirby increased very slowly in the first 12 WAP followed by rapid growth until harvest. These contrasting patterns may be due to (a) the higher cumulative rainfall in the first 10 WAP at Yarrowitch (233 mm compared with 103 mm at Kirby) which could have promoted early weed germination and growth (Bond and Baker 1990), and (b) the competitive effects of greater echinacea growth at Yarrowitch (49% relative cover at 12 WAP compared with 12% at Kirby) (Figure 3.18). Another possible cause is that the weed flora in each trial had different emergence patterns in relation to the timing of the establishment of the experiment and the tillage operations (Rasmussen 1996). However, specific data about weed species was not recorded in these trials.

Control (unweeded)
The unweeded control treatment provided a measure of the pre-existing weed levels in each trial and a basis for evaluating the extent of weed control achieved by the other treatments. In most trials, weeds in the control plots grew rapidly and achieved a high relative cover by harvest time, although this was not as great in the shorter lettuce trials. The late decrease in weed relative cover in the control treatment at Yarrowitch in the echinacea trials (Figure 3.10) may have been due to the lodging by the tall grass weeds that were about 0.8 - 1 m tall and had begun the seed. The weeds had begun leaning out beyond the beds and opened up the canopy slightly to show the stunted echinacea plants.

3.4.3 Crop response- variation between trials

Lettuce
The lettuce yields were ranked by trial as follows: Yarrowitch 1999 > Kirby 2000 > Kirby 2001 > Laureldale 2000. The variation in overall lettuce yields between trials may be due largely to differences in the amount of rainfall received in the latter part of the experiments. Lettuce is usually grown with irrigation on commercial farms (Heisswolf *et al.* 1999), but irrigation was not readily available in these trials. Therefore the observed lettuce yields would be expected to be affected by the amount of rainfall received in each trial. The high correlation between cumulative rainfall and crop relative cover ($r^2 \geq 0.81$) appears to confirm that lettuce growth (and yield) was influenced to the amount of rainfall received. The soil test data (Table 3.1), especially those for nitrogen, phosphorus, potassium and soil pH, did not appear to show a pattern that is consistent with the observed yields.

The poor growth of lettuce in the trial at Laureldale in 2000 is difficult to explain conclusively. One factor that was not seen in the other trials was the sporadic evidence of leaf chewing by either rabbits (*Oryctolagus cuniculus*), hares (*Lepus capensis*) or kangaroos (*Macropus giganteus*) during the second week after planting the lettuce seedlings. The trial area at Laureldale has a complex history of uses with a mosaic of previous crops, fertiliser regimes and herbicide applications, some of which may have had residual effects. The soil analyses did not reveal any serious deficiencies, although nitrogen was slightly lower than at Kirby in 2000.

The average lettuce yield in the hand weeded plots was about 27 tonnes/hectare, not including the low yielding trial at Laureldale (average for all trials was 23 tonnes/hectare). Industry benchmarking for conventional lettuce yields in Australia ranges from 17 - 29 tonnes/hectare (Titley 2000) to 20 - 45 tonnes/hectare (NSW Agriculture 2001). The observed yields in the non-control treatments in these trials were similar to commercial yields, despite the lack of irrigation and supplementary fertilising.

Lettuce bolting varied significantly between Kirby 2001 and the other trials. Bolting was greater in the hand weeding and tillage treatments at Kirby in 2001 than in the other three trials and this may be to have been due to the drier soils in the later part of the growing season causing greater fluctuations in soil temperature (Titley 2000). During the same trial periods, the 2001 season was also slightly warmer. Although the difference is not statistically significant, the difference may have biological importance. The effect of the treatments on bolting is discussed below.

Echinacea
The yield of echinacea at Yarrowitch was significantly greater than at Kirby, with growth parameters indicating a two- to four-fold difference, and the response of crop relative cover over time indicated that echinacea reached an upper asymptote of growth at Yarrowitch, but not at Kirby. Rainfall seemed to be an important factor in determining overall echinacea growth, as indicated by a high correlation between cumulative rainfall and crop relative cover ($r^2 \geq 0.76$ for all treatment combinations except the control) and the significantly lower rainfall received at Kirby, 43% that received at Yarrowitch. Soil analyses from the two sites (Table 3.1) indicated several differences in nutrient concentrations and leaf tissue analyses from the harvested echinacea plants (unpublished data) suggesting that whilst the leaf nitrogen levels were low in both trials, cation levels were generally adequate (Reuter and Robinson 1997). However, an analysis of the effects of cumulative rainfall and various leaf nutrient concentrations (i.e. N, K, Ca, Mg and Al) on echinacea yield indicated that the nutrients were not significant but rainfall was. No differences in degree days were recorded between the two trials, and no pest or disease infestations were observed at either trial.

The shoot:root biomass ratio was lower at Kirby. This may have been due to the drier conditions limiting the growth of stem and leaf and/or inducing more root growth in order to access soil moisture. Shoots biomass was 80% lower at Kirby, but root biomass was 63% lower, suggesting that shoots growth became limited by the drier conditions. Echinacea is reported to be tolerant of dry conditions, with a number of leaf adaptations to water stress (Chapman and Auge 1994).

The average echinacea root yield in the hand weeded plots was 1.2 tonnes/hectare at Yarrowitch and 0.5 tonnes/hectare at Kirby. Echinacea root yields reported elsewhere include range from 1 - 3.7 tonnes/hectare (Parmenter *et al.* 1992, Galambosi 1993, Polachic 1996, Buntain 1999), although yields can vary widely depending on planting density (Parmenter and Littlejohn 1997) and site (Parmenter *et al.* 1992). The average yield of echinacea shoots in the hand weeded plots was 6.6 tonnes/hectare at Yarrowitch and 1.8 tonnes/hectare at Kirby for shoots, while others have reported yields of 6.4 - 17.5 tonnes/hectare (Bomme *et al.* 1992, Butler 1997, Buntain 1999). The observed yields in the non-control treatments at Yarrowitch showed reasonable equivalence with commercial yields, but the yields at Kirby were lower than those reported in the literature.

3.4.4 Crop response to treatments

The weed control treatments had a significant effect on all of the crop variables measured in the lettuce trials. The highest yields were recorded in the hand weeding and hay much, followed by tillage plots (87% of hand weeding yields) the control treatment (75%), then the paper mulch (45%). The treatments also had a significant effect on crop variables in the echinacea trials. The highest yields were again recorded in the hand weeding and hay mulch plots. At Yarrowitch, paper mulch had lower yields (66%), followed by tillage treatment (46%). At Kirby, paper mulch yields were considerably reduced in proportion to the hand weeded plots (27%), and paper mulch was therefore ranked lower than tillage (41%). The control treatment had poor yields in both trials. The only crop parameter to show little variation in response to the treatments was the shoot:root ratio. The proportion of echinacea shoots biomass was lower in the control treatment, particularly at Kirby, but that there was little difference in the shoot:root ratio in response to the other weed control treatments. This indicates that heavy weed competition had a greater limiting effect on shoots growth than on root growth in echinacea.

Hand weeding and hay mulch
Lettuces and echinacea in the hand weeding and hay mulch treatments grew the quickest and were the largest by size and weight at harvest. The positive response to these treatments is presumably a consequence of having low weed levels throughout their growing season and an absence of other potential limiting factors. Hand weeding is generally acknowledged to be an effective method of

weed control in organic and conventional herb and vegetable production (Whitten 1999, Napier 2001b) and, although it is often considered to be expensive (Rasmussen and Ascard 1995, Melander 1998a), that is not always the case (Alemán 2001). Mulches composed of crop residues such as hay and straw have been used successfully for weed control and generally produce good crop yields (Bond and Grundy 2001). However, positive (Hutchinson and McGiffen 2000), neutral (Abdul-Baki *et al.* 1999) and negative (Munn 1992) effects on crop yield have reported.

Bolting

Despite the yield benefits observed in the hand weeded plots, a noteworthy short-coming of that treatment was the high incidence of early bolting, especially at Kirby. Bolting in lettuce, a quantitative long-day plant (Waycott 1995), is generally caused by high daily maximum temperatures, large fluctuations in diurnal temperature and/or longer daylengths (Waycott 1995, Napier 2001a). In these trials, daylength would not have varied between treatments. However, the hand weeded plots were likely to have had higher soil temperatures and larger fluctuations in daily soil temperatures than the mulched plots (Olasantan 1999) and such conditions were more likely to induce bolting in lettuce. Soil temperature maxima and diurnal fluctuation were tested in the echinacea trial at Kirby in 2001 and found to be significantly greater in the hand weeding and tillage treatments (unpublished data). Root zone cooling has been shown to reduce the incidence of bolting in lettuces (Lee and Cheong 1996), and other vegetables such as pak choi (*Brassica campestris* var. *chinensis*) (Vogel and Flogel 1992) and radicchio (*Cichorium intybus* var. *silvestre*) (Rangarajan and Ingall 2001) have also experienced less bolting when grown with soil coverings that reduced soil temperature. The tillage treatment also had a high percentage of bare soil and it too had a higher incidence of bolting than the weedy control treatment and the mulches. The relationship between soil cover and bolting was highly significant. Other untested factors besides soil cover may also have influenced soil temperature such as changes in soil bulk density (Andales *et al.* 2000) due to the disturbance by the hand weeding and tillage, and crop root damage may also have been a stress factor that could affect plant maturation (Das and Ahmed 1989).

Paper mulch

While paper mulch kept the level of weeds very low, lettuce yield was greatly reduced in comparison to the other treatments. Echinacea yields were also significantly reduced compared to hand weeding, but only at Kirby. Reports vary about the effect of paper mulches on crop yields, with some research finding no negative effect on yield (Munn 1992, Matitschka 1996, Unger 2001), and others finding yield reductions (Guertal and Edwards 1996, Monks *et al.* 1997, Tyler 1999). The lower yields are commonly attributed to soil nitrogen immobilisation in response to the high carbon:nitrogen ratio of the mulch. However, other factors that may have affected crop growth under a paper mulch include altered soil hydrothermal conditions (e.g. cooler soil temperatures, water-logging) or the effect of phytotoxins. The proportion of root biomass at Kirby, where yields were especially poor, was relatively high amongst of the non-control treatments, suggesting that soil conditions were not unfavourable.

Tillage

The tillage treatment produced moderate crop yields compared with the other weed control treatments. The lettuce yields were 13% lower than hand weeding (averaged across trials), a difference that was not significant. The single weeding operation at 4 WAP appears to have reduced weed competition sufficiently to avoid crop yield losses observed in the unweeded control treatment at Yarrowitch in 1999 and Kirby in 2001, although with the lower weed levels at Laureldale and Kirby in 2000, little difference in yield between treatments was detected. A low yields in the tillage treatment at Kirby in 2000 is likely to have been due to soil disturbance and/or root damage by the tines. In the echinacea trials, the crop yields for tillage were about half of hand weeding yields, most likely because of the considerably higher weed levels in the tillage plots. The tillage treatment consisted of three passes with a chisel plough with follow-up chipping each time. The efficacy would be improved by carrying out more hand weeding near the crop plants so that the competitive effects of weeds were reduced.

It might be expected that the impact of soil disturbance and root damage would be greater with the tillage treatment, with a consequent reduction in yield as observed in the lettuce trial at Kirby in 2000. However, the relatively high root biomass proportion in both trials indicates that tillage did not have a negative effect on root yields, and that the lower overall yield was due more to reduced shoots growth.

The weedy control treatment also had a high proportion of root biomass, which may imply that echinacea plants favour root growth when subjected to competition for resources. Plants often respond to stresses (e.g. drought, inadequate nutrients, defoliation) by partitioning growth in various ways. A range of plants have been reported to respond to such stresses by increasing root biomass at the expense of shoot biomass (Traore and Maranville 1999, Maillard *et al.* 2001, Strand and Weisner 2001).

Control (unweeded)
The crop yields unweeded control treatment were generally lower than the other treatments. This was especially so in the longer-season echinacea where weeds had many weeks to compete with the crop plants and where the early growth rate of the crop is low. At harvest, the ratio of weed to crop biomass for the control treatment was about 25:1, whereas the same ratio in the lettuce trials was 3:1.

In 2000, the lettuce yields at Laureldale and Kirby were equivalent to the other treatments. The result at Laureldale may have been due to the overall low yields at that site not being sensitive to treatment effects, and the over-riding influence of other limiting factors such as inadequate rainfall, less degree day accumulation, low or unavailable soil nutrients, or residual effects from previous crops. The overall crop yields at Kirby in 2000 were not low compared to Yarrowitch in 1999 and Kirby in 2001, however the background weed levels were the lowest of all trials (50% of Laureldale, the next lowest). Therefore, the competitive pressure from weeds would be considerably lower and any benefits from reduced weed levels in the other treatments would be less obvious or even negligible (Martinez-Ghersa *et al.* 2000). Studies on a crop with a very short growing season, radish (*Raphanus sativus*), have demonstrated how rapid crop development can avoid the need for weeding in short-season species (Turner *et al.* 1999). Adequate pre-cropping weed control can reduce the risk of weed inundation (Wallace 2000).

3.4.5 Economic analysis
While crop yield is usually considered to be a key indicator of the performance of a weed control treatment in research trials, it is possible to get good yields from treatments that may be uneconomical in practice. Therefore, taking account of the cost of each treatment and incorporating that variable into the analysis allows for an economic evaluation of the performance of the various treatments, rather than a merely agronomic evaluation. This analysis did not account for the cost of environmental impacts due to the weed control treatments (Roberts and Swinton 1996), such as soil loss in the tillage treatment (Gilley and Doran 1997), or soil moisture conservation in the mulched treatments (Rahman and Khan 2001). It is also recognised that the costs of implementing weed control methods on research plots may differ from implementation costs in a commercial setting (Anuebunwa 2000).

The most expensive treatment was paper mulch, followed by hay mulch and hand weeding. Tillage was comparatively cheap, and the control treatment cost nothing. Other research has also found that tillage can be less costly than hand weeding (Melander 1998a, Alemán 2001) and mulching (Edwards *et al.* 1995, Litterick *et al.* 1999, Alemán 2001). The amount time used in each application of the hand weeding treatment (268 - 312 hours/hectare and 198 - 228 hours/hectare for lettuce and echinacea respectively) was within the range of reported times for various vegetable crops, which include 100 - 300 hours/hectare in organic carrots (Rasmussen and Ascard 1995), 256 hours/hectare in echinacea (Buntain 1999) and up to 500 hours/hectare in organic onions (Melander 1998a). The mulches differed in the proportion of cost that was due purchase of materials. Paper mulch was expensive to buy, but was in a form that enabled quicker and more even application to the cropping beds than the cheaper hay mulch. Paper mulch also required less follow-up hand weeding than hay mulch. However, a major short-coming of the paper mulch treatment, besides the initial cost, was the strongly negative effect on crop yield. This would appear to limit the use of such a mulch unless soil nutrient issues are addressed, for example by adding manure or slurry to the mulch to reduce the carbon:nitrogen ratio.

In the lettuce trials, the treatment ranking for crop yield was altered when treatments were compared by their adjusted crop values (ACV). The more expensive treatments, particularly the mulches, became less profitable and the cheaper treatments became more profitable. The control treatment had high ACVs, especially in 2000 at Laureldale and Kirby. Even under the higher weed loads at Yarrowitch, the control and tillage treatments were cost effective compared with hand weeding.

In the echinacea trials, there was no re-ranking of treatments by ACV compared with gross crop value at Yarrowitch. Hand weeding and hay mulch remained highly ranked even with the inclusion of their higher costs. The yields at Yarrowitch were considerably higher than at Kirby, and that appeared to make the investment in more expensive weeding methods (e.g. hand weeding and hay mulch) worthwhile. At Kirby the treatments were re-ranked by taking cost into account. The lower yields meant that cheaper treatments (e.g. control, tillage) had relative higher ACVs, and paper mulch yields were so low that a substantial loss was incurred.

The relative costs of the treatments differed between lettuce and echinacea. Relative to hand weeding, the cost of tillage in the echinacea trials was twice that of the lettuce trials whereas the relative cost of hay and paper mulch was about half as much in lettuce compared with echinacea. The mulch treatments incurred substantial initial costs with purchase and laying of the mulch materials, but on-going costs were low, especially for paper mulch. Tillage did not require a high initial outlay, but over time on-going costs remained fairly constant. In a short-season crop like lettuce, a weed control treatment with a high initial outlay gave a comparatively low return and increased the risk of loss if the crop failed (e.g. paper mulch at Kirby 2000). In a longer-season crop such as echinacea, the on-going, low maintenance weed suppression provided by mulches became economically attractive compared with repeated tillage operations. The higher value of echinacea in the market place would also mean that more expensive weeding methods were relatively cost-effective, although the prices are unlikely to remain stable (P. Green, pers. comm.).

These results indicate that in short-season crops (and under lower weed loads), the use of cheaper, low intensity weeding methods (e.g. control, tillage) may be the most profitable option, and that mulches are more suited to high-value crops (Runham and Town 1995) or perennial crops (Bond and Grundy 2001). In organic farming systems, where weed seed bank depletion may be an important goal (Geier 1990, Merfield 2000), the longer term implications of uncontrolled weeds in a crop need to be considered by growers (Jones and Medd 2000).

There was no correlation between cost of weeding method and the crop yield ($r^2 \leq 0.270$). This result is similar to the finding reported in the Organic Weed Management survey in the previous chapter, where the perceived expense of a weed control method was not related to the success of that method at managing weeds. Bond and Lennartsson note that relatively expensive methods should not necessarily be dismissed because they are uneconomic in large acreage arable crops, and that different techniques are appropriate for different crops, and success depends on matching up the weed control and cropping strategies (1999). Other factors that can have an influence on the economics weed management include the size of cropping area, prevailing weed density, the cost of labour and commodity price fluctuations (Melander 1998a, Alemán 2001).

3.5 Conclusions

The weed control treatments had important agronomic and economic effects in the lettuce and echinacea trials reported above. The treatments showed clear differences in their ability to control weeds effectively, their impact on the growth of the crop and their cost effectiveness. The economic analysis of the treatments is specific to the time and location of the trials, and outcomes may vary depending on the availability of labour, machinery and implements, and suitable mulch materials. However, similar trends have been reported in other organic and conventional trials.

For lettuce, a crop with a short growing season, cheaper weed control methods such as tillage with limited follow-up hand weeding may be sufficient to ensure a reasonable crop yield. The acceptable economic return of the control treatment suggests that good weed control in the cropping area prior to planting may even be adequate. Hay mulch provided good yields but was less cost-effective due to the high labour requirement for mulch laying and follow-up hand weeding. However, this treatment greatly reduced bolting in the lettuces and may give more flexibility in terms of harvesting than tillage or hand weeding. Paper mulch stunted the growth of lettuce, presumably due to nitrogen immobilisation, although it also provided excellent weed control. It could not be recommended without reformulation with a nitrogenous fertiliser or some other method of improving available soil nutrient levels.

The results from the echinacea trials suggest that more expensive weeding methods are cost-effective for longer-season and higher-value crops. Hand weeding and hay mulch both provided cost-effective weed management. The differing effects of those two treatments on soil structure, carbon and moisture conservation were not evaluated, although these factors may be considered important by growers. The paper mulch again reduced crop yields and, combined with high purchase cost, appeared to be unreliable. The moderate ACV for paper mulch at Yarrowitch suggests that the treatment may have some potential as a weed control method in certain circumstances.

4. Industry significance of findings

The survey data indicated that the majority of organic producers were relatively small operators with a large part of their management time spent on weed control. The surveyed growers also reported that weed control was an important problem in their production system. Financial data assessed at the field sites also indicated that weed control costs as a percentage of gross returns were an important factor affecting profitability. Thus the examination of alternative methods of weed control is important for organic crop growers.

The two crops used in this study covered the range from a short season crop (lettuce) to a longer growing season species (echinacea). At each of the experimental sites different weed species occurred which suggest that the research findings should apply to many commonly occurring weeds. The control treatments (with no weed control attempted) generally had high levels of weed cover which also suggested that the two crops had relatively little potential for weed suppression through competitive effects. This effect also suggests that for many horticultural crops, especially those which are transplanted under field conditions at relatively low planting densities (such as tomatoes), suitable weed control treatments will be needed to achieve economic yields.

The longer growing season echinacea produced top and root cover levels which were strongly related to the relative levels of weeds. Thus the comparisons of hand weeding and the control treatments in Figures 3.10 and 3.18 showed that where high levels of weeds were present, there was low ground cover of the crop, and *vice versa.* With lettuce, this relationship was much poorer; this suggests that individual crops may differ in their ability to be suppressed by weeds. Whilst there were large differences in the levels of ground cover achieved by weeds in the different weeding treatments their effects on final crop yields were strongest with the longer growing echinacea crop.

Thus the best options for weed control in organic crops appear to be strongly related to their length of growing season. For a short season crop such as lettuce inter-row tillage followed by limited hand weeding may produce adequate crop yields. Hay mulch with lettuce gave high yields: it had a high labour requirement but it greatly reduced bolting (premature seed head production), which gave an improved financial return. Unfortunately, the best treatment for weed control (paper mulch) gave poor lettuce yields; this appeared to be related to nitrogen immobilisation but further research work with this treatment is warranted. Paper mulch cannot be recommended without an assessment of the causes of any yield reductions associated with its usage.

Weed control options for the longer growing season crops such as echinacea are broader and the high financial returns permit the use of high cost systems such as hand weeding and hay mulch. Thus hand weeding and hay mulch both provided cost -effective weed control.

For both crops the ranking of the weed control treatments for their weed biomass accumulation at crop harvest was hand weeding = paper mulch followed by hay mulch, tillage and then the control treatment. Weed control levels ranged from 98% through to approximately 60% for the tillage treatments. Although these levels of weed control have been achieved there remains a considerable number of questions concerning optimal weed management in these organically grown crops. A range of problem weeds are still poorly controlled in such production systems; these include couch, sorrel and nutgrass. An examination of the biology and ecology of these weeds should identify lifecycle vulnerability's which can be exploited for their control. There also appeared to be some interest from the survey respondents in novel weeding techniques such as flame weeding, steam weeding, improved tillage implements and organic sprays; these systems were not examined in the current study but they are worthy of further study. Cultural strategies such as techniques for weed seed bank reduction and the development of weed suppressing cover crops (which do not become weeds) should also be assessed.

5. Appendices

5.1 Personal communications

The following people provided information that has been cited as personal communications in this report.

- Doug Andrews, Organic Herb Growers of Australia, South Lismore, NSW 2480
- Phillip Brown, Subiaco Herbs Pty. Ltd., Yarrowitch via Walcha, NSW 2354
- Viv Burnett, Department of Natural Resources and Environment, Rutherglen, Victoria 3685
- Rod Dyke, National Association for Sustainable Agriculture Australia, Stirling, SA, 5152
- Peter Green, Corindi Beach, NSW 2456
- Helen Mason, Upper Yarrowitch Pastoral Company, Yarrowitch via Walcha, NSW 2354
- Ian Reeve, Institute for Rural Futures, University of New England, Armidale, NSW 2351
- Norm Thomas, Rural Properties, University of New England, Armidale, NSW 2351

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Unrefereed

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