Non-chemical Weed Management

Principles, Concepts and Technology

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Principles, Concepts and Technology

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Preface

The increased availability and acceptability of highly effective and selective synthetic herbicides in the decades following World War II diverted the focus of weed researchers and managers away from non-chemical weed management. Herbicides became the predominant option for weed control, with the ecological and social consequences of herbicide use being ignored or downplayed. An over-reliance on herbicide use led to the widespread development of herbicide-resistant weeds and concerns about potential negative effects on human health and the environment.

The sustainability of our food production systems and the health and environmental consequences of pesticide use are rapidly becoming important global issues. Organic farming is increasing in popularity in many parts of the world due to an increasing demand for pesticide-free food. Weeds pose a serious problem in organic farming. Several weed management options that were once labelled 'uneconomic' or 'impractical', and their technology development practically discontinued, are now being revisited.

The unavailability of a comprehensive book on non-chemical weed management has been a problem for weed science students and instructors around the world. We feel that this book, which deals with the principles, concepts, technology, potential, limitations and impacts of various non-chemical weed management options, will fill this gap. The book consists of chapters on prevention strategies in weed management, exploitation of weed–crop interactions to manage weed problems, cultural methods, cover crops, allelopathy, classical biological control using phytophagous insects, bioherbicides, mechanical weed control, non-living mulches, thermal weed control and soil solarization. The final chapter is a synopsis and integration of all the information presented in the various chapters. We expect that this book will serve as a valuable source of information on non-chemical weed management options and will stimulate research in this area.

Since protection of the environment is a global concern, specialists from around the world have been selected to write these chapters, with an international focus wherever possible. While different options for non-chemical weed management are covered in different chapters, an optimal integration of these alternatives is necessary in order to achieve weed management objectives. The need for a more holistic way of thinking in weed management cannot be over-emphasized.

While the academic level of this book is aimed at upper-level undergraduate courses in weed science and vegetation management, it could also be used for some graduate level courses, and as a supplementary text or reference book for agroecology and organic agriculture courses. Weed scientists and vegetation management professionals working for academic institutions or government agencies, agri-business consultants, organic farmers and other environmentally conscious producers will find this publication to be a valuable resource. The learning objective for students using this book is to understand the principles, concepts, technology, potentials and limitations of various non-chemical weed management options and to think holistically by considering the entire agro- or natural ecosystem involved while managing weed problems. The options described in this book indeed have a variety of impacts on different aspects of ecosystems.

Lastly, we would like to thank all the authors of this book for their hard work in writing chapters in their areas of specialization, peer reviewers for their critical and constructive comments, and our families for their cooperation, patience and encouragement.

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1 Prevention Strategies in Weed Management

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1.1 Introduction

Prevention has been a cornerstone of weed management throughout history. The importance of prevention to early farmers can be inferred from religious references and other historical documents. For instance the biblical parable of the tares in Matthew 13, in which an enemy invades a farmer's field at night to sow tares (probably Persian darnel (*Lolium persicum*)) undoes the farmer's sound weed control practices. In addition several quotations from ancient sources recorded in *Farm Weeds of Canada* illustrate the respect for weed prevention apparent during the medieval period (Clark and Fletcher, 1906). Muenscher (1955) in his classic book *Weeds*, written before the discovery of selective herbicides, recommended three fundamental objectives that farmers should strive for in weed control; prevention, eradication and control. Muenscher defined prevention as the exclusion of weeds from areas not yet infested or preventing spread from infested to clean fields.

Prevention is a pillar of integrated pest management (IPM) (Norris *et al*., 2003) and arguably the most cost-effective approach that a grower can take. However, preventive management is complex, involving integration of a group of practices and policies that avoids introduction, infestation, or dispersion of certain weed species to areas free of those species (Rizzardi *et al*., 2004). Preventive management is a very efficient technique for any property size, from a small vegetable crop seedbed to large areas devoted to major field crops.

Many government agencies have laws and regulations prohibiting the movement of weed propagules. Seed purity laws are designed to ensure the purity of crop seeds and prevent the spread of weed seeds. Species that are regulated by government statutes are usually designated as exotic or noxious, carrying requirements to mitigate introduction or dispersal, and requiring owners of infested properties to eradicate or prevent propagule production. Generally these regulated weed species are not indigenous to the protected region.

Private landowners may practise elements of weed prevention on their own farms and individual farmers evaluate the risks associated with new weed problems according to their experiences (Slovic, 1987; Pidgeon and Beattie, 1998). Farmers in many countries perceive weeds as familiar, controllable, not catastrophic, and caused by natural forces rather than human failure (Pidgeon and Beattie, 1998). This attitude can be attributed largely to herbicide availability. Prevention also requires management

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that many farmers are unwilling to practise, particularly if the land is rented or leased.

At the agroecosystem level, seed or propagule dispersion from field to field and from farm to farm needs to be recognized as an important factor that affects the whole agricultural system and should be included in comprehensive weed management planning (Thill and Mallory-Smith, 1997; Woolcock and Cousens, 2000). Preventive management at the farm and at the landscape/ecosystem level require awareness of the processes and practices that contribute to species introduction and proliferation. Integration of preventing new weed infestations, controlling isolated weed patches in the area, as well as preventing seed production are important components of any weed prevention strategy. In some special cases, mainly in areas where exotic weeds are present, eradication should be considered (Woolcock and Cousens, 2000). Prevention should be implemented at all crop production stages, from the acquisition of machinery, seed, water and fertilizers, to crop harvest and processing. The practices of weed prevention are similar to the weed management elements of best production practices; however, they differ because of a requirement for management that is more intensive and the need to amortize costs over the longer term.

Practices that contribute to weed dispersal and which are amenable to prevention are described in this chapter. Attention is given to preventive actions during crop seed purchase, transport of harvested material, cleaning of machinery and equipment, and irrigation, livestock farming and soil management.

1.2 Dispersal of Weeds by Environmental and Ecological Processes

Adaptations for efficient dispersal within and between ecosystems are characteristic of many weeds. In the absence of human activity, weeds rely upon the same natural processes for dissemination as do other plants: dispersal by wind and water, adhesion to fur or feathers, and through food webs. However, farming, trade, and human migration usually amplify the impact of these dispersal adaptations.

Many weed species are disseminated by wind; some as whole plants that shed seed as they move across the landscape, while others rely on the wind to move only the seed. Russian thistle (*Salsola kali*) and kochia (*Kochia scoparia*) are species specially adapted to tumbling with the wind and disperse seeds as the plants move across the landscape. Seed of many species have adaptations to aid in wind dispersal. Examples include the pappus, which is common to many species of the Asteraceae as well as the winged fruits (samaras) of many woody species. However, there is very little information on the distances that weed species may be dispersed by the wind. Research with horseweed (*Conyza canadensis*) identified seeds at altitudes of 140 m, which implies that seeds can travel hundreds of kilometres while remaining aloft in the wind (Shields *et al*., 2006).

Seeds of some weeds possess special modifications to provide greater buoyancy for efficient transport in open water channels including rivers, streams, and irrigation and drainage channels (Dastgheib, 1989; Lorenzi, 2000). Because rivers may traverse ecosystems, they are conduits for long-distance dispersal of plants. Water corridors are regularly disturbed by natural processes such as flooding and ice movement, and weeds dispersing in the water are thereby provided with an ideal habitat to colonize along the banks and shorelines.

Seed transportation by animals is used by many plants (Harper, 1977). The efficiency of animals in dispersing seeds depends on the specific animal and plant species involved (Couvreur *et al*. 2005; Mouissie *et al*. 2005). Dispersion of weed seeds through adherence of fruits or seeds to fur and feathers, or by ingestion, has been mainly attributed to birds and mammals. Birds may contribute to both short- and long-distance dispersion. The range of some large vertebrates and various endemic plant species have overlapped, resulting in distribution across ecosystems during annual migrations. Invertebrates and small mammals such as rodents regularly play a role in short-distance dispersion within the agroecosystem.

Dispersal by environmental and ecological processes is complex, and prevention practices intended to minimize dispersal by these means are generally unlikely to be effective. However, at the farm and community levels, preventing seed production of newly introduced species will eliminate the opportunity for dispersal by these natural processes. The remainder of this chapter will address the role of humans in opportunities to practise prevention within that dimension.

1.3 Dispersal of Weeds by Human Activities

Because weeds are adapted to the disturbance regimes of agriculture and human activity, it should come as no surprise that nearly every human activity plays a role in their spread and distribution. A complete treatment of the role that humans have played and continue to play in weed dissemination is beyond the scope of this chapter and we will restrict our discussion to those activities with direct impact upon food and fibre production.

Plant introductions

Several of the most highly competitive or troublesome weeds have at one time been introduced to a new area as a potential food or medicinal crop, livestock feed, fibre or ornamental plant. *Panicum miliaceum* was initially introduced in Canada in the mid-1800s for grain production, but it adapted to the new habitat and became an aggressive weed in North America over the last 25 years (Bough *et al*., 1986). *Cynodon dactylon*, *Sorghum halepense* and *Digitaria* spp. were introduced to many countries as pasture species and subsequently have become significant weeds (Kissmann, 1997; Zimdahl, 1999). Many other species can be mentioned as examples of intentional human dispersion (e.g. *Ageratum conyzoides*, *Linaria vulgaris*, *Nicandra physalodes*, *Opuntia stricta*, *Pistia stratiotes*, *Salvinia* spp. and *Sagittaria montevidensis*) (Kissmann and Groth, 2000).

Despite laws that have been passed by many national governments to prevent the introduction of invasive plants, this problem continues. Laws and regulations are for the most part reactive; therefore, prohibitions are generally not in place until after introduction and widespread distribution of a weed in the new habitat has already occurred. Efforts to develop predictive models that will enable governments to regulate species before they are introduced are under way in Australia and in Hawaii, USA. However, enhanced regulation alone will not prevent the introduction of new noxious species. Prevention requires individual responsibility – not only of regulators but also of individual property owners, and those involved in the discovery and commercialization of novel plants.

Crop seeds

The production, selection and use of quality seed has direct implications for weed prevention as well as crop yield. Several problematic weed species can be traced back to the use of weed-infested crop seed. Some of these examples include *Echinochloa* spp. with rice (*Oryza sativa*), *Lolium persicum* or *Agrostemma githago* in small grains, and *Vicia sativa* in lentils (*Lens culinaris*) (Harper, 1977; Lorenzi, 2000). Many countries have laws establishing purity standards for commercial crop seeds. These laws also identify species that are unacceptable at any number in commercial lots (Thill and Mallory-Smith, 1997; Zimdahl, 1999). Some species are specifically targeted by seed laws due to their aggressiveness, difficulty of obtaining control, or difficulty in removing the weed seed from the harvested crop seed.

Even in those countries where seed purity laws are enforced there are generally no laws that require farmers to use commercial seed. Dastgheib (1989) analysed the influence of different sources of weed infestation of wheat (*Triticum aestivum*) in the Fars province of Iran, and observed that the use of 'saved seeds', produced on-farm, contributed 182,000 weed seeds/ha, representing 11 species (Table 1.1). This practice of 'saving seeds' continues to be a problem globally. For instance in Utah, USA, small grain seeds showed a decline in wild oat (*Avena fatua*) contamination from 1958 until 1988, yet an appreciable number of the farmers surveyed were continuing to plant wild-oat-infested crop seed (Thill and Mallory-Smith, 1997).

A similarity between certain weed and crop seeds in shape and size makes it very difficult to distinguish between species during the seed-cleaning process. Some of the best-known examples of this phenomenon are *Camelina*

Table 1.1. Various sources contributing weed seeds, based on studies attempting to quantify the input of weed seeds.

Seed source	Estimated number of seeds/ha[a]	Number of species collected	Reference
Irrigation water	48,400	34	Wilson, 1980
Irrigation water	10,000–94,000	137	Kelley and Bruns, 1975
Irrigation water	92	4	Dastgheib, 1989
Dairy farms	91,000–1,000,000[b]	na	Cudney *et al.*, 1992
Dairy farms	3,400,000[c]	48	Mt Pleasant and Schlather, 1994
Sheep pasture	9,900,000	92	Dastgheib, 1989
Cattle pens	5,300,000[d]	23	Rupende *et al.*, 1998
Wheat 'saved seed'	182,000	11	Dastgheib, 1989

[a] Based on authors' estimates or 22 t/ha for manure as a fertilizer source.
[b] Seven dairies were sampled.
[c] Twenty farms were sampled: four farms had no detectable seeds, and only one farm had >200,000 seeds per tonne of manure. Value presented is mean of 16 farms, with weed seeds at 75,100 seeds per tonne.
[d] Four farms sampled.
na = not available.

sativa in flax (*Linum usitatissimum*) seed lots, *Echinochloa* spp. in cultivated rice seed (Baker, 1974), soybean (*Glycine max*) seed infested with balloonvine (*Cardiospermum halicacabum*) and *Polygonum convolvulus* in wheat seed (Lorenzi, 2000; Rizzardi *et al*., 2004). Such problems pose great challenges for both the producer of commercial seed and the farmer using 'saved seed'.

These examples illustrate the limitations of a regulatory approach to seed purity and the ongoing need for educational activities that will help farmers appreciate the long-term impacts of using weed-free crop seeds. Recent initiatives in developing countries to preserve biodiversity and improve quality of 'saved seed' through social network seed-cooperatives should be expanded to train farmers on the risks associated with planting crop seeds contaminated with weed seeds (Seboka and Deressa, 2000).

Machinery

Agricultural machinery disperses weeds during field preparation, cultivation and harvesting. Cultivation disperses weeds over short distances, while harvesters can transport seeds over greater distances in the field; and both can move propagules extensive distances if the machinery is moved from one location to another (Thill and Mallory-Smith, 1997; Bischoff, 2005). This includes the purchase of previously owned machinery, since farm equipment is often sold at great distances from the location of original use.

Dispersion by harvesters has been mentioned in several studies (Ghersa *et al*., 1993; Thill and Mallory-Smith, 1997; Blanco-Moreno *et al*., 2004). Seed dispersal associated with harvesting is dependent on the number of weed seeds remaining with the plant at time of harvest and varies by seed shape and size. Examples where harvesters are implicated in weed dissemination to previously uninfested fields include *Rottboellia exaltata* spread among soybean fields (Zimdahl, 1999) and the spread of jointed goatgrass (*Aegilops cylindrica*) in the wheat-producing region of the USA (Donald and Ogg, 1991).

Few studies have attempted to quantify the amount of propagules dispersed by machinery because so many variables are involved. In one of the few studies on dispersal by machinery, Ghersa *et al*. (1993) studied *Sorghum halepense* dispersal from isolated clumps (about 2 m diameter) in a maize (*Zea mays*) field due to machine harvesting. At harvest, 40 to 60% of the seeds had naturally dispersed. The combine dispersed 50% of the remaining seeds within the first 5 m from the clumps and the remainder dispersed uniformly over 50 m at a rate of 1% per metre

(~5 per m^2). The dispersal potential of combine harvesters has been reported to exceed 18 m (Blanco-Moreno *et al*., 2004) and 50 m (Ghersa *et al*., 1993). Modifications to harvesters can reduce the in-field spread of weed seeds in some situations, in particular the collection of chaff where the majority of the weed seeds are located (Matthews *et al*., 1996; Shirtliffe and Entz, 2005). Shirtliffe and Entz (2005) reported that 74% of wild oats seed dispersed from a combine were distributed in the chaff.

Cultivation disperses species that propagate by seeds and/or vegetatively. Bischoff (2005) observed that cultivation promoted dispersion of *Lithospermum arvense* and *Silene noctiflora* seeds short distances (1 to 2 m) (Fig. 1.1). Guglielmini and Satorre (2004) observed that 50% of the vegetative parts of *Cynodon dactylon*

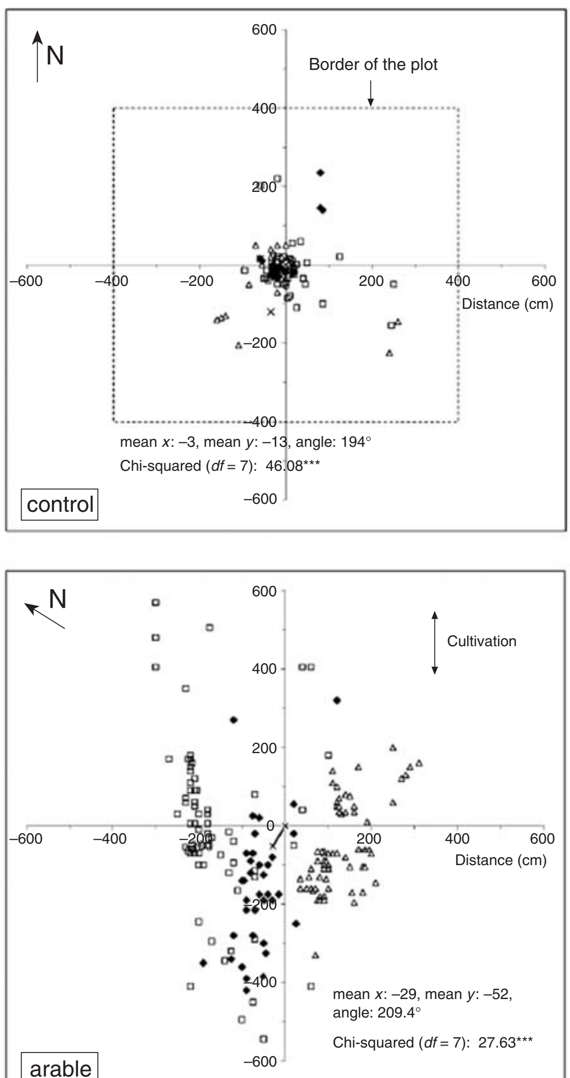

Fig. 1.1. Distribution of *Lithospermum arvense* seedlings from mother plants, with different symbols for different patches; *y* axis represents north–south direction in the control (upper panel) and direction of cultivation in the arable treatment (lower panel) (Bischoff, 2005).

dispersed by chisel-ploughing were between 0.9 and 2.0 m from the initial patches. Similar distances have been reported for other species, although distances do vary with size of seed and depth of seed in the soil profile (Rew and Cussans, 1997). Soil conditions at the time of cultivation influence the amount of seed, rhizomes or tubers dispersed, with moist soil resulting in more propagules being moved (Mayer *et al*., 2002).

Fields infested with weed species that farmers are trying to prevent from spreading require additional management. Weed seeds and vegetative propagules imbedded in soil and debris inside the machine or adhering to surfaces should be removed by thoroughly cleaning before using the machine at the new location. Careful cleaning of tractor wheels, parts of implements used in soil preparation and seeding, as well as horizontal surfaces of harvesters, are important (Thill and Mallory-Smith, 1997; Rizzardi *et al*., 2004).

Infested areas can be sprayed with a desiccant to kill the weeds and increase the seed shed of the weeds before harvesting, or harvest can be delayed to allow for greater seed shed. When the infestation is too dense or the risk of transporting undesirable seed is too great, the area should not be harvested.

Transportation of plant parts

Harvest operations that remove the entire plant require additional caution for preventing weed seed spread. Weed propagules are more likely to be harvested when the entire crop plant is removed for uses such as straw, silage, or further processing (e.g. sugarcane, machine-harvested vegetables). For many species, immature seeds can ripen after harvest and are capable of producing viable offspring. Because agricultural products are marketed globally, the likelihood of transporting weed seeds with the commodity over great distances is high.

Plant dissemination through straw of cereals has occurred with long-distance transport of humans and goods. During the colonization of the Americas, several weed species were introduced with the material transported in the ships. Straw was a common packing material or bedding that was discarded at the final destination. This brought weed species to both sides of the Atlantic Ocean (Baker, 1974).

Transport of raw commodities contributes to local and long-distance dispersal of weeds. The relative small seed size of most weed species makes them prone to be blown by the wind when plant material is transported in uncovered

Fig. 1.2. Trucking bales of sugarcane (*Saccharum officinarum*) straw, providing an opportunity for weed seeds to be blown along the roadside.

vehicles (Fig. 1.2). The diversity of weeds alongside roads and highways is often greater than in fields a short distance from the road. In Brazil, *Ricinus communis* dispersion is believed to be related to truck traffic (Kissmann and Groth, 1999). *Sorghum halepense* was introduced in the southern region of Brazil by the rail transport of flax, lucerne (*Medicago sativa*), sunflower (*Helianthus annuus*) and sorghum (*Sorghum bicolor*) from Argentina (Kissmann, 1997). Velvetleaf (*Abutilon theophrasti*) infestation of dairy farms in Nova Scotia, Canada, was directly associated with long-distance shipments (2000 km or more) of contaminated maize from fields in south-western Ontario and the US 'corn belt' (LeBlanc and Doohan, 1992).

In sugarcane (*Saccharum officinarum*)-producing areas of Brazil, an increase in weed density, especially that of *Cyperus rotundus* and *Cynodon dactylon,* has been observed. This phenomenon has been attributed to the transport of baled sugarcane straw and its disposal after processing for either ethanol or sugar (Medeiros, 2001). In the case of ethanol production, the crop residues are deposited in fields following processing. During sugar extraction, crop materials are decanted into discharge tanks. This liquid suspension, as well as the filter cake, is a potential reservoir of weed seeds and propagules. These materials, known as vinasse, are usually transported and returned as organic matter to the fields, sometimes via irrigation canals. Similarly, discarded plant materials from vegetable-processing facilities can contain weed seeds. These materials are often fed to cattle or returned to the fields as organic material. As described later in this chapter, animal digestion often does not destroy all weed seeds.

Transporting recently harvested commodities with coverings will minimize the dispersion of weed seeds along roadways and rail systems. However, this will not influence the final dispersal of alien weeds in a new area when the transported crop is fed to livestock. Once weed-seed-contaminated commodities arrive at the farm or the processing facility, grinding, palletizing or fermentation processes can be applied to reduce or eliminate viable weed seeds.

Composting is an approach to reduce weed seed density in organic matter prior to land application. Techniques for composting are beyond the scope of this chapter, but there are a number of references available (Cooperband, 2002; Anonymous, 2005). It is generally recommended that the temperature of the composted material should reach 60°C and be held at that temperature for 7 days to kill weed seeds and vegetative propagles. However, it is very difficult to reach this temperature near the surface of compost piles, and thus only weed seeds in the interior of the pile are killed. As a result, compost piles need to be turned or mixed to ensure that all seeds are exposed to the internal temperatures.

Transportation of plants, plant parts and associated soil is often regulated in a highly variable manner. The individual farmer needs to be zealously cautious when purchasing plant materials for planting or feeding to livestock in order to be certain that new weeds are not introduced.

Transportation of soil

Transport of soil, intentionally or otherwise, contributes significantly to the dispersal of weeds. Soil that adheres to roots of transplant seedlings and nursery stock is a source of weed seeds and vegetative propagules which may be transported to new areas. For example, the installation of new fruit orchards or coffee (*Coffea arabica*) crops demands the acquisition and transport of a great quantity of young plants. The nurseries that produce these plants must be rigorous regarding the cleanness of saleable material, especially with the substrate used for plant development. To prevent the introduction of weeds with nursery seedlings, use of media with little or no soil is recommended. However, this may be practical only with container-grown plants.

Animals and manure

The dispersion of weeds promoted by animals can be divided into two methods: dispersion by adherence and dispersion by ingestion. Dispersion by adherence occurs due to fixative structures present on seeds and fruits (i.e. thorns, awns and hooks) that allow them to stick in an animal's fur, promoting their dispersion throughout new areas. Weed species that are disseminated in this manner include *Bidens* spp., *Cenchrus echinatus*, *Cynodon dactylon*, *Desmodium tortuosum*, *Digitaria sanguinalis*, *Hypericum perforatum* and *Xanthium strumarium* (Radosevich and Holt, 1984). Livestock may also play a role in spreading weeds to and from rivers and streams. Paths to watering holes create the disturbance needed for weed establishment and provide a corridor between watering holes and pastures.

Dastgheib (1989) compared the weed seed contributed to fields by irrigation water, using 'saved seeds', and fertilizing with sheep (*Ovis aries*) manure. From these three sources, the author observed that the manure had the highest contribution of seeds, with 9.9 million seeds per hectare; approximately 54 and 107,000 times more than saved seeds and irrigation water, respectively (Table 1.1).

Manure from dairy cows (*Bos* spp.) was collected from various sites on seven farms in California, USA, and 2 to 21.7 thousand seeds per tonne of manure were recovered (Cudney *et al.*, 1992). Some of the differences between the sites were attributed to the quality of feed used for milking cows versus non-lactating cows. Mt. Pleasant and Schlather (1994) analysed the presence of plant seeds in bovine manure from 20 farms in New York, USA. They documented viable seeds of 13 grass species and of 35 broadleaved species, with *Chenopodium album*, found in manure from more than half of the analysed farms. Number of seeds per tonne of manure ranged from 0 to 400 thousand, with an average of 75 thousand seeds per tonne. In Zimbabwe, 6 grass species and 17 broadleaved species were identified in cattle manure (Rupende *et al.*, 1998). One tonne of manure was estimated to contain 66 thousand seeds.

The percentage of seeds that pass through the animal's intestinal tract and remain viable varies according to the weed species, and to the animal species that has eaten them (Thill *et al.*, 1986). Weed seeds passing through pigs or cattle had higher viability than seeds passing through horses or sheep, while poultry was the most efficient at destroying weed seeds (Table 1.2) (Harmon and Keim, 1934). Neto *et al.* (1987) and Stanton *et al.* (2002) also compared farm animals for their ability to reduce weed seed viability and reported sheep to be more effective in destroying seeds than cattle. Although animals differ in their ability to reduce weed seed viability, complete destruction of weed seeds is often not achieved (Blackshaw and Rode, 1991; Gardener *et al.*, 1993; Mt. Pleasant and Schlather, 1994; Wallander *et al.*, 1995).

Composting manure is a common practice for many livestock farmers, and dramatic declines in weed seed viability have been documented with increased composting time and/or adequate moisture levels (Table 1.3) (Grundy *et al.*, 1998; Rupende *et al.*, 1998; Eghball and

Table 1.2. Percentage of viable seeds passed by various animals. Percentage is based on the total number of seeds fed.

	Percentage of viable seeds passed by					
Kinds of seeds	Calves	Horses	Sheep	Pigs	Chickens	Mean
Field bindweed *Convolvulus arvensis*	22.3	6.2	9.0	21.0	0.0	11.7
White sweetclover *Melilotus alba*	13.7	14.9	5.4	16.1	0.0	10.0
Pennsylvania smartweed *Polygonum pennsylvanicum*	0.3	0.4	2.3	0.0	0.0	0.6
Red sorrel *Rumex acetocella*	4.5	6.5	7.4	2.2	0.0	4.1
Velvetleaf *Abutilon theophrasti*	11.3	4.6	5.7	10.3	1.2	6.6
Whitetop *Cardaria draba, Lepidium draba*	5.4	19.8	8.4	3.1	0.0	7.3
Mean	9.6	8.7	6.4	8.8	0.2	6.7

From Harmon and Keim (1934).

Table 1.3. Effect of time of removal from compost windrow on weed seed viability averaged for 1997 and 1999 studies.

Weed	Control	Time of removal: Day 14	Day 21	Days 42–50[a]	Days 70–91[a]
	Viable seed (%)				
Green foxtail *Setaria viridis*	86	4	1	0	0
Redroot pigweed *Amaranthus retroflexus*	78	6	4	0	0
Pennycress *Thlaspi arvense*	11	5	4	1	4
Wild buckwheat *Polygonum convolvulus*	47	32	15	4	0
Wild oats *Avena fatua*	72	13	1	0	0

[a] The earlier date is for 1997 and the later date for 1999 data. Adapted from Larney and Blackshaw (2003).

Table 1.4. Average weed seed viability after ensiling in a silo, fermentation in the rumen, or both, 1986–1989.

Species	Control	Ensiling in a silo	Rumen	Silo and rumen
	Viable seed (%)			
Green foxtail *Setaria viridis*	96	0	17	0
Downy brome *Bromus tectorum*	98	0	0	0
Foxtail barley *Hordeum jubatum*	87	0	0	0
Barnyardgrass *Echinochloa crus-galli*	97	0	0	0
Flixweed *Descurainia sophia*	92	5	7	5
Kochia *Kochia scoparia*	94	10	15	10
Redroot pigweed *Amaranthus retroflexus*	93	6	45	4
Lambsquarters *Chenopodium album*	87	3	52	2
Wild buckwheat *Polygonum convolvulus*	96	30	56	16
Round-leaved mallow *Malva pusilla*	93	23	57	17
Pennycress *Thlaspi arvense*	98	10	68	10

Adapted from Blackshaw and Rode (1991).

Lesoing, 2000; Larney and Blackshaw, 2003). At five dairy farms in California, USA, the amount of seed in compost ranged from 323 to 4128 viable seeds per tonne of manure (Cudney *et al*., 1992). Lethal temperatures for manure composting were dependent upon the weed species and the length of time the manure was allowed to compost. Tompkins *et al*. (1998) reported ≤1% viable seed after 2 weeks in a windrow of typical beef feedlot manure for 9 out of 12 weed species. *Amaranthus retroflexus* had the highest viability (3.5%) after 2 weeks. No viable seeds were detected after 4 weeks. Eghball and Lesoing (2000) reported no viable seeds after 1 week in beef feedlot manure that had adequate moisture, while dry manure required at least 3 months to destroy all the seeds. In the same study, composted dairy manure had destroyed all seeds except velvetleaf (*Abutilon theophrasti*), which was <17% viable after 3–4 months of composting. Anaerobic digesters are also able to reduce the viability of weed seeds (Katovich *et al.*, 2006). However, neither an animal digestive tract, composting, nor anaerobic digesters consistently eliminated all weed seeds.

Providing a weed propagule-free diet is one method of eliminating weed seeds associated with the digestion system and the manure. Good weed control can be used to minimize weed growth and weed seed contamination of forages. Mowing or removing weeds at or prior to the bud stage is necessary in order to ensure that no seeds are produced. However, some weed species cut early in the flowering stage were capable of producing viable weed seeds (Gill, 1938; Derscheid and Schultz, 1960).

The nutritional content of some weed species is high and, as such, farmers may make a conscious decision to allow some weeds in pastures, hay, silage or feed (Mueller *et al.*, 1993; Stanford *et al.*, 2000), or weeds may not be controlled in order to increase the tonnage of a pasture. Statutes that govern contents and quality of livestock feedstuffs may also play a role in the proliferation of certain species. For instance the 'mixed feed oats' classification that is used in the USA and in Canada may allow for a wild oat content of up to 50%. This statute has effectively enhanced the general distribution of wild oats throughout these countries, as elevators typically add wild oats to the grade, up to the maximum allowable level.

The farmer can take specific actions to reduce the viability of weed seeds that are harvested with the crop. Grinding or pelleting feed can reduce weed seed viability, but it does not consistently kill all seeds (Zamora and Olivarez, 1994; Cash *et al.*, 1998). Seed viability after processing depends on how finely ground the material is and the plant species involved. Grinding reduced viability of sulphur cinquefoil (*Potentilla recta*) seeds by 98%, but reduced spotted knapweed (*Centaurea maculosa*) by only 15% (Zamora and Olivarez, 1994).

The fermentation process of producing silage from maize or forages can have an impact on weed seed viability with reductions for some species, ranging from 70% to 100% (Table 1.4) (Zahnley and Fitch, 1941; Blackshaw and Rode, 1991). The reduction in seed viability differed by weed species, with the viability of grass species being reduced more than that of broadleaved species. Tildesley (1937) reported all seeds of 18 species were destroyed within 14 days in a silo, while one species, *Chenopodium album*, required 21 days. However, seeds at the top of the silo were not impacted by the ensiling process.

Livestock farmers need to recall that rotating pasture systems, where animals remain for a short time in each pasture and later go to an adjacent area or even to other properties, may also contribute to weed dispersion. In order to prevent weed seed dispersal, animals could be kept in a confined area for a period of time to allow for clearing their digestive tract of viable weed seeds prior to moving to uninfested areas. The period of time is dependent on seed shape, type of animal, and type of diet. Most studies have shown that at least 4 days is required to eliminate seeds from the digestive tract for a variety of livestock (Neto *et al.*, 1987; Gardener *et al.*, 1993; Willms *et al.*, 1995). However, this will not remove seeds that have adhered to the animals' fur or skin. Adhesion to animal fur or skin is also dependent on the characteristics of the seeds and animals (Couvreur *et al.*, 2005; Mouissie *et al.*, 2005).

Water and wind

As previously described in Section 1.2, seeds of some weeds possess specialized structures that facilitate their transport through water channels (Dastgheib, 1989; Lorenzi, 2000) and many species that do not have these special adaptations can still float temporarily and disperse through water (Wilson, 1980; Radosevich and Holt, 1984). When agricultural or food-processing plant wastes are deposited in rivers and irrigation canals (as previously described for sugarcane), weed seeds accompanying these wastes may be redistributed to nearby irrigated fields or dispersed to new habitats. Thus, irrigation of agricultural crops with surface waters may introduce new weed species to farm fields and/or deposit seeds of endemic species that grow along the water corridor or in nearby fields (Hope, 1927). Kelley and Bruns (1975) recorded seeds of 137 species in sources of irrigation water over the course of a season. Furthermore, they calculated that 10,000–94,000 seeds/ha would be distributed over the course of a season due to the contamination of irrigation water. Wilson (1980) monitored seeds in irrigation canals as well as a major river (Platte River) in Nebraska, USA, and found that weed seed content was higher in the irrigation canals. During one season, an irrigated field received 48,400 seeds/ha from 34 different species.

Seed of many species remain viable for months in water, sometimes for periods of 5 years. Seed viability can decrease with submersion time, depending on the species and duration of submersion (Kelley and Bruns, 1975; Comes *et al*., 1978). In a limited number of situations, maintaining seeds in water can break dormancy and increase germination rates (Comes *et al*., 1978).

Farm managers should consider the role that irrigation water may play in replenishing soil weed seed banks. In cases of severe contamination where the species number and seed density is high or it is likely that water contains problematic or invasive species, the water source might be changed or filters or decanting tanks installed. The most cost-effective method for farmers within an irrigation district may be to collectively maintain a zone adjacent to the irrigation canals where weed seed production is prevented in order to reduce the number of seeds in the irrigation water. Growers may be able to avoid the use of suspected irrigation water during times of peak seed shed. In the case of irrigation canals that are only used seasonally, it is wise to avoid the use of irrigation water early in the season, before the canals have been ‘flushed’ of deposited weed seeds.

Dispersal by wind was discussed in Section 1.2, and while many weed species are disseminated by wind, the special case of ‘tumbleweeds’ is worthy of closer examination. *Salsola kali* and *Kochia scoparia* are dispersed as whole plants that shed seed as they move across the landscape. Erecting fences has a limited impact on reducing seed dispersal of tumbleweeds, as strong winds can cause the weeds to be blown over the fences.

1.4 When Prevention is not Successful

Muenscher (1955) wrote that the aim of eradication is the elimination of a weed after it has become established in an area. That requires stopping the production of further propagules and the depletion of propagule reservoirs in the soil. As illustrated throughout this chapter, this needs to occur within the infested field as well as within distances that the species is capable of disseminating. Control methods will receive comprehensive discussion in other chapters within this book.

Control prior to seed development

Weed seed development is a complex phenomenon influenced by many variables. Farmers recognize that weeds are most detrimental to the crop during its establishment. This observation has been confirmed experimentally and has led to development of the ‘critical period of competition’ concept. One of the consequences of this approach is that farmers generally neglect weed control late in the season and/or do not focus on eliminating seed production. Weed growth late in the season replenishes the soil weed seed bank and perpetuates weed infestations. Some farmers in California, USA, who have practised scrupulous weed control for many decades, have succeeded in largely depleting the soil weed seed reservoir and, in so doing, have achieved extremely low annual weed control costs. Factors that influence the seed return include crop competition (with the level of seed production dependent upon the crop’s competitiveness), time of weed emergence in relation to the crop’s emergence, and time of the planting season.

Seed bank depletion

Complete depletion of the soil weed seed bank is not realistic under most circumstances. However, reducing the number of seeds in the soil ultimately reduces weed density and the opportunity presented by this approach should not be overlooked. Eliminating seeds entering into the seed bank is based on obtaining excellent (or complete) weed control. Weed species differ in the number of seeds they can produce as well as longevity of the seed in the soil seed banks (Davis *et al*., 2005). The time required to reduce seed viability by 50% ranged from <1 to 12 years for a select number of species. Yet the time to reduce seed viability by 99% ranged from 2 to 78 years for this same group of species.

Destroying perennial root systems and other vegetative propagules

Perennial weeds are a unique challenge to prevention. In addition to preventing seed production, prevention also implies eliminating the production and storage of food reserves into underground organs. Many species develop perennial characteristics as early as 2–3 weeks after emerging (McWhorter, 1989; Bhowmik, 1994). Tillage is the most effective non-chemical means to eliminate vegetative propagules from the soil. Frequent removal of above-ground biomass over an extended period of time is necessary to effectively deplete the food reserves in the underground organs. For example, multiple cultivations at 2–3 week intervals for 3 or more years have been effective in controlling many perennial weed species (Anderson, 1999).

1.5 Integrating Prevention into Weed Management

Agricultural systems need to optimize weed management. The critical, but often overlooked, first step is preventing weed infestations. At every step of production (such as seed selection, field preparation, planting, fertilization, irrigation, weed control, harvest and transport), prevention can be implemented and can impact the crop and cropping patterns in future years. Prevention is not, and cannot be considered as an isolated activity. Prevention is awareness and as such, it should be a daily activity which needs to be incorporated into the routines of all the people involved in agricultural production, at farm, state and national levels.

In this chapter, we have enumerated several agricultural practices that contribute to the long- and short-distance weed dispersal if complete weed control is not achieved. For the most part, managers can make relatively simple, cost-effective modifications to their practices to eliminate or greatly reduce the risk of introducing new weed seeds to the field; however, these opportunities require awareness and vigilance. Key considerations include:

- diligent monitoring for sources and vectors of new weed introductions to the ecosystem and to the individual farm property;
- proactive government laws and regulations that control the introduction and movement of plants and plant materials;
- preventing problems caused by perennial weeds by eradicating vegetative propagules;
- depleting the soil weed seed bank whenever possible;
- considering the probability of a devastating weed problem resulting from the introduction of a non-indigenous plant or transport of plant materials or soil from one location to another;
- producing and planting seed, seedling transplants and nursery stock that are free of weed propagules;
- preventing weed seed production in crop fields;
- preventing spread of weeds by farm machinery and transport and processing of agricultural commodities;
- adopting practices that minimize the presence of weed seed in livestock feed, manures and composts;
- preventing weed seed introduction into rivers and irrigation canals.

The focus of a prevention programme is twofold: to eliminate the introduction of new species as well as reducing the number of seeds in the soil seed bank. Once a species is introduced and is allowed to emerge, become established and produce seed, there is the potential to become a significant component of the weed seed bank in a relatively short period of time. For preventive approaches to be integrated into on-farm weed management practices we believe that agricultural educators, especially those who advise farmers, must reconsider the great importance of preventative weed control. As educators lead the way, prevention can be re-integrated into all aspects of agricultural production so that it is always the first line of defence.

1.6 Implications at the Farm Level

Manure application, irrigation water, use of plant material as organic matter (although not quantified in the literature), and use of weed-seed-contaminated crop seed all contribute thousands to hundreds of thousands of seeds per hectare (Table 1.1). Mt. Pleasant and Schlather (1994) calculated that >20 million seeds per hectare would be applied with cow manure in the worst-case scenario. In order to put this into perspective, in terms of contributing to the soil seed bank, we need a point of reference on the expected size of the seed bank. A study examining weed seed density in agricultural fields ranged from 6 million to 1.6 billion seeds per hectare at eight sites in the north-central region of the USA (Forcella *et al*., 1992); 255 million seeds/ha was the second-highest seed density. A sample of 58 fields throughout England, mostly used for vegetable production, had a range of 16 million to 861 million seeds/ha (Roberts and Stokes, 1966), with half of the fields having a density of 62 to 222 million seeds/ha. Roberts (1983) summarized six additional studies from Europe, representing 310 fields, averaging 225 million seeds/ha. The extremes were 2.5 million to 5 billion seeds/ha. Across all the soil seed bank surveys, a relatively small number of species comprised >70% of the seed bank.

The size of the seed bank can substantially increase under the combination of a low weed seed bank density and a high number of seeds in the manure. Likewise, a number of activities (i.e. composting, feed to animals) can reduce the viability of weed seeds and lessen the impact the seeds have on the weed seed bank. Activities to reduce weed seed viability seldom result in 100% loss of viability. In some cases, multiple practices complemented each other, such as ensiling and rumen digestion (Table 1.4) (Blackshaw and Rode, 1991). Due diligence is important in order to prevent the introduction of weed seeds into a farming system. As noted previously, the number of seeds introduced may not be as important as the introduction of a new species or weed biotype.

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