Sustainable weed control in small grain cereals (wheat/barley)

Book or Report Section

Accepted Version

Murdoch, A. (2018) Sustainable weed control in small grain cereals (wheat/barley). In: Korres, N. E., Burgos, N. R. and Duke, S. O. (eds.) Weed Control: Sustainability, Hazards and Risks in Cropping Systems Worldwide. CRC Press, pp. 215-237. ISBN 9781498787468 Available at https://centaur.reading.ac.uk/80098/

Publisher: CRC Press

Sustainable Weed Control in Small Grain Cereals (Wheat/Barley)

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Abstract

Wheat, barley, oats, rye and triticale are important food and feed crops. Chemical weed control has become increasingly challenging through loss of herbicide actives, regulations and the diminished efficacy of active ingredients due to the evolution of herbicide resistance in weeds. In this chapter, the characteristics of some important weeds of cereal crops are described and more rational methods of weed control based on an understanding of weed biology are evaluated. Non-chemical methods are not silver bullets and it is a mistake to expect them ever achieve the levels of efficacy demanded by intensive large-scale farming systems. It is therefore clear that an integration and stacking of such methods is needed and even then, the efficacy may be insufficient. Longer-term approaches must therefore be included and these are not rocket science! The long-standing practice of crop rotation allows weed life cycles to be targeted in different ways in different crops, and growing a more competitive cereal species and/or switching from winter to spring cropping may be required. Integrating these methods with the use of herbicides is suggested as one way of preserving the chemical portfolio still available and making the evolution of herbicide resistance less likely. At the same time, financial concerns of farmers and the environmental concerns of policy makers and the public at large, need to be addressed and the use of more precise approaches and spatially-variable weed management is advocated for both organic and conventional farmers.

Importance of Small Grain Cereal Cropping Systems

Small grain cereals are important food and feed crops, and in 2014 were grown on 289 million ha (mi ha) resulting in 928 million tonnes (mi t) grain (**Table 1**). This chapter focusses on the two main crops – wheat and barley – though oats, rye and triticale are locally important (**Table 1**).

Table 1 Global production of small-grained cereals in 2014. Compiled and calculated from data in FAOSTAT (2017).

Crop	Area, mi ha	Production, mi t	Yield, t/ha
Wheat	220.42	729.0	3.31
Barley	49.43	144.5	2.92
Oats	9.59	22.7	2.37
Rye	5.31	15.2	2.87
Triticale	4.14	17.0	4.10

Wheat (*Triticum* spp.) grows most successfully at latitudes of 30° to 60°N and 27° to 40°S (Nuttonson, 1955), but it is found in the tropics at higher altitudes and even within the Arctic. Percival (1921) reported wheat was grown in Tibet at altitudes up to 4570 metres above sea level. It is the world's most important small-grained temperate cereal crop with production of 729 mi t in 2014 (**Table 1**), production having been similar since then (736 mi t in 2016, FAO 2017).

Barley is also an important temperate cereal, being fourth in global importance among cereals after wheat, rice and maize. Like wheat, it is commonly grown in temperate cereal systems, but also at a wide range of latitudes and altitudes. It is particularly favoured in more hostile, drier environments (Crop Trust 2017).

Impact of Weeds on Small Grain Cereals

Potential crop losses due to weeds were estimated at 32% (range 26-40%) exceeding those of pests (18%) and pathogens (15%) (Royal Society, 2009). Yield loss is, however, only part of the story; the social consequences and the opportunity costs of the other economic activities people could do if they did not have to weed their crops are often ignored especially for small-scale, resource-poor farmers. For example, Holm (1971) argued that, *"more energy is expended for the* ***weeding*** *of man's crops than for any other single human task"*. The need for weed control in wheat is shown by the potential losses due to weeds being greater than for other crop protection problems (**Table 2**). The success of the efforts expended on weeding in wheat is illustrated first of all by the estimate that potential losses due to weeds are nearly a half of the total for all crop protection problems (23% out of 49.8%) whereas they are close to a quarter of actual losses (7.7% out of 28.2%:) and secondly, by the efficacy of control being much greater for weeds of wheat than for pests and diseases (**Table 2**).

Table 2 Estimated global potential and actual yield losses of wheat attributable to weeds, pests and diseases, together with efficacy of control. Estimates assume global wheat production of 785 mi t in 2001-2003. Ranges were estimated across 19 regions. Adapted and calculated from Oerke (2006).

	Potential yield losses, %		**Actual yield losses, %**		**† Efficacy of control, %**	
	Mean	Range	Mean	Range	Mean	Range
Weeds	23.0	18 – 29	7.7	3 – 13	67	55 – 83
Animal pests	8.7	7 – 10	7.9	5 – 10	9	0 – 29
Pathogens	15.6	12 – 20	10.2	5 – 14	35	30 – 58
Viruses	2.5	2 – 3	2.4	2 – 4	4	-33 – 0
Total	49.8	44 – 54	28.2	14 – 40	43	26 – 68

† Efficacy calculated as (1-[actual yield loss]/[potential yield loss])*100. Ranges of efficacy are of limited accuracy due to low values and method of calculation.

Major Weeds

Black-grass (*Alopecurus myosuroides* Huds) is native to Eurasia and is widespread in Europe. It has become a significant, invasive weed of rotations including winter cereals in Western Europe. Changes in farming practice such as the widespread adoption of minimum tillage instead of ploughing and a decrease in spring cropping have encouraged its spread (CABI 2017b). It is a major challenge to cereal growers in England, France, Germany, Belgium and the Netherlands. It is also spreading northwards in the UK and increasing in Denmark, southern Sweden and Poland (Moss, 2013). For conventional (non-organic) systems, its importance is exacerbated by the evolution of herbicide resistant populations.

Table 3 Relative importance† of six most troublesome weed species of spring and winter cereals in the United States and Canada calculated from responses in the 2015 Survey of Weeds (Van Wychen, 2016).

Weeds of spring cereals		Weeds of winter cereals	
Avena fatua	57%	*Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot	35%
Kochia scoparia	24%	*Bromus tectorum* L.	30%
Galium spp.	10%	*Secale cereale* L.	17%
Cirsium arvense (L.) Scop.	8%	*Aegilops cylindrica* Host	13%
Setaria viridis (L.) Beauv.	7%	*Kochia scoparia*	10%
Polygonum convolvulus L.	7%	*Stellaria media* (L.) Vill.	9%

† Calculation of relative importance: Respondents listed the five most troublesome weeds in their area. Taking the first three, the species a respondent ranked as the most troublesome was scored 3, the second, 2, and the third, 1. The weighted scores were summed for each species and expressed as a percentage of the maximum score ($3n$) where n is the number of respondents giving a valid response. $n = 30$ and 34 for spring and winter cereals, respectively.

Using data in the 2015 survey of weeds in the United States and Canada (Van Wychen, 2016), the most troublesome species in spring cereals were *Avena fatua* and *Kochia scoparia* (L.) Schrad with four of the top six, broad-leaved weeds (**Table 3**). In winter grains, the top four were grass weeds but the broad-leaved weed, *K. scoparia*, was the only species appearing in the top six for both winter and spring cereals (**Table 3**).

Wild-oat (*A. fatua*) probably has its centre of origin in Central Asia, but occurs globally in crops within arable rotations. As just noted, it is a particular problem in spring cereals, although it frequently infests winter cereals also. It competes particularly successfully with small grain cereals such as wheat and barley in part due to its greater height (up to 120 cm) compared to modern semi-dwarf cultivars (Holm et al. 1977, CABI 2017a).

Weeds in arable fields tend to reflect the soil seed bank of the weeds and, for example, the median soil seed bank of 64 arable fields comprised 4360 viable seeds per square metre with a range of 1500 to 67000 (Roberts and Chancellor, 1986). The most prevalent weeds were present in a majority of fields, with *Poa annua* L. present in all 64 fields assessed and >625 viable seeds m^{-2} in 35 of them (**Table 4**). These are some of the common annual weeds of arable fields.

Table 4 Prevalence of annual weeds in the soil seed banks of 64 arable fields in Midlands of England in 1976-77. (Data from Roberts and Chancellor, 1986).

Weed species	Present in fields, % (n=64)	Number of fields containing >625 viable seeds m^{-2}
Poa annua L.	100	35
Polygonum aviculare L.	92	17
Stellaria media (L.) Vill.	90	20
Fallopia convolvulus (L.) Á. Löve *	70	2
Aethusa cynapium L.	68	7
Veronica persica Poir.	67	19
Alopecurus myosuroides Huds.	67	18
Chenopodium album L.	66	7

* Synonym: *Bilderdykia convolvulus* (L.) Dumort.

The incidence of these weeds does not, however, reflect their economic importance. For example, Wilson and Wright (1990) reported 2% yield losses of cereals occurred with populations of 0.5, 1.6, 5.4, 8.3 and 39 plants m^{-2} for *Avena fatua*, *Galium aparine* L., *Poa trivialis* L., *Alopecurus myosuroides* and *Veronica hederifolia* L., respectively.

Much higher numbers of seeds were found in 37 Danish cereal fields by Jensen (1969). He reported an average of 62700 seeds m^{-2} in “heavily infested” fields. It is probably possible to account for the large seed banks by high numbers of *Juncus bufonius* L. var. *bufonius* seeds in some fields and methodological differences (Murdoch, 2006).

Weed Life Cycle

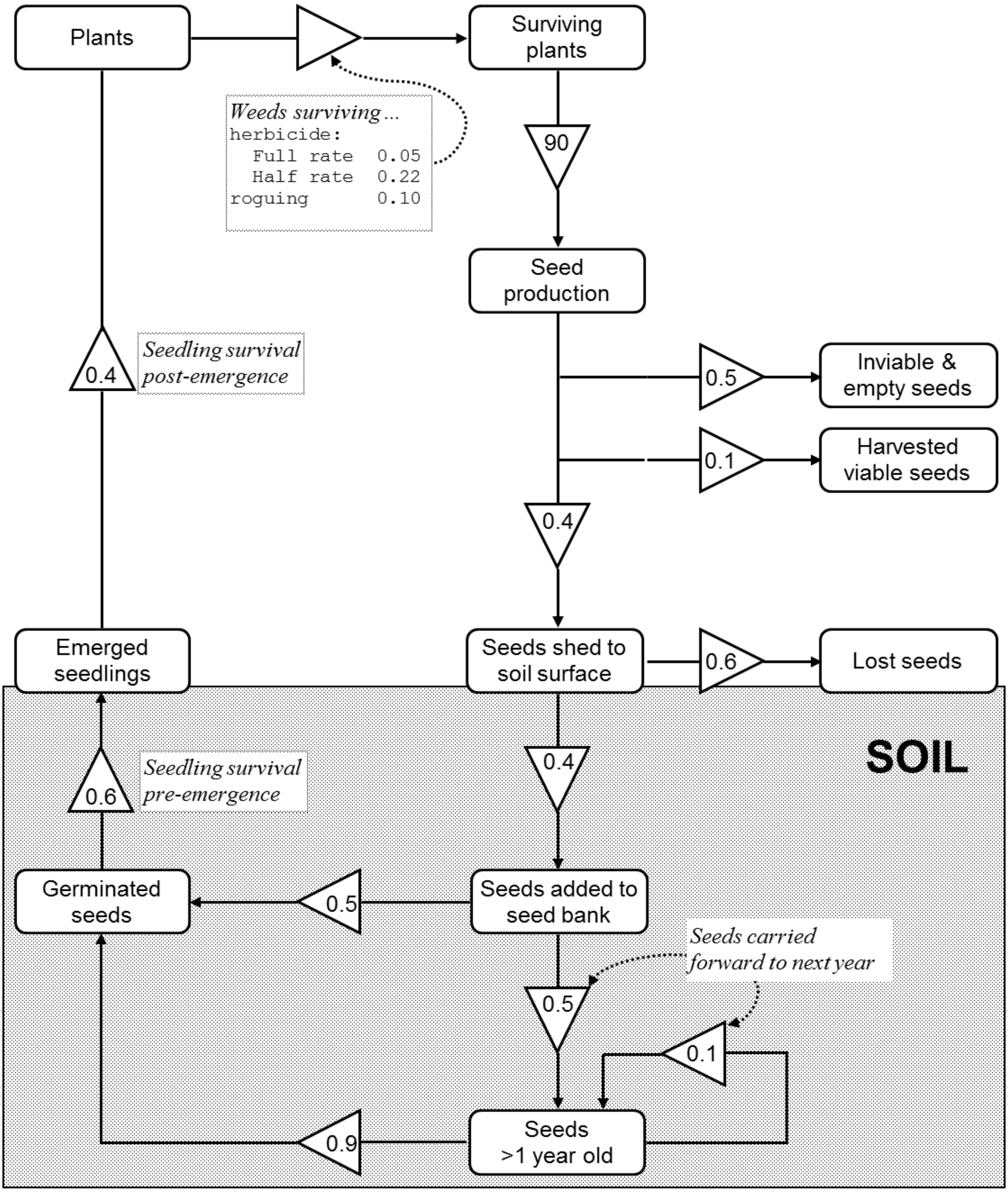

Figure 1. Life cycle of wild-oat (*Avena fatua*). Arrows show multiplication factors for each stage of the life cycle based on assumptions in Murdoch (1988) but values range widely. Depletion of buried seeds by loss of viability is not shown.

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Understanding and quantifying the life cycles and ecology of weeds is a key element in devising more rational and integrated methods of weed control. This knowledge may assist in exploring options for sustainable intensification of cereal growing designed to minimise unnecessary use of herbicides and to mitigate the potential for development of herbicide resistance. Using *Avena fatua* as a case study, it is clear that although perhaps half of the potential seeds produced may be inviable or empty, 10% may contaminate the harvested grain (**Figure 1**). Losses in the soil may be considerable (90% of seeds >one year old may be depleted per annum, shown as a proportion of 0.1 in **Figure 1**.) but only if there is a high level of available nitrate in the soil (Murdoch and Roberts, 1982). Integrated weed management strategies may exploit the latter in order to increase the rate of depletion of the soil seed bank. Conversely, inappropriate agronomy may mean smaller losses or greater seed production than suggested (**Figure 1**).

Weed Strengths and Weaknesses

Life cycle diagrams (**Figure 1**) linked to an understanding of driving variables can be a powerful tool for a systematic consideration of the strengths and weaknesses of different weed species and to identify vulnerabilities which may be exploited for Integrated Weed Management (IWM).

Seed production is frequently a defining trait in annual arable weeds, characterised both by fecundity and plasticity, such that large numbers of seeds may be produced in favourable conditions, but even in adverse conditions such as in a highly competitive crop, at least some seeds are produced (**Table 5**). These large numbers give rise to the old adage: “One year’s seeding: seven years’ weeding”, a statement which is well-supported by experimental evidence of the longevity of arable weed seeds in cultivated soil (Murdoch, 2006).

Table 5 Seed outputs per unit area and per plant per year of selected species. Sources: Salisbury (1961); Sagar and Mortimer (1976).

Species	Seeds per plant	Seeds m^{-2}
Alopecurus myosuroides Huds.	43	2500
Avena fatua L.	22 (range: 16-184)	1000 (range: 393-4784)
Chenopodium album L.	3000	-
Papaver rhoeas L.	17000 (1300 per fruit)	-
Stellaria media (L.) Vill.	2500 (5-16 seeds per capsule)	-

- not available

This fecundity gives rise to another strength of many but not all arable weeds, namely the size of the soil seed bank as discussed above.

Contrary to notion that a weed is "a plant out of place" (Blatchley, 1912), a further strength of weeds is that the dormancy of many, especially small-seeded weed species facilitates their survival in the soil seed bank of arable fields for many years and then to germinate in the right place at the right time, when conditions are most favourable to their establishment (Murdoch, 2013). Arable weeds are arguably, therefore, very much in their "place"! Examples of this adaptation are numerous. For example seeds of *Stellaria media* L. failed to germinate at constant temperature in darkness on paper moistened with water. Even exposure to an alternating temperature only gave 6% germination. However, exposure to light produced about 50% while combining light and nitrate increased germination to 100% (**Figure 2**). *Chenopodium album* L. shows greater adaptation to alternating temperatures provided light and nitrate are available, with a preference for longer periods each day at the upper temperature (**Figure 3**) and an optimum of approximately (3/20°C, 8h/16h). Soil disturbance can only serve to increase the probability that such species will germinate and emerge, an inference of considerable relevance especially when shallow or inter-row tillage is used to control weeds of cereals.

It is equally important and somewhat surprising to learn that some weeds of cereal crops have very little seed dormancy, an example being *Bromus sterilis* L. (syn. *Anisantha sterilis* (L.) Nevski). While the seeds have sufficient dormancy to prevent precocious germination on the mother plant, and while secondary dormancy may be induced through exposure to light, most seeds are non-dormant and seeds can be eliminated by a combination of burial after shedding and delayed drilling such as spring cropping (Peters et al., 1993; Andersson et al., 2002). Burial at a depth from which they will not emerge by total inversion ploughing is a totally effective option for recently-shed seed. Unfortunately in the UK, adoption of earlier autumn drilling of winter cereals in combination with dry autumns led to this weed causing significant infestations in some fields (Peters et al., 1993).

Other grass weeds show more primary dormancy (Murdoch, 2013) but requirements for relief of this dormancy mean they will not respond to creation of a false seedbed. For example, *Avena fatua* is better adapted to germinate under cool conditions without exposure to either light or fluctuating temperatures (Figure 4). Such seeds will remain largely unaffected by creating a false seedbed, and indeed their longevity will be enhanced since burial of the seeds by the creation of the false seedbed will remove them from seed-eating birds and exposure to the environmental fluctuations of the soil surface (Wilson and Cussans, 1975).

To complete the picture, characteristics of treatments which relieve primary dormancy of freshly-harvested or dry-stored weed seeds can only give a rough indication of what might happen to seeds in the soil. Buried seeds generally exhibit an annual dormancy cycle in which secondary dormancy is induced and relieved over the course of a year. Such cycles were first clearly described for a common weed of cereal crops, namely *Polygonum aviculare* L. (Courtney, 1968). Many other examples occur (Murdoch and Roberts, 1998) and the seasons in which low dormancy occurs is linked to periodicity of seedling emergence (Baskin and Baskin, 1985). For example, a spring-germinating summer annual like *P. aviculare* loses dormancy in winter and dormancy is induced in late spring (Courtney, 1968). The dormancy observed in the seed population is a combination of any residual innate dormancy plus induced dormancy - the two types of dormancy being generally indistinguishable after burial. Seeds germinate when times of low dormancy coincide with environmental conditions suitable for germination (Murdoch and Roberts, 1996) resulting in the periodicity of seedling emergence which characterises many species (Roberts, 1986) provided moisture is available (Roberts and Potter, 1980).

In *A. fatua*, for example, the dormancy of seeds retrieved over four years followed an annual cycle (Murdoch and Roberts, 1996). Induction of dormancy in the late spring was especially associated with increasing daily maximum soil temperatures above 20°C provided the soil water potential at the soil surface was between field capacity (-10 kPa) and *c*.-100 kPa. Even lower water potentials during summer led to a slight loss of dormancy presumably due to dry after-ripening; but the main decline in dormancy, when seeds regained their responsiveness to low temperatures and nitrate, occurred in autumn and early winter when the soil was again at field capacity and the daily maximum soil temperature was below 20°C (Figure 4). These responses also reflect seed-to-seed variation in dormancy. Thus *in situ* germination occurred late in winter when dormancy was least and some retrieved seeds had lost sufficient dormancy that they would germinate given water and air. Other seeds from exactly the same seed population retained a measure of dormancy such that they still required darkness and/or nitrate and/or low temperatures to germinate. Understanding that there is seed-to-seed variation in dormancy even within seed populations originating from the same field and at the same time in the same year is essential to the development of more rational weed management strategies which are designed to exploit weaknesses in the life cycles of weeds (compare **Figure 1**). This variation in relative dormancy in an ostensibly homogenous population of seeds of *Avena fatua* can be illustrated clearly by the population response to temperatures between 3 and 20°C (**Figure 4**). This seed-to-seed variation in dormancy is a common feature of all germination studies and quantifying this variation is a key component in modelling germination and dormancy (Murdoch, 2013; Murdoch and Kebreab, 2013).

Vleeshowers (1997) also distinguished between the seasonal cycle of dormancy and residual dormancy calling the latter a germination requirement. The results in **Figure 2**,**Figure** 3 and**Figure** 4 emphasise that the practical outworking of dormancy is not an identical characteristic of all seeds in the seed population. A germination test estimates what can be thought of as the mean level of dormancy.

Thus dormancy of buried seeds of *A. fatua* was relieved from October through to March and secondary dormancy appeared to be induced after the end of March (Figure 4). The induction of dormancy is only partly accounted for by the loss of relatively non-dormant seeds by *in situ* germination leaving a residual population of more dormant seeds.

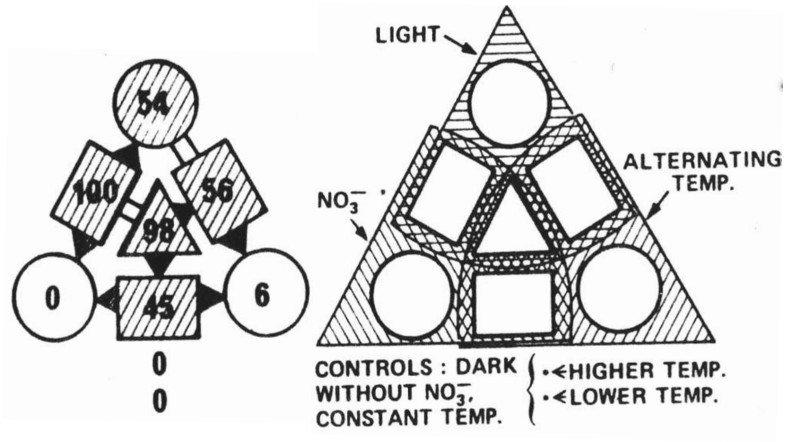

Figure 2. Germination of *Stellaria media* seeds. Germination in factorial combinations of constant temperature (25°C) compared to alternating (3/25°C, 16h/8h), in water compared to 0.01 M KNO_3, and with or without exposure to light. Germination at both control constant temperatures is shown underneath the triangular diagram. Cross-hatching indicates germination is significantly higher than in the control. The solid greater than (>) symbols indicate statistically significant differences. The equals (=) symbols indicate no significant difference. From Roberts (1973).

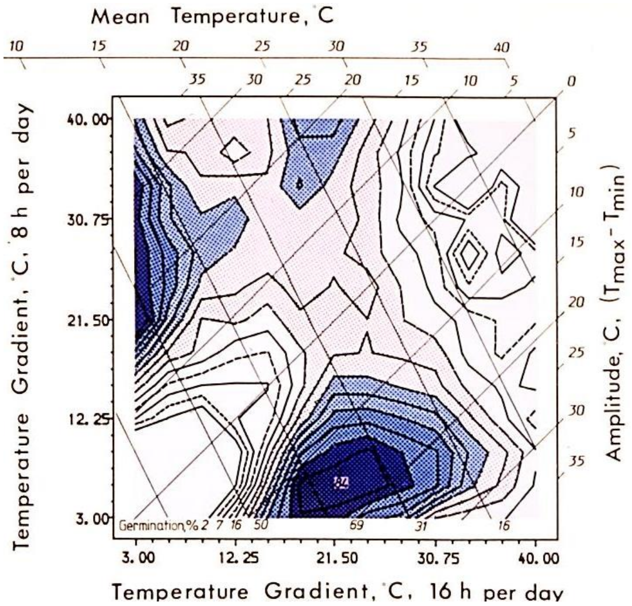

Figure 3. Germination of *Chenopodium album* seeds on a temperature gradient plate with gradients operating from left to right for 16 h per day and from bottom to top for 8 h. The darker the shading the higher the germination, plotted as contours on a scale of normal deviates, back-transformed values being given at the bottom of the diagram. From Murdoch et al. (1989).

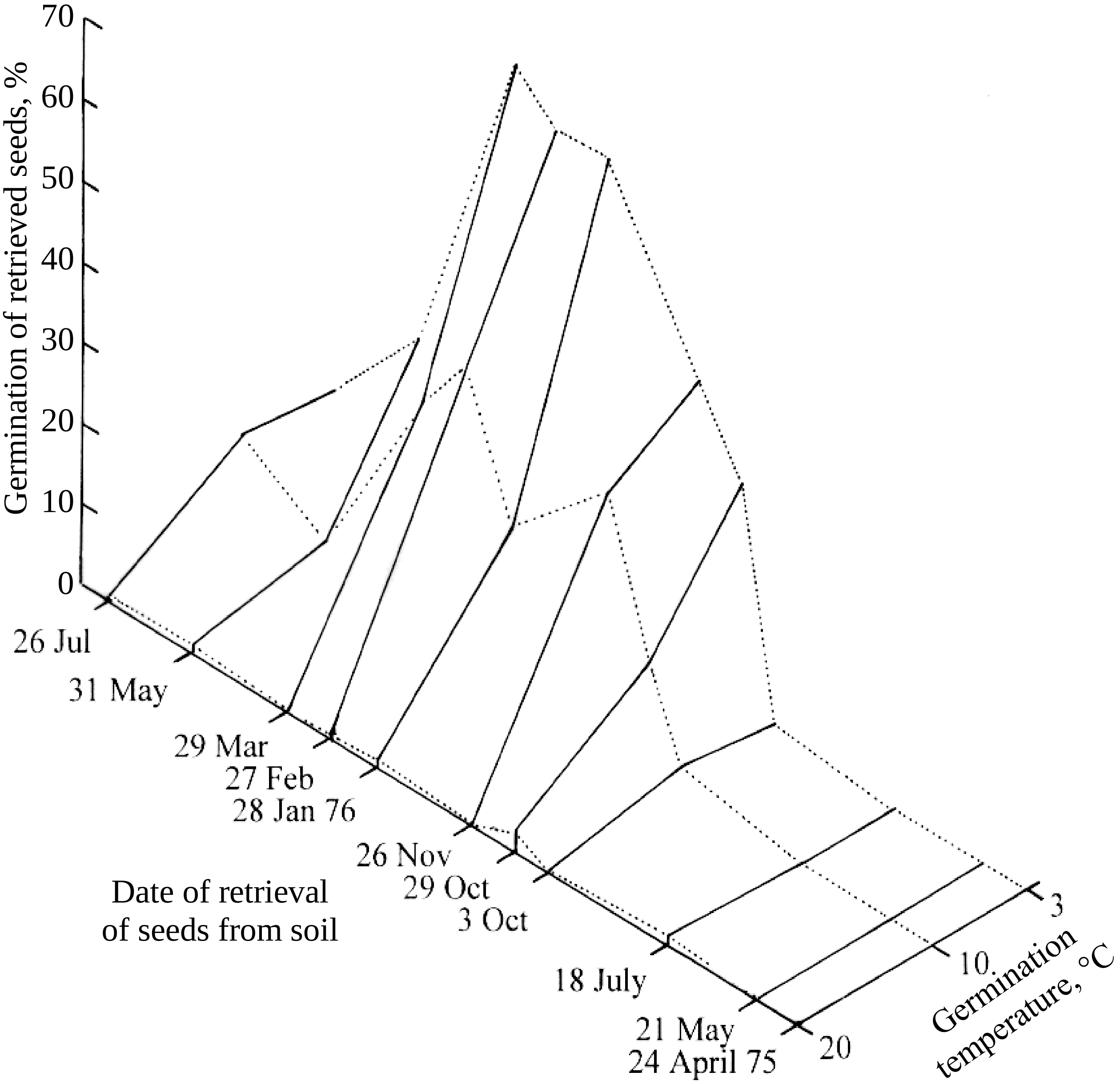

Figure 4. Germination of seeds of *Avena fatua* after retrieval on various dates from a 23 cm burial depth. Seeds were buried in December 1975, retrieved on the dates shown and then processed in a dark room equipped with a green safe light. Germination was carried out in incubators at temperatures of 3, 10 and 20°C in 0.01 M KNO3 and in darkness (Original data, A J Murdoch).

Fecundity, the annual dormancy cycle and periodicity of seedling emergence are major traits conferring weediness of weeds of small-grained cereals and also make elimination of these weeds problematical due to longevity of seeds in the soil. Circumstantial evidence for the longevity of seeds is supported by classical seed burial trials commenced by Beal in 1879 in Michigan and Duvel in 1902 at Arlington, Virginia as well as more recent examples (Murdoch and Ellis, 2000). Shorter-term studies are more useful from a farming perspective since they put reports of record-breaking, extreme individuals into the context of the overall seed population and allow the probabilities of persistence from year-to-year to be calculated and compared between species and environments.

Without further seed introductions, that is with 100% weed control, persistent soil seed banks approximately follow a negative exponential decay model on a year-to-year basis although decay in the first year may differ from that in subsequent years (as implied for buried seeds of *Avena fatua* in **Figure 4**). Annual probabilities of decline vary greatly both with species and environment, the frequency of tillage, soil type and fertility being significant factors (Roberts, 1970, 1981; Murdoch and Ellis, 2000; Lutman et al., 2002). For example, while the annual rates of depletion of some weeds typical of small-grained cereal crops declined rapidly (e.g. *Galium aparine* – 58% decline pa) and others very slowly (e.g. *Papaver rhoeas* L. – 9% decline pa), most declined at 20-40% pa.

Predicting germination and emergence of weeds is needed to optimize timings of post-emergence herbicides and also of non-chemical methods such as inter-row tillage. Various models have been developed and compared (e.g. Chantre et al., 2013), but these need to be combined with models of dormancy release (e.g. Blanco et al., 2014). Parameterising such models for different agro-ecosystems and different ages and cohorts of seeds in the soil seed bank is probably unrealistic especially as the influence of the crop is not accounted for. Simpler approaches may be all that is needed. For example, many years ago, Roberts at the then National Vegetable Research Station in the UK, showed the association of flushes of weed seed germination of annual broad-leaved weeds in conjunction with cultivation (seed-bed preparation) and rainfall (Roberts and Ricketts, 1979).

Current Weed Control Practices

Prevention:

Seed influx from sources of seeds outside a given field are unlikely to cause a significant infestation in the year of their introduction. Such introductions are however highly significant as a factor to consider in IWM: the numbers may seem insignificant and indeed, they usually are. The risk, however, is a new weed species or a new and perhaps herbicide-resistant biotype, may be introduced. For example, standard certified cereal seed in the UK, must not contain more than 20 weed seeds kg^{-1}, equivalent to 0.3 seeds m^{-2} for a seed rate of 150 kg ha^{-1}. A similar argument applies to irrigation water, but contamination of manure and compost can be more significant (Fenner and Thompson, 2005). Avoiding the introduction of new species should be a key element of IWM and so if there is a risk of such introductions, then monitoring is essential. The method of monitoring should also be evaluated; isolated introductions are likely to be missed if weed scouting is dependent on images captured by anything other than proximal sensors since the spatial resolution of images captured by remote sensing by RPAS, aircraft or satellite are currently only sufficient to detect fairly dense patches of weeds – isolated individuals will be missed (Murdoch et al., 2014). Biosecurity should therefore be considered and the IWM message is: look out for new weed species and herbicide tolerant biotypes, since these may in time become serious problems.

Mechanical/Physical Weed Control

Soil disturbance is one of the oldest methods of weed control and may be utilised for this purpose before drilling as part of both primary and secondary cultivations (e.g. ploughing and harrowing). In a meta-analysis of 25 experiments, Lutman et al. (2013) found that, relative to non-inversion tine tillage, direct drilling led to a (non-significant) 16 % increase in the number of *A. myosuroides* plants in the following crop, total inversion tillage with a mouldboard plough reduced the infestation by an average of 69%. Scherner et al. (2016) similarly showed that the annual grass weeds, *Apera spica-venti* L. and *Vulpia myuros* L., which like *A. myosuroides* have relatively short-lived soil seed banks, have become more widespread with the adoption of non-inversion tillage when preparing seedbeds for winter cereals in Europe. Interestingly, Scherner et al. (2017) found that that direct drilling (zero tillage) increased the thermal time for emergence of *A. spica-venti* and *V. myuros* meaning they were more likely to escape early autumn herbicide treatments.

It is therefore important to stress that, unless integrated with other approaches, total inversion tillage is often essential to ensure seeds are buried at depths from which they cannot emerge. Moreover, for ploughing to be effective where there is a persistent soil seed bank, rotational tillage should be practised to avoid restoring surviving seeds to the soil surface in the next season! The variability of the responses to tillage is perhaps more important to a farmer than the average effect. Thus although direct drilling had no significant effect on final emergence, in Lutman et al.’s (2013) meta-analysis, over half the experiments (13) had increases in infestation – up to 344% in the worst case, while six showed a decrease of up to 78%.

Post-emergence weed control can be carried out with shallow tines although incurring some damage to the crop (Welsh et al., 1996) but the net effect of the weed control achieved appears to be positive (Melander et al., 2005). Inter-row cultivations can be carried out without crop damage but a row spacing wider than the usual 12 cm is desirable for small-grained cereals even with a vision guided hoe to reduce the risk of crop damage. While wider row spacing up to 22 cm was claimed not to incur a yield penalty (Tillett et al., 1999), further studies in Italy have suggested the contrary as discussed below under seed rates. For non-chemical weed control, the yield losses are a cost, but for conventional farming systems using herbicides, the risks may not be acceptable.

Shallow tillage can also be used to exploit the stimulatory effects of light, nitrate and fluctuating temperatures on the germination of some weed seeds (see above). No-till cereal systems can exploit this trait to suppress germination, since the soil remains undisturbed, or shallow tillage can be used to promote germination prior to crop drilling by creating a “stale” or “false” seedbed in order to “fool” the weed seeds into germinating. They may then be controlled by harrowing before the crop is drilled or by spraying before it emerges.

It should also be noted that tillage will almost always lead to a flush of weed seedlings and so it is important to note that inter-row tillage systems mentioned must be designed with this probability in mind. A good rule of thumb is that given moisture, shallow tillage will stimulate 3-6% of the viable seeds in the soil seedbank to germinate (compare Roberts and Ricketts, 1979). So systems designed to use inter-row tillage must ensure that the crop is kept weed-free for the duration of the critical weed-free period of the crop. As a minimum, tillage is needed by the start of the weed-free period and is not needed after the end of it. For winter wheat in the UK, yield losses in excess of 5% were predicted if the crop was not kept weed-free between 500 and 1000°C days after sowing (October to January) (Welsh et al., 1999).

Cultural Weed Control

Seed Rates and Seed Quality

Andrew and Storkey (2017) simulated yield losses of winter wheat caused by an infestation of 80 *A. myosuroides* plants m^{-2} over ten years and the average yield loss increased from 9.4% with a crop plant density of 300 plants m^{-2} to 15% as crop density decreased to 150 plants m^{-2}. Korres and Froud-Williams (2002) studied weed suppression of a natural weed infestation comprising mainly annual broad-leaved weeds and *Poa annua* by six winter wheat cultivars. Averaged across all cultivars, weed dry weight in late June, approximately eight months after sowing, was reduced by more than 50% by approximately doubling crop plant density (125 compared to 270 wheat plants m^{-2}). Although a yet higher density of 380 plants m^{-2} failed to affect weed dry weight, the numbers of weed reproductive structures were approximately halved relative to 270 plants m^{-2} (1387 compared to 2736 m^{-2}). Sowing the crop 30 days later (in late October rather than late September) also reduced percentage yield loss from 19 to 5%.

Many reports confirm that increasing seed rate may enhance crop competitiveness and/or weed suppression although close examination shows some results are more equivocal. Thus in Korres and Froud-Williams (2002), crop plant density did not significantly affect weed dry weights or reproductive structures when assessed 70 days after sowing, whereas differences became apparent later during the growing season.

One problem with increasing seed rate is that intraspecific competition among crop plants may increase due to the increase in rectangularity of the crop. For example, using 12 cm rows, the distance between wheat plants within each row decreases from 5.6 cm to 2.8 cm if crop density is doubled from the 150 to 300 m^{-2}. Each plant is therefore "allocated" a rectangle of 2.8 x 12 cm or 33.3 cm^2 (**Table** 6). Planting "on the square" with 5.8 cm between rows and the same distance between plants within the row, would make a lot more sense for the crop and increase its potential competitiveness. The argument becomes even more compelling at a crop density of 450 plants m^{-2} (**Table** 6). In a study of the weed competition on yield and quality of durum wheat (*Triticum durum* Desf.) in Italy, de Vita et al. (2017) planted the crop at rates of 190, 380 and 570 seeds m^{-2} and row spacings of 5, 15 and 25 cm. Interestingly, in this experiment, seed rate did not affect weed dry biomass when assessed at the end of tillering (presumably GS30) which may explain the conflict with Korres and Froud-Williams (2002) who found very large differences with seed rate after GS69. Reduced inter-row distance, however, at about GS30, reduced the weed dry biomass of mostly broad-leaved weeds from approx. 110 to 70 and 22 g m^{-2} for the semi-dwarf cv. PR22D89 at 25, 15 and 5 cm row spacings, respectively. Wheat yields and crop nitrogen uptake were also higher for the narrow row-spacing even in the weed-free controls. The benefits of less rectangular planting arrangements are supported by other studies including simulation modelling (e.g. Evers and Bastiaans, 2016; Renton and Chauhan, 2017).

Table 6 Crop architecture and rectangularity for different seed rates at row spacings of 12 and 25 cm.

Crop density, plants m^{-2}	Crop density per linear metre	Land area per plant, cm^2	Gap between rows, cm, (A)	Gap between plants within rows, cm, (B)	Rectangularity, (A)/(B)	Optimum distance between plants, cm
150	18	66.7	12	5.6	2.2	8.2
300	36	33.3	12	2.8	4.3	5.8
450	54	22.2	12	1.8	6.5	4.7
150	37.5	66.7	25	2.7	9.4	8.2
300	75	33.3	25	1.3	18.8	5.8
450	112	22.2	25	0.9	28.1	4.7

A somewhat neglected aspect of weed suppression is that of seed quality even though high vigour seeds emerge more rapidly but also give higher emergence in stressful environments (Khah et al., 1986, 1989). These effects of crop seed vigour on emergence are given added importance since crop yield losses are greatly affected by the relative times of emergence of crops and weeds (O'Donovan et al., 1985; Cousens et al., 1987). Combined effects of seed vigour and seed rate can, therefore, be highly significant and, without other weed control interventions, may make the difference between some yield and no yield (**Figure 5**).

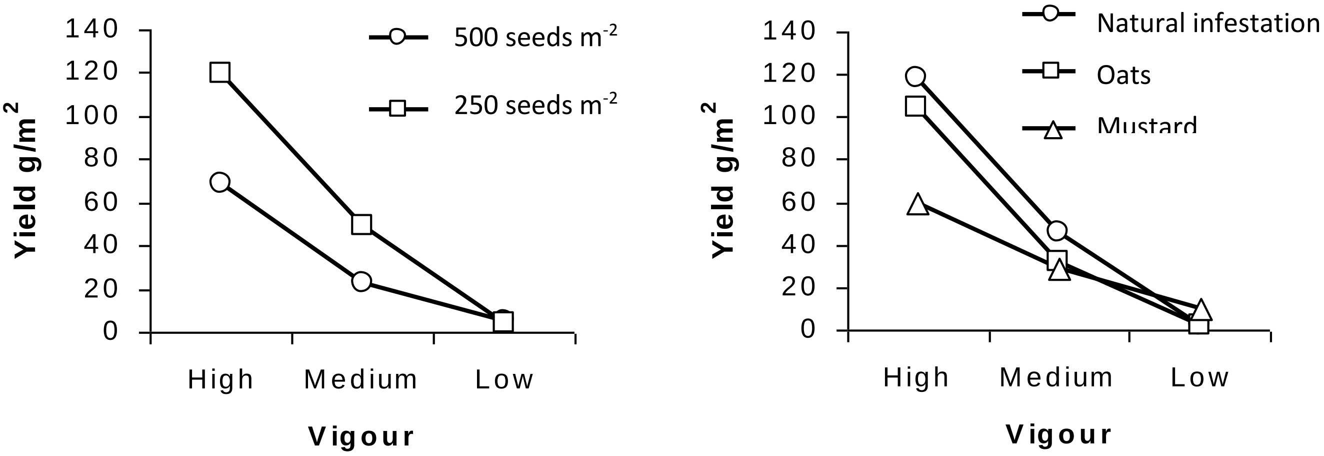

Figure 5. Impacts of seed rate and seed quality (vigour) on grain yield of spring wheat cultivar Chablis in a field experiment near Reading, Berkshire, UK, during the 2002 growing season. Seed vigour levels were achieved by ageing subsamples of the same seed lot for 38 (medium vigour, germination 87%) and 48 h (low vigour, germination 77%), the high vigour being the untreated control (germination 98%). Treatments comprised two seed rates (recommended and twice the recommended rate, SED=11, DF=17) and three weed treatments (SED=13): (i) naturally occurring weeds or as model weeds, (ii) *Avena sativa* var. Firth (oats) and (iii) *Sinapis alba* L. (mustard). From Al Allagi and Murdoch (2003).

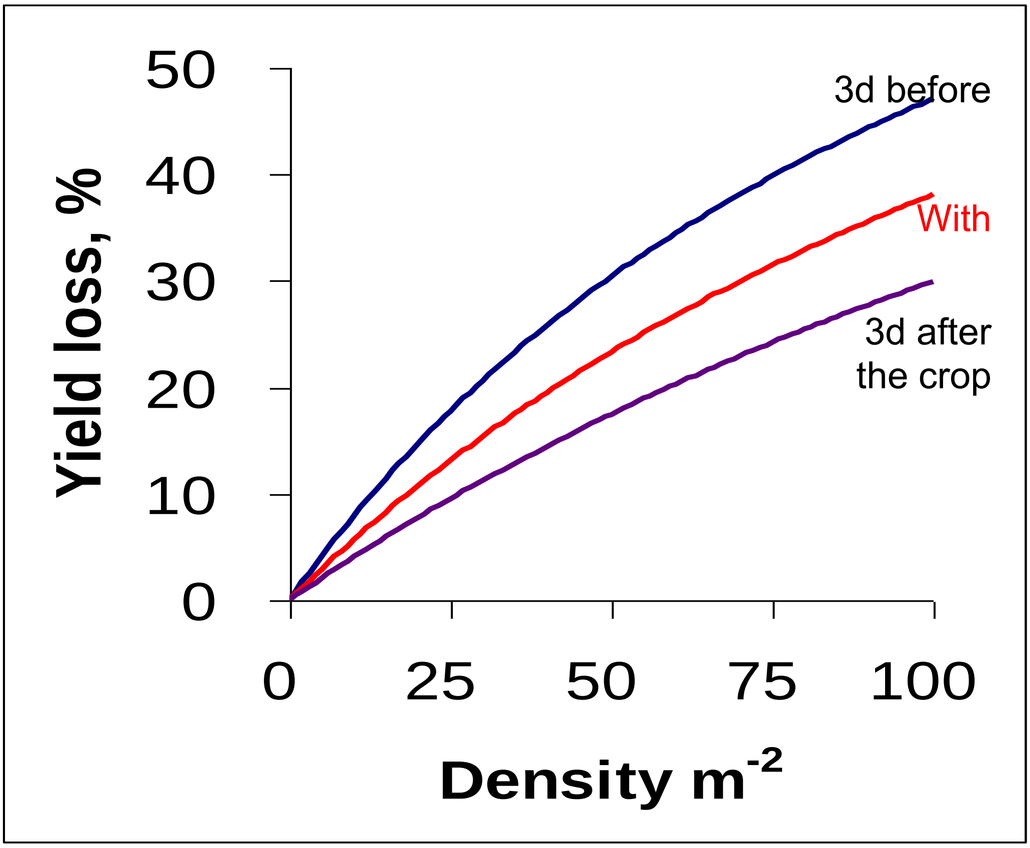

Figure 6 Predicted yield loss of spring wheat as a function of the density of *Avena fatua* and its time of emergence relative to that of the crop. Curves are calculated from parameter values in Cousens et al. (1987).

Advancing crop emergence by two or three days can have a significant effect on yield losses and weed competitiveness is affected by the relative time of emergence (RTE) of weeds relative to the emergence of the crop (**Figure 6**). It is likely that the impact of RTE on crop yields is insufficiently recognised and, as a result, factors likely to shift this parameter in ways designed to enhance the crop's competitiveness are not given due weight.

Competitive Crops

The Green Revolution has been of particular importance from the perspective of weed control, since many current commercial wheat cultivars are now semi-dwarf, shorter-stemmed cultivars due to expression of reduced height genes (*Rht*) (Addisu et al., 2008; Gooding et al., 2012).

This observation is important since agronomic cultivar traits are evaluated in weed free conditions. Indeed, unlike other biotic constraints such as pests and diseases, competitiveness against weeds is not typically a criterion for plant breeding (Seefeldt et al., 1999) and nor is it generally quantified as a trait to help farmers choose varieties (e.g. AHDB 2017). The main exception to these generalisations is for organic farming where the effect of dwarfing genes in wheat is recognised to lead to increased weed infestations (Cosser et al., 1996, 1997) such that taller and traditional cultivars tend to more weed suppressive (Hoad et al., 2008; Wolfe et al., 2008). More generally, crop height may be more important than relative time of emergence in mitigating yield losses from weeds in winter wheat (Harris, 2011).

In evaluating varietal traits, it is difficult to isolate effects of single traits like plant height on weed suppression. Using Near Isogenic Lines (NILs) in a common genetic background can help to overcome the problem of comparing different cultivars where various traits may be influencing competitiveness. Thus, using NILs in the genetic background of the wheat cultivar, Mercia, Kumuthini et al. (2010) compared percentage yield losses due to weed infestations for the "tall" 90 cm NIL (*rht*) with a dwarf NIL (<40 cm) containing *Rht12*. The taller line had 67 and 23% yield losses in 2007/8 and 2008/9, respectively, compared to 95 and 63% for the dwarf one in experiments where the weeds emerged at the same time as the crop.

In addition to cultivar height at harvest, other traits associated with greater weed suppression by wheat and barley cultivars include early ground cover and tillering, leaf angle and canopy structure, early vigour and allelopathy (Worthington and Reberg-Horton, 2013). However, not only are varietal characteristics important, cereal species themselves differ qualitatively in competitiveness, due to differences in these traits.

Table 7 Grain yields (t/ha) of spring cereal genotypes grown near Reading, U.K., in weed free plots and the percentage grain yield loss (GYL) in plots sown with either *Avena sativa* or *Sinapis alba* as model weeds. Genotypes are placed in order of their ability to maintain the yield relative to the weed-free yield in the absence of any other weed control. (DF for SED: 44). Adapted from Al-Allagi (2007).

Genotype	Weed-free yield, t/ha	GYL due to *Avena*, %	GYL due to *Sinapis*, %	Mean GYL, %
Barley	7.44	27.2	28.1	27.6
Triticale	5.39	25.3	53	39.2
Wheat cv. Axona	4.74	36.3	55.6	46.0
Wheat cv. Paragon	6.01	53.3	63.8	58.6
Wheat cv. Alder	4.83	53.6	73.8	63.7
Wheat cv. Status	6.19	72.4	77.8	75.1
SED Genotypes	0.34	5.46		
SED Weeds		3.15		
SED Genotype x Weed		9.45		

In experiments with *Avena sativa* L. and *Sinapis alba* L. as model weeds, spring barley and triticale were better able to maintain their yield under severe weed pressure, showing 27.6% and 39.2% yield loss compared to the weed-free control, whereas the most competitive wheat cultivars tested (Axona) had a 46% yield loss while and the least competitive (cv. Status) sustained a 75.1% yield loss (Table 7).

The weed suppressive ability of a crop tends to be a corollary of the ability to maintain yields in a weedy environment. Thus, barley and triticale suppressed weeds by 59% and 15% respectively more than the average for wheat cultivars. Among wheat cultivars, Axona and Paragon had 50% less weed dry matter compared to the poor competitor, Status (Al-Allagi 2007; compare with yield maintenance in Table 7). Using Principal Components Analysis, Al-Allagi (2007) showed that the importance of traits linked to the ability to maintain their yields under weed pressure could be ranked in order of importance as follows: 1) maintaining fertile tillers under weed pressure; 2) ground cover at Growth Stage (GS) 15-16; 3) height at GS 83; 4) leaf area at GS 15-16; 5) dry biomass at GS 15-16; 6) height at GS 15-16; and 7) mean time to emergence. Variations in plant architecture especially during early growth thus appear to be of value in enhancing crop competitive ability. In a more recent study with winter wheat, barley and oats, Andrew et al. (2014, 2015) identified similar traits in suppression of *A. myosuroides* and *S. media*, although their significance varied between experiments.

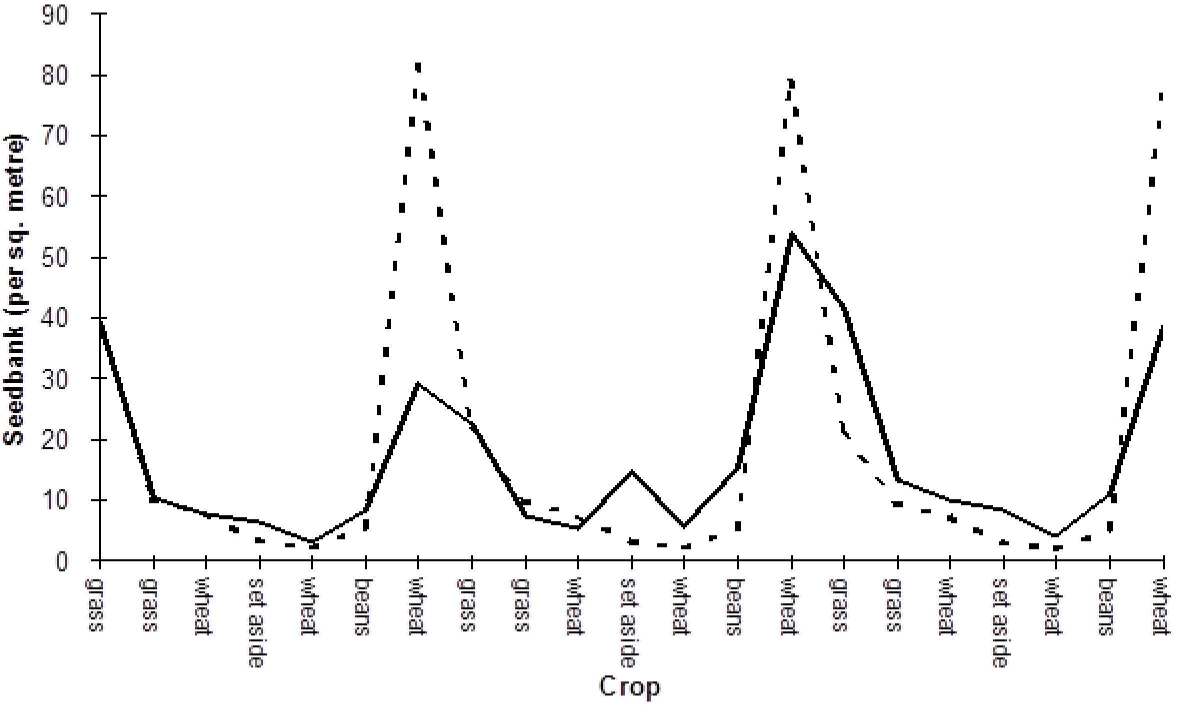

Figure 7. Predicted soil seed bank of *Avena fatua* in a seven-year arable farming rotation, which included a two-year grass ley. Herbicide use for *A. fatua* was modelled on the basis that herbicides were applied to infestations of 1 plant m^{-2} requiring either six full rate (- - - -) or eight half rate (____) herbicide applications, which were assumed to achieve 95 or 78 % control of seed production, respectively. Adapted from Murdoch et al. (2003).

Rotations

Rotations have been a key element of non-chemical weed control strategies since they give the opportunity to break the life cycle of problem weeds and to use different control methods. Adapting the life cycle model of *A. fatua* (**Figure 7**), the potential impacts of "cleaning" crops for weed management in an arable rotation are apparent since full-rate herbicide was required in only six out of 21 seasons or in eight for half-rate treatment (**Figure 7**, Murdoch et al., 2003).

Sowing Date

A further critical factor which can reduce the impacts of weeds on small-grained cereal crops is sowing date. Where drilling can be delayed without an unacceptable yield penalty and/or risk of an adverse sowing environment, weed control can be enhanced especially if the weeds emerge and can be controlled prior to crop drilling. Moreover, the efficacy of the pre- and post-emergence herbicides may increase significantly with later drilling (Hull et al., 2014).

Chemical Weed Control

Availability of herbicides is subject to commercial constraints, societal and political pressures, legislation and resistance in target organisms. Most countries seek to impose some restrictions on the use of pesticides. In the European Union for example, active substances are given EU-wide approval, but are subject to various directives governing their sustainable use and the need to keep contamination of waterways below certain levels. In addition, approved chemicals must only be applied to crops for which the approval has been granted and according to “label”. The label specifies measures to minimise the risks to people, non-target organisms and the environment and, for food crops, there are also maximum permissible residue limits. Under these rules, some chemicals which are important in arable rotations have lost approval and Clark (2014) considered that others of importance to European cereal growers are at risk including, 2,4-D, glyphosate and mecoprop (Clark, 2014). In addition some products of importance in crop rotations involving cereals and which can applied to control weeds such as *Alopecurus myosuroides* in crops other than cereals, are at risk of losing their approved status (for example, carbetamide, clopyralid and propyzamide, which are used in oilseed rape/canola). Nevertheless, a range of pre-, peri- and post-emergence herbicides are available and those most commonly applied to wheat and barley crops are tabulated for broadleaved and grass wheat weeds in small-grain cereals (Table 8). Out of 15087 t of all pesticides applied to all arable crops in the UK, over half was applied to wheat (8296 t) and nearly one fifth of all UK pesticide applications to arable crops were the herbicides applied to the wheat crop (2925 t) (Garthwaite et al., 2015).

Table 8 The top five active ingredients applied to wheat and winter barley in the UK in the 2013/2014 growing season. Numerical information adapted from Garthwaite et al. (2015).

Wheat	**Action/inhibitory mode of action (HRAC class*)**	**Weeds**	**Timing**	**Area treated, 1000s ha†**	**Amount used in UK, t a.i.**	**Proportion of full rate**
Iodosulfuron-methyl-sodium/ mesosulfuron-methyl (Atlantis)	ALS inhibitor (branched chain amino acid synthesis) (B)	G	Post	825	12	0.95
Glyphosate	EPSP synthase (G)	All	Predrill or pre-harvest	818	601	0.47
Diflufenican/flufenacet (Liberator)	Pigment synthesis (F_1)/ Cell division (K_3)	G+B	Pre	748	173	0.84
Fluroxypyr (e.g. Starane)	Auxin (O)	B	Post	478	64	0.38
Flufenacet/pendimethalin	As above/ Microtubule assembly (K_1)	G+B	Pre- to GS23	460	505	0.76
Winter barley						
Glyphosate	As above	All	Predrill or pre-harvest	187	132	0.46
Diflufenican/Flufenacet (Liberator)	As above	G+B	Pre	184	41	0.80
Pinoxaden	ACCase (lipid synthesis)	G	Post to GS41	166	6	0.61
Chlorotoluron/Diflufenican	Photosynthesis at PS II (C2) / As above	G+B	Pre-Post	91	127	0.47
Pendimethalin/Picolinafen	As above/ Pigment synthesis (F_1)	G+B	Pre	89	67	0.69

G: grass weeds; B: broad-leaved weeds; Pre: pre-emergence; Post: post-emergence
† Total areas: 1.94 mi ha (wheat); 0.429 mi ha (winter barley). * (HRAC, 2017)

Herbicide resistance

Heap (2017) lists 315 records of herbicide resistance in wheat. Of these, 62 reported multiple resistance to two (43/62) or to three or more (19/62) modes of action. The most extreme case was a population of the grass weed, *Lolium rigidum* Gaudin in South Australia, where it occurs in spring barley and wheat and has evolved multiple resistance to chlorpropham, chlorsulfuron, clomazone, diclofop-methyl, ethalfluralin, fluazifop-P-butyl, imazapyr, metolachlor, metsulfuron-methyl, quizalofop-P-ethyl, sethoxydim, tralkoxydim, triallate, triasulfuron, and trifluralin and there may be cross-resistance to yet other herbicides with the same modes of action. This population is also the only reported instance of a weed infesting wheat crops with resistance to mitosis inhibitors and DOXP inhibitors (Report by Preston (2012) in Heap (2017)).

Resistance to ALS inhibiting herbicides is the most frequent in weeds of wheat (192/315 reports in Heap, 2017) and the second most common is ACC-ase inhibitors (116/315 reports) and both of these are represented by the most common herbicides used in wheat and barley in the UK (**Table** 8). Resistance in weeds of small-grained cereals is widespread and increasing (Hull et al., 2014). Trends towards the use of herbicide tolerant crops and, where these are not used, to shorter rotations and earlier drilling as is the case for winter cereals in the UK for example, has increased the likelihood of herbicide resistance. Resistance is "seen" by farmers in that doses, which were once effective, no longer appear to be, even where application conditions are ideal and the product is applied correctly. Pragmatically, the dose required for efficacy exceeds the permitted "label" rate and indeed resistance may appear to be total in many plants within weed populations such that no dose appears to be sufficient to control them. This is well-illustrated by comparing the dose response curves of susceptible and resistant *A. myosuroides* populations to the post-emergence graminicide, Atlantis (Iodosulfuron-methyl-sodium/ mesosulfuron-methyl). In 2014, this herbicide was applied to a larger area (c. 43%) of the UK wheat crop than any other herbicide including glyphosate (**Table** 8). In glasshouse trials, the "Rothamsted Susceptible" biotype was controlled at 1/8th of the recommended (approved) dose rate whereas the two resistant lines tolerated 4x that dose. Despite the use of a herbicide mixture, the tolerant genotypes were resistant to both herbicides, exhibiting cross-resistance (Moss, 2010).

Integrating Weed Control Methods to Achieve Sustainability

Integrated weed control should enhance the efficacy of weed control but is unlikely to attract high rates of adoption among farmers unless gross margins are maintained or improved; it is not sufficient to minimise the application costs. Integration at its simplest may simply combine pre and post-emergence herbicides as well as herbicide mixtures (Pannacci and Onofri, 2016). The next step is integration with non-chemical weed control methods (Pannacci and Tei, 2014) and this is clearly needed to minimise risks of herbicide resistance. An important goal of integrating methods is to contribute to the sustainability of crop production by balancing crop productivity with the use of finite resources, while always seeking to minimise adverse environmental impacts (Dorwin and Lesch, 2010).

Integrated and sustainable weed control for small-grained cereals must first minimise the risk of introducing new weeds at every management level. Legislation is appropriate at national and regional levels. But the ultimate responsibility has to be the farmer's and at farm, field and perhaps within fields, standard operating procedures are needed to reduce the risk of introducing new weed problems or spreading them to clean areas during agricultural operations.

Where a weed is present in a field or farm, the goals of weed control need to be agronomically sustainable. Simplistically, irrespective of the short-term measures needed to control a current infestation, the long-term goals of weed control must have a sound basis in weed population dynamics. Should the goal be to contain the infestation and minimise yield losses in each crop or would a long-term goal of elimination be applicable? Modelling weed populations helps to answer the question. For example, given a soil seed bank of 500 viable weed seeds m^{-2} and an infestation of only 10 weeds m^{-2} (assuming only 2% emergence from the soil seedbank into the crop), would elimination be feasible? Assuming a negative exponential decline of the soil seed bank with 33% depletion of the soil seed bank each year and 100% effective weed control so that no new seeds are produced, 23 years are predicted to be needed to reach 10 weeds ha^{-1} (Murdoch, 1988). Clearly 10 weeds ha^{-1} is not elimination and since 100% efficacy is unlikely, the goal for most annual weeds of small-grained cereals has to be containment. Only in exceptional cases where depletion rates exceed 90% per annum, is elimination likely to become a realistic goal. Moreover because of the fecundity of most weeds (**Table** 5), the efficacy of weed control required to contain an infestation is very high. While it is clear that crop rotation is a key contribution to long-term sustainability (**Figure 7**), the problem of occasional crops where weeds fail to be controlled must be addressed (**Figure 7**). Using results in Lutman et al. (2013), Moss (unpublished) suggested it may be possible to "stack" several methods to control *A. myosuroides* even in a crop like winter wheat. Thus, although non-chemical approaches do not offer silver bullets, the individual efficacies of control by ploughing, delayed drilling, an increased seed rate and a more competitive cultivar are on average, respectively, 69%, 31%, 26% and 22%. Assuming these are independent effects and can be stacked, their combined effect would result in 88% control of A. *myosuroides* in winter wheat. The remaining 12% of uncontrolled plants may still affect yield and will certainly produce seeds and so a crop rotation would be needed for an organic system or a herbicide could be added for the conventional. Assuming 90% control were achieved with the herbicide, the overall efficacy of the stacked, integrated strategy would be close to 99%.

Sustaining the use of herbicides

Should some land be devoted to intensive cereal production, while other zones are kept for environmental benefits and ecosystem services? This question has an underpinning premise: that intensive cereal production especially where it involves the use of agro-chemicals cannot be sustainable. Use of many herbicides can, however, be sustainable if their application rates are optimised and if risks to people and the environment are minimised, mitigated and monitored. The trade-off between these dual requirements is less than might be imagined. First of all, the efficacy of herbicides can be enhanced and so the amounts required can be reduced by more efficient application methods (Butler Ellis et al., 2006; Jensen 2010). Moreover, efficacy is only achievable if the herbicide actually hits the weeds and run-off is avoided; for example, arable weeds with erectiform rather than planiform and/or needle-like leaves are more difficult to target.

Given a goal of reducing the amount of herbicide used without compromising efficacy, it is self-evident that efficacy will be greater if herbicides are applied when weeds are most susceptible and accessible, such as at early growth stages before canopy closure when weeds are less likely to be protected by the crop. More precise targeting is also possible for weeds which occur in patches, when patch spraying minimises unnecessary applications to the soil and crop. The trade-off is more difficult to avoid where adverse environmental impacts are likely to vulnerable zones such as headlands and field margins close to waterways or hedges. Finally, post-emergence, non-residual herbicides usually have less environmental impact and where available and effective, their use is preferable.

Sustainable use of chemicals is also much more likely if integrated with non-chemical weed and crop management. Not only does this reduce risks of herbicide resistance, but dose rates required or the frequency of treatment will also be lowered. For the farmers, the real trade-off is an economic one such that the decision to control weeds must be based on the probability that a profit will be achieved through their control – whether by chemical or non-chemical means or an integration of several approaches. This profit may be considered on a year-to-year or crop-to-crop basis, but the biology of weeds and the longevity of their soil seed banks, means that longer-term implication of allowing seed shedding on subsequent crops must be considered. Similarly, as noted already, crop hygiene must be observed to prevent new introductions.

Where herbicides are to be used, an environmental risk assessment of spray drift or to non-target organisms is desirable. Options designed to mitigate risks in small-grained cereal crops include operating nozzles at lower pressures; using air assistance and directing it downwards; and, for the last swath, either leaving it untreated or using lower drift nozzles and perhaps only applying sprayer washings.

For post-emergence herbicides, the dose to optimise efficacy needs to be determined for common weed species (Pannacci, 2016). Optimising herbicide dose rates and use of improved weed emergence models may improve the targetting and efficacy of post-emergence weed control (Masin et al., 2014).

Understanding how spatial variation in abiotic constraints affects cereal yields, weed infestations and herbicide efficacy, may also help in optimisation. The approaches and technologies of precision agriculture within individual fields are then likely to yield more sustainable and integrated approaches to weed and indeed cereal crop management.

Even in developing countries, farmers are well aware of spatial variability, at least at the level of farms and villages (Samake et al., 2005). Within farmers' fields, however, spatial variation of the key biotic constraints including weeds and their association with spatial variation of abiotic constraints, such as soil moisture and fertility is seldom known or understood. Most advice to farmers, therefore, follows a "one-size-fits-all" approach, ignoring the typically patchy distribution of many weeds in cereal fields. New technologies such as Remotely Piloted Aircraft Systems (popularly known as UAVs or drones) allow weed mapping, but often "after the horse has bolted", that is when it is too too late for treatment and there may also be too little information if ground truthing is needed.

Patchy distributions of weeds in fields are frequently noted (Murdoch et al., 2014). In such cases, should the whole field be treated uniformly or the patches differently? Treating the whole field uniformly is likely to waste resources and money and may risk an adverse environmental impact. However, if only patches are sprayed, is that sufficient to control weeds and maintain yields across the whole field? A related question is: how stable are these patches? When should and how easy is it for weeds to be mapped? For example, mapping might seem relatively simple with an RPAS or proximal sensor when the weeds are flowering or fruiting, but that is too late to apply anything other than the most drastic control measures – such as destroying the patches. Indeed such patches reflect failure of control earlier in the growing seasons and so some have sought to eliminate such patches where they have problems with herbicide resistance.

In general adoption of site specific weed management has been limited because of the uncertainty and research is needed to quantify probabilities of outcomes so that farmers different risk and time preferences can be accommodated in decision support systems. A recent report (EIP-Agri 2015) emphasised that one of the "challenges for innovation in the coming years [is that] a change in research attitudes is needed encouraging researchers to take into account farmers' opinions and advice."

More precise application technologies are challenging for small grain cereals due to narrow row spacing. For example, Midtiby et al. (2011) described a microspraying system, which worked well between rows but incurred unacceptable risks of crop damage within rows due to the tendency of spray droplets to drift. Similarly, Miller et al.'s (2010) spot sprayer was only suitable for large weeds. Christensen et al. (2009) described a droplet applicator rather than a sprayer. Here the risk of drift is lower, due to use of gravity-fed droplets applied via a field robot (see Klose et al., 2008). Leaf-specific control with a 'point and shoot' ejector emitting individually metered and targetted droplets is an advance on this but currently most applicable for field vegetables (Murdoc h et al., 2017) and use for small grain cereals is unlikely to be achieved for several years.

Concluding Remarks

The concept of sustainability for farmers must connect with the maintenance of their livelihoods as well as their self-interest in wanting to preserve the land for their posterity. With increasing problems of herbicide resistance, and because the efficacy of weed control from non-chemical methods is seldom sufficient to contain infestations, integrated weed management for small grain cereals is essential especially in temperate latitudes. For policy makers, drivers are more complex but are driven by the need to preserve food and nutritional security in the long-term. These get translated into various legal frameworks and various Directives and Regulations relate to the use of pesticides in general and herbicides in particular. For example in EU, concerns about pesticides in waterways are such that the Water Framework Directive (2000/60/EC) allows maxima per litre of drinking water of 1 µg of any one pesticide and a total of 5 µg for all pesticides. The Sustainable Use Directive (SUD, 2009/128/EC) explicitly promotes integrated weed management (IWM) designed to reduce or even eliminate the need for herbicides and the "risks and impacts of [their] use on human health and the environment".

The issue of loss of approvals of active ingredients and the numerous hurdles and dossiers of information required to develop new actives are a strong disincentive to manufacturers. Nevertheless unless a range of products is available, the risks of losing actives due to herbicide resistance is also greater since farmers will have to resort to using chemicals with the same mode of action. Moreover, the "greater the use of one active, over a large area, the more likely it is to appear in water" (Clark et al., 2009).

Overall, chemical weed control must be integrated with non-chemical approaches to be sustainable. The "many little hammers" (Liebmann and Gallandt 1997) approach of stacking treatments is also vital for non-chemical methods, as their efficacy is lower and there are no silver bullets. Another reason for stacking is that weeds are just as capable of developing "resistance" to non-chemical methods as they are to chemical ones (Harker, 2013). Adaptation is a key trait for weed survival for a weeds is ultimately the right plant in the right place at the right time. Integrated and sustainable weed management in small grain cereal crops must therefore be flexible and varied to limit the likelihood of such adaptation.

Acknowledgment

The author would like to thank Dr. Peter Lutman for reviewing the chapter.

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