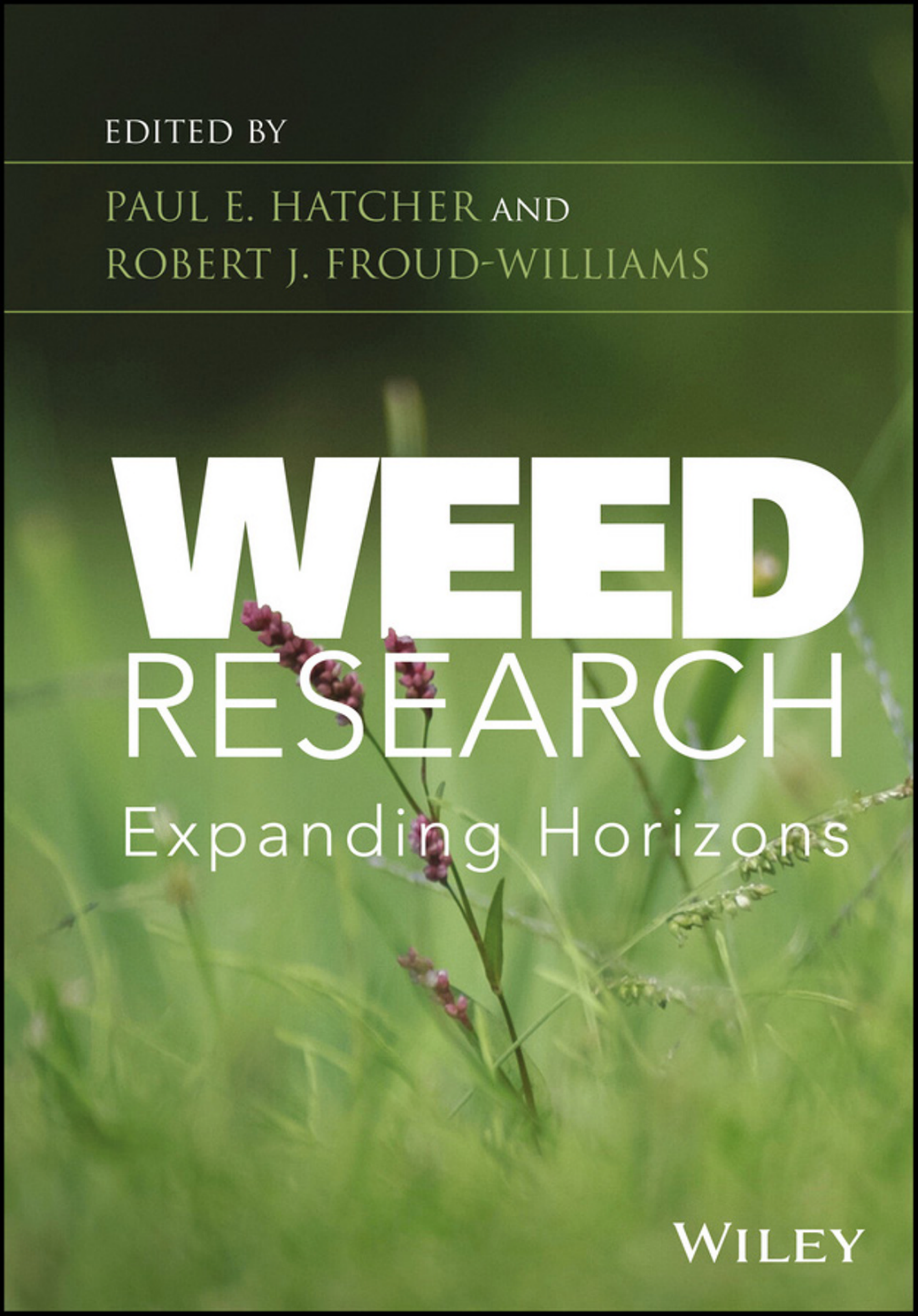

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PAUL E. HATCHER AND
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WEED RESEARCH

Expanding Horizons

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Weed Research

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Edited by Paul E. Hatcher and Robert J. Froud-Williams

University of Reading, Reading, UK

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Preface

Weed science is a very broad discipline, encompassing not only many aspects of pure and applied biology but also areas as diverse as agricultural economics, precision engineering, spray systems technology and plant taxonomy. This is due in part to the evolution of the subject, from one with an original overriding concern with pragmatic weed control to one having a greater understanding of weeds and their ecology, including interactions with other organisms. For many years the working groups of the European Weed Research Society (EWRS) have enabled weed scientists to keep up-to-date in their areas of weed research, and through regular workshops and conferences to meet other scientists working in their fields. In this book, the leaders of the current EWRS working groups have described the state-of the-art and future prospects in their areas. After an introduction which puts recent developments in weed research and the EWRS into context, there are chapters on mapping and describing weed populations, weed seed biology, modelling weed effects on the crop and the effects of weeds on biodiversity. Other chapters deal with particular types of weeds, such as parasitic weeds, perennial weeds and invasive weeds, and a chapter describes the special case of weed management in vegetables. Further chapters are concerned with weed management systems, including optimising herbicide use and the problems of herbicide resistance, the use of non-chemical weed management and biological control of weeds. Although by necessity the chapters have a broadly European focus, the areas covered and future prospects have a world-wide relevance.

We hope that this book will bridge the gap between one-volume weed science textbooks and specialist reviews in scientific journals and will prove useful to higher-level students, those starting their academic career in weed science and academics in related areas.

Paul E. Hatcher
Robert J. Froud-Williams

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Weed Science Research: Past, Present and Future Perspectives

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Introduction

Plants popularly referred to as weeds have been described by Sir E.J. Russell (1958) as 'The ancient enemy'. In his text on agricultural botany, Sir John Percival (1936) made the observation that the idea of uselessness was always present in the mind when weeds are being spoken of, while, in the editor's preface to *Weeds and Aliens* by Sir Edward Salisbury (1961), weeds are likened to criminals – when not engaged in their nefarious activities both may have admirable qualities: 'an aggressive weed in one environment may be a charming wild flower in another'. Our relationship with weeds certainly is as old as agriculture itself and the concept of weediness was recognised from biblical abstracts, for example the gospel according to St Matthew (Ch. 13 v. 7, the parable of the sower): 'Other seed fell among thorns, which grew up and choked them'. Yet weed science as a discipline is less than one hundred years old, albeit Fitzherbert (1523) in his *Complete Boke of Husbandry* recognised the injurious effect of weeds on crop production: 'Weeds that doth moche harme' included kedlokes, coceledrake, darnolde, gouldes, dodder, haudoddes, mathe, dogfennel, ter, thystles, dockes and nettylles'. These are recognised today as corncockle, charlock, darnel, corn marigold, dodder, cornflower, mayweed, stinking mayweed, fumitory, thistles, docks and nettles, several of which are now greatly diminished in abundance.

A major development in weed removal from within crops was achieved with the development of the seed drill by Jethro Tull *c.* 1701. Initially, the objective of this invention was to enable cereals to be sown in rows, whereby a horse-drawn hoe could be used to pulverise the soil in the inter-row. Tull conjectured that such 'pulverisation' would release nutrients beneficial to the crop, but coincidentally enabled weed removal, whereby 'horse-hoeing husbandry' became standard practice, reducing weed competition and the necessity of fallow, a serendipitous discovery.

Despite the efficacy of technological advances in weed control, weeds still exert great potential to reduce crop yields. Weeds are considered the major cause of yield loss in five crops (wheat, rice, maize, potato and soybean and a close second in cotton) (Oerke, 2006). Estimated potential losses due to weeds in the absence of herbicides were 23, 37,

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40, 30, 37 and 36% for the six crops respectively, while weed control reduced these losses to 7.7, 10.2, 10.5, 8.3, 7.5 and 8.6%, albeit with considerable regional variation (Oerke, 2006). Efficacy of crop protection practices varied between geographic regions, but whereas efficacy of disease and pest control was only 32 and 39% respectively, efficacy of weed control was almost 75%. The greater efficacy of weed control was attributed to the ability to employ both physical and chemical methods. Possible reasons for the apparent mismatch between weed control efficacy and actual yield losses were ascribed to changing cultural practices such as monoculture, multiple cropping, reduced rotation and tillage and the introduction of more vulnerable crop cultivars dependent on increased fertilisation.

Weeds have a major impact on human activities for not only do they adversely affect economic crop yield indirectly through interspecific competition (see Bastiaans & Storkey, Chapter 2) directly as a result of parasitism (see Vurro *et al.*, Chapter 11) and allelopathy, but also they affect human health and the well-being of livestock through physical and chemical toxicity. Additionally they may negatively impact environmental quality and functionality, such as that posed by alien invasive species including aquatic weeds (see Bohren, Chapter 10).

The objective of this preliminary chapter is one of scene setting. It seeks to associate 'man's' controversy with weeds as a consequence of their detrimental as well as beneficial relationships. Our changing perception of weeds is examined in terms of a shift in emphasis from that of pragmatic weed destruction to one of management and rational justification for their suppression.

Agronomic practices greatly influence weed population dynamics and these are outlined with particular attention to the UK weed floras. The history of weed science is explored as a discipline, together with a brief history of weed control technology including the discovery and development of synthetic herbicides. The origins of the Weed Research Organization (WRO) are discussed, together with the subsequent formation of the European Weed Research Society.

Weed science as a discipline originated at Rothamsted in England, the first agricultural research institute to be established in the world, with the pioneering work of Winifred Brenchley on the classic long-term continuous winter wheat experiment, Broadbalk, where she investigated the impact of various agronomic factors such as manuring, liming and fallow on the arable weed flora.

Factors Influencing the Weed Flora

Succession

The British flora is not an event, but a process that is continuing both with respect to accretions and diminutions (Salisbury, 1961). Vegetation is never static and weed populations are probably subject to greatest fluctuation as their habitat is continually disturbed. Two types of change within plant communities may be recognised: fluctuating and successional. Arable plant communities are subject to fluctuations as a consequence of direct intervention. Weeds are fugitives of ecological succession; were it not for the activities of man they would be doomed to local extinction and relegated to naturally disturbed habitats such as dune and scree. Weeds have been described as the pioneers of secondary succession, of which the weedy arable field is a special case (Bunting, 1960).

Successional change is less likely within ephemeral communities, although potentially capable in systems of prolonged monoculture and non-tillage. Two types of successional change may be recognised – autogenic and allogenic. Autogenic succession occurs in response to changes within the habitat, as species better adapted to a changing habitat oust previous inhabitants. A classic example of autogenic succession is Broadbalk Wilderness, whereby climax vegetation was achieved 30 years after the abandonment of an arable crop (Brenchley & Adam, 1915). Allogenic succession occurs in response to modified environmental factors such as fertiliser and herbicide input.

Prior to the advent of selective herbicides in 1945, weeds were kept in check by a combination of rotation, cultivation and clean seed, the three tenets of good husbandry. Previously, weed control was strategic, but the availability of herbicides enabled a tactical approach. However, the realisation that some weed species are of beneficial value to the arable ecosystem rendered the pragmatic destruction of weeds other than those that were most intransigent less acceptable; maximisation of yield was not necessarily synonymous with maximisation of profit.

Clean Seed

The use of clean seed as a consequence of the development of threshing machinery was greatly assisted by improvements in seed screening and legislation such as the 1920 Seeds Act designed to reduce the number of impurities. Regular inspection by the Official Seed Testing Station (OSTS) provides testament to the merits of seed certification. Early casualties of improved sanitation were the mimetic weeds such as *Agrostemma githago* L. (corncockle)*, a formerly characteristic weed of cereals which could be separated by seed screening. Prior to 1930 it was a frequent grain contaminant, as witnessed by records of the OSTS; the last authenticated record of its occurrence was documented in 1968 (Tonkin, 1968). A further factor contributing to its demise was the fact that its seeds are of short persistency in soil and require continual replenishment for survival. A survey of cereal seed drills in 1973 indicated considerable contamination by weed seeds including wild oats (*Avena* spp.) and couch grass *Elymus repens* (L.) Gould) as well as *Galium aparine* L. (cleavers) and *Polygonum* spp. (Tonkin & Phillipson, 1973). EU legislation designed to reduce the incidence of weed seed impurities in crop seed has certainly reduced this as a source of infestation, with, for example, only a single wild oat seed permitted per 500-g sample, provided that the next 500-g sample is entirely free of contamination.

Rotation

The season of sowing is the greatest determinant of weed occurrence (Brenchley & Warington, 1930). Hence, in the 1960s when spring barley predominated, spring-germinating species were prolific, the most significant of which was *Avena fatua* L., but also a diverse array of broad-leaved species, the periodicity of which is predominantly or entirely in the spring. The shift to autumn cropping in the 1980s disadvantaged spring-germinating species as a consequence of crop competition. *Avena fatua* exhibits a bimodal pattern of germination such that it was not necessarily disadvantaged, but it is possible that the related *Avena sterilis* ssp. *ludoviciana* (Durieu) Gillet & Magne.,

* Botanical nomenclature follows Stace (1997).

which is entirely autumnal in germination periodicity, may have supplanted it as the dominance of winter cropping continues. Previously, rotation for a spring-sown crop would have detrimentally affected the incidence of *Avena sterilis*.

The switch to autumn-sown cereals sown increasingly earlier and established by minimal tillage has exacerbated the incidence of annual grass-weeds, most notably *Alopecurus myosuroides* Huds. (Moss, 1980). Delayed drilling enables the use of stale seedbeds, thereby eliminating earlier weed emergence. It is of note that fallowing was introduced on the classic Broadbalk continuous winter wheat experiment as a response to the increasing problem posed by *A. myosuroides* (black-grass) in the 1930s and 1940s (Moss *et al.*, 2011).

A deviant of rotation was fallow, designed to reduce the incidence of perennial weeds on heavy soils by means of repeated cultivation through desiccation and exhaustion of vegetative propagules. Indeed, prior to the advent of herbicides this was the favoured means of reducing infestations of perennial grass-weeds, notably the five species of couch grass.

Fallow

Traditionally, perennial grass-weeds proved intractable and control depended on the inclusion of rotation and fallowing to enable mechanical weed control. The development of the non-selective herbicide aminotriazole in 1955, providing both soil and foliar activity, offered opportunities for couch grass control in the uncropped situations of autumn stubble.

Diquat and paraquat, introduced in 1957 and 1958 respectively, similarly allowed control of *Elytrigia* in non-crop situations. Because of the limited translocated activity of diquat, it proved desirable to cultivate stubbles prior to treatment in order to fragment rhizomes, thus alleviating apical dominance and enabling bud regeneration and regrowth.

It was not until the advent of glyphosate in 1971 that a non-selective foliar-translocated herbicide no longer necessitated rhizome fragmentation. Its ability to be applied pre-harvest of cereals following crop senescence further enabled a reduction in the incidence of couch. Now in English farmland couch is not a problem. However, couch does remain a significant problem in Scotland owing to the delayed senescence of the crop, and the benefits of pre-harvest application in wheat are disputed.

Subsequently, the introduction of sulfosulfuron and propoxycarbazone-sodium in 2002 for the selective control of couch and other grass-weeds within crop situations has further contributed to the reduced incidence of these perennial grass-weeds.

The additional inclusion of winter oilseed rape as an alternative autumn-sown crop resulted in considerable modification of the weed flora. By virtue of its optimal early sowing date, mid–late August, a number of late-season germinating species became characteristic of the crop, including *Sonchus* spp. and *Matricaria* spp. (Froud-Williams & Chancellor, 1987). Also, notable gaps in the herbicide arsenal enabled species such as *Galium aparine* and *Geranium dissectum* L. (cut-leaved cranesbill) to proliferate, as well as unlikely candidates such as *Lactuca serriola* L. (prickly lettuce), *Conium maculatum* L. (hemlock) and *Sisymbrium officinale* (L.) Scop. (hedge mustard). Hitherto, *Papaver rhoeas* L. (field poppy) that was highly susceptible to the phenoxyacetic acid herbicides in cereals became prominent in the absence of an effective treatment prior to the advent of metazachlor. The acreage of oilseed rape in the UK increased dramatically from *c.* 1000 ha in 1970 to 705,000 ha in 2011. One consequence of the expansion of oilseed rape was the legacy of feral rape as a roadside weed.

Cultivation

The transition from traditional systems of cultivation based on mouldboard ploughing to non-inversion tillage, made possible by the advent of paraquat and glyphosate, exacerbated the incidence of grass-weeds to the detriment of broad-leaved weeds characteristic of arable land. In particular this was exemplified by species such as *Alopecurus myosuroides* and *Anisantha sterilis* (L.) Nevski (barren brome), the latter particularly prevalent on shallow calcareous soils. A combination of straw burning and soil-acting residual herbicides such as isoproturon and pendimethalin contributed to management of black-grass, but during the 1970s suitable herbicides for brome management were lacking other than expensive combinations such as tri-allate followed by a sequence of metoxuron. By comparison, inversion tillage with or without straw burning had prevented brome from becoming a significant problem prior to the uptake of minimal tillage and autumn cropping. That said, the incidence of *Anisantha sterilis* as a weed of cereals was documented in the 1960s (Whybrew, 1969).

Straw Burning

A further contributory factor enabling the adoption of non-inversion tillage was the ability to remove previous straw residues by stubble burning. This had a sanitary effect, destroying a considerable number of weed seeds on the soil surface, albeit some impairment of herbicide performance was observed with the phenylureas, most notably chlorotoluron. However, the UK straw burning ban introduced in 1993 necessitated some return to traditional cultivation practices, as did the increasing threat of herbicide-resistant black-grass. Since the mid-1990s there has been a resurgence of non-inversion tillage made possible through stubble incorporation and treatment with glyphosate.

The overall effect of various agronomic practices on an individual weed species has been demonstrated in relation to black-grass (Lutman *et al.*, 2013). The greatest reduction was achieved by rotation with a spring-sown cereal which reduced populations on average by 88%. Mouldboard ploughing prior to winter cropping reduced plant densities on average by 69% relative to non-inversion tillage, while delaying drilling from September to October reduced densities by up to 50%. Increasing crop seed rate and selecting for more competitive cultivars reduced the number of reproductive heads by up to 15 and 22% respectively.

Soil Amelioration, Drainage and Fertiliser Use

Other characteristic cornfield weeds such as *Chrysanthemum segetum* L. (corn marigold) have further suffered decline despite being relatively non-susceptible to herbicides, as a consequence of amelioration of soil conditions by liming. A weed more typical of the north and west of the British Isles, it is associated with sandy soils of low pH. Although it exhibits a bi-modal pattern of germination in autumn and spring, the autumn-emerging cohort is particularly prone to frost damage, and so it is more likely encountered in spring barley.

Large-scale soil drainage during the 1960s has resulted in decline of those species tolerant of a high water table, such as *Gnaphalium uliginosum* L. (marsh cudweed), *Polygonum cuspidatum* L. (amphibious bistort) and *Polygonum hydropiper* L. (water pepper). Consequently, many species have retreated to their climatic and geographic refugia (Holzner, 1978).

Nitrogen

Changes in the use of nitrogenous fertilisers have also had a considerable impact on those species that are least competitive, such as *Legousia hybrida* (L.) Delarbre (Venus's looking glass), partly as a consequence of their inability to compete with nitrophilous species such as *Galium aparine*. It has been stated that the most effective means of weed suppression is a healthy vigorous crop. Studies at Broadbalk indicate that leguminous species such as *Medicago lupulina* L. are more prevalent on low nitrogen plots, as is also *Equisetum arvense* L., partly as a consequence of their tolerance or lack of suppression by nitrophilous species (Moss *et al.*, 2004; Storkey *et al.*, 2010). Conversely, *Stellaria media* (L.) Vill. (chickweed) showed a positive correlation with increasing nitrogen amount. Use of nitrogen in UK cereals increased dramatically between the 1960s and 1980s (Chalmers *et al.*, 1990). Despite increased rates of nitrogen application this does not explain the demise of *Lithospermum arvense* L. (corn gromwell), which is nitrophilous and highly competitive and not excessively susceptible to herbicides. A major factor here has been the earlier drilling date of cereals (Wilson & King, 2004). Species that are adversely affected by fertiliser and herbicides have been shown to share characteristic traits of short stature, late flowering and large seed size (Storkey *et al.*, 2010). Traits such as short stature and large seed size were shown to be of competitive advantage under conditions of low fertility. So too, Storkey *et al.* (2012) have shown a correlation between arable intensification and the proportion of rare, threatened or recently extinct arable plants within the European flora, with the greatest variance attributed to fertiliser use. Thus, the proportion of endangered species was positively related to increasing wheat yield.

Despite the transitory effects of cultural practices on weed populations, herbicides* have most probably exerted the greatest impact on species diversity and abundance. This is further evident from depletion of arable weed seedbanks, which often exhibited densities of between 30,000 and 80,000 m^{-2} in the pre-herbicide era but have shown substantial reductions in recent years (Robinson & Sutherland, 2002).

Herbicides

The earliest attempts at chemical weed control involved inorganic salts and acids, perhaps the earliest example of which was the use of sodium chloride for total vegetation control, as occurred following the sacking of Carthage in 146 BC. During the latter half of the nineteenth century, inorganic salts were developed for selective weed control, for example, copper sulphate used selectively in France (1896) for control of charlock (*Sinapis arvensis* L.) in wheat (Smith & Secoy, 1976). Ferrous sulphate and sodium chlorate were introduced between 1901 and 1919; the latter for total weed control in France,

* Herbicide chemical nomenclature follows Tomlin (2006).

as reported in Timmons (2005). Ferrous sulphate is still used for moss control in lawns. Sulphuric acid introduced from 1930 for selective control of annual weeds in cereals was first used in France in 1911, but superseded by DNOC (4,6-dinitro-ortho-cresol), developed as the first organic herbicide in 1932 and originally discovered to have insecticidal properties (Ivens, 1980) and used in early locust control. However, perhaps the earliest example of an organic herbicide was amurca derived from olive residue, used by the romans for weed control in olive groves (Smith & Secoy, 1976).

Until 1945, chemical weed control was largely limited to the use of arsenical and copper salts and sulphuric acid, the only organic substance being DNOC. Development of modern herbicides stems from the development of the growth regulator (hormone) herbicides during the 1940s following independent research of Imperial Chemicals Industry (ICI) and Rothamsted. ICI discovered the selective action of NAA (α-naphthyl-acetic acid), whilst the Rothamsted team demonstrated the selectivity of IAA (indole acetic acid) against clovers at low concentrations. Results of both groups were communicated to Professor G.E. Blackman at the ARC Unit of Agronomy in Oxford, who led search for related structures of greater potency. Because of wartime secrecy, results were not disclosed until 1945. This research led to the development of MCPA (4-chloro 2-methyl phenoxy acetic acid) (Blackman, 1945) and of 2,4-D (2-4 dichloro-phenoxy acetic acid) independently in the USA.

Following the advent of herbicides, methods of weed control departed considerably from hand hoeing and the use of steerage hoes. A survey of herbicide practice in four arable districts of eastern England in the cropping year 1959–60, of which about 80% of crops sown were cereals, indicated that herbicides were used on almost 80% of cereals in three of the areas (Lincolnshire Wolds, West Suffolk and Humber Warp) and 95% in the other (Isle of Ely). This compares with 56% usage on cereals in north-west Oxfordshire 2 years previous (Church *et al.*, 1962). MCPA was the most widely used herbicide, followed by mecoprop. By comparison, herbicide use in other arable crops ranged between 9 and 21%. Weeds that were targeted in these crops were *Cirsium* spp., *Sinapis arvensis*, *Galium aparine*, *Stellaria media*, *Chenopodium album* L. and *Rumex* spp. However, those species considered most intransigent were *Avena* spp., *Persicaria maculosa* Gray syn. *Polygonum persicaria* (L.), *Tussilago farfara* (L.), *Stellaria media* and *Matricaria perforata* Mérat. A comprehensive account of herbicide development prior to 1980 is provided by Ivens (1980).

The recent history of weed communities has been one of acclimation to the introduction of herbicides. Initially, the introduction of phenoxy-acetic acids reduced the incidence of susceptible weeds such as *Sinapis arvensis* (charlock), only to find the niche vacated occupied by less susceptible species such as *Galium aparine* and *Stellaria media*, necessitating the introduction of phenoxy-propionic acids such as mecoprop in 1957. So too were benzoic acids developed to address the incidence of *Polygonum* spp., while the hydroxybenzonitriles were introduced to target *Matricaria* spp. Following the introduction of the phenylurea herbicide isoproturon, *Veronica persica* (field speedwell) increased in prominence.

Evidence for such a shift in weed floras is documented in studies conducted in Germany by Koch (1964) where depletion of weeds susceptible to DNOC resulted in increased occurrence of *Alopecurus myosuroides*, and that of Bachthaler (1967) where repeated application of phenoxy-acetic acids over a 17-year period displaced susceptible species in favour of *Matricaria* spp., *Polygonum* spp. and *Avena fatua*.

Likewise, Rademacher *et al.* (1970) observed a change in weed species dominance over a 12-year period, while Hurle (1974) reported declines in the arable seedbank, particularly of *Sinapis arvensis* in response to repeated application of phenoxyacetic acids. However, in France, Barralis (1972) found little change in weed flora composition over 5 years. Similarly, Roberts and Neilson (1981) observed a progressive decline of *Papaver rhoeas* and *Raphanus raphanistrum* L. (wild radish) following application of simazine in maize, but substitution by *Urtica urens* L. (annual nettle) and *Solanum nigrum* L. (black nightshade). That said, other factors may contribute to fluctuations in weed populations, as indicated in a study by Chancellor (1979) where following application of a mixture of ioxynil, bromoxynil and dichlorprop to spring barley, most dicotyledonous species declined, whereas *Papaver rhoeas* decreased 92% on sprayed plots and by 91% on unsprayed plots. Conversely, *Polygonum aviculare* L. (knotgrass) increased by 67% on sprayed and by 189% on unsprayed plots. Such inexplicable dynamics have been reported for populations on Broadbalk (Warington, 1958).

Despite the early success of discovering phenoxyalkanoic acid herbicides (hormone herbicides), row crops such as sugar beet benefited from the early discovery of carbamates, for example, propham (IPC) in 1945. Chloridazon, a pyridazinone, was introduced in 1962, metamitron, a triazinone, and phenmedipham in 1965 and 1968 respectively. For use on mineral soils, lenacil was introduced in 1966. Likewise, horticultural crops such as leeks and carrots benefited from the introduction of the substituted phenyl ureas monolinuron (1958) and linuron (1960), as did potatoes with regard to the latter. It is somewhat ironic that linuron use has been restricted in potatoes following EU legislation. Triazines became the mainstay of the horticultural fruit sector following the introduction of simazine in 1956, being applied to 62% of the blackcurrant crop in 1962 (Davison, 1978). Usage in the amenity sector was revoked on 31 August 1993 and in the horticultural sector on 31 December 2007. Approval for the use of paraquat expired in July 2008.

Inevitably, resistance to herbicides became an issue in the 1980s with resistance first appearing to the s-triazines, notably simazine and atrazine. Resistance to the triazines had been predicted as a consequence of their persistency and, based on knowledge of selection pressure and ecological fitness, development of resistance could be foretold. Initially in the UK, resistance was confirmed in populations of *Senecio vulgaris* L. (groundsel) in geographically diverse locations, but with the common denominator of orchards and nurseries (Putwain, 1982). Resistance to s-triazines involves a mutation of the chloroplast thylakoid membrane and is conferred by cytoplasmic inheritance involving maternal inheritance, and so is particularly likely to occur in inbreeding species such as *Senecio vulgaris*. Subsequently triazine resistance occurred in other weeds of fruit orchards, most notably *Epilobium* spp. The nature of resistance to the triazines somewhat misled subsequent conceptions concerning resistance to other herbicide classes such as the phenylureas, where resistance most commonly involves enhanced metabolism and was first evident in outcrossing *Alopecurus myosuroides*. Following the first reported incidence of resistance to chlorotoluron in 1982, resistance to ACCase inhibitors and ALS inhibitors such as sulfonylureas is now well documented in *A. myosuroides*, the latter often involving target site resistance. Furthermore, target site resistance has been documented in *Stellaria media* and *Papaver rhoeas* (see Moss, Chapter 7).