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Advances in integrated weed management

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Contents

Introduction

Weed management continues to face many challenges, including herbicide resistance, invasive species, climate change and how best to deploy the range of non-chemical control methods available. To tackle these challenges, integrated weed management (IWM) needs to evolve to embrace a more holistic, landscape-based and agroecological approach.

This volume provides an authoritative review of the latest developments in IWM, including the changes in understanding the complex ways weeds interact with their environment and with each other, as well as how some weed species may contribute to ecosystem services such as soil health. The book is split into three parts. Chapters in Part 1 focus on weed ecology, Part 2 chapters examine intelligent weed control technologies and Part 3 provides five case study chapters that focus on the use of IWM in various settings.

Part 1 Weed ecology

The first chapter of the book discusses advances in understanding the contribution of weeds to the functioning of agroecosystems. Chapter 1 first reviews key aspects of weed ecology, focusing on areas such as weed diversity, weed functional traits and ways of accounting for intraspecific variation in weeds. It also highlights the use of a response-effect model to assess weed multi-functionality and trade-offs between negative and positive effects of weeds. The chapter includes a case study showing how farmers can manage weeds beneficially, followed by a summary on how important implanting effective IWM is to food security in the future.

Chapter 2 focuses on advances in understanding the dynamics of weed communities and their responses to different IWM approaches. The chapter assesses the role of a functional trait-based approach able to capture both the complexity of weed communities and the ways they might react to different combinations of IWM techniques. Rather than weed eradication, which might be neither feasible or environmentally beneficial, such an approach can potentially lead to a more functionally diverse weed community that is less competitive in any given crop. Adopting this more holistic approach will allow IWM to create both more productive and more sustainable cropping systems.

Moving on from Chapter 2, Chapter 3 discusses advances in managing arable weed propagules which can have a major impact on weed survival and spread. The chapter first describes the ways by which weed propagules have been historically managed. It then discusses advances in managing weed propagules with a special focus on inactive propagules i.e. those that are not germinated or sprouted. Ways of managing inactive propagules reviewed in the chapter includecrop harvest (weed seed crushing and milling), weed seeds on the soil surface (weed seed predation), weed propagules in the soil matrix (weed seed decay and mechanical destruction of ramets) and the process chains around arable farming (managing manure or crop biomass transport and processing). Finally, the chapter suggests new avenues for research.

Chapter 4 considers advances in allelopathic interactions between weeds and crops. The chapter begins by highlighting allelochemical classes and plant defence, how allelochemicals can be produced in plants and the use of a rhizosphere model for belowground microbial interactions in allelopathy. It also illustrates allelochemical interactions in wheat, rice, buckwheat and sorghum, reviews experimental methodology and allelopathic trait selection and provides a case study on the weed-suppressive effect of buckwheat. A section on using allelopathy as a future component of IWM is also included, focusing on the development of new herbicides based on allelochemical templates, the use of allelopathic crops and breeding for allelopathic traits in crops. The chapter then summarises how allelopathy can potentially be used in the future for IWM practices.

The final chapter of Part 1 focuses on advances in understanding invasive characteristics in weed species. Chapter 5 first examines how genetic modifications in plants can be considered a factor in invasiveness. It then goes on to discuss the four main epigenetic modifications that effect invasiveness: DNA methylation, histone modifications, chromatin configuration and actions of non-coding RNA species that affect messenger RNA availability. The chapter concludes by emphasising how both genetic and epigenetic modification analysis is important in understanding invasiveness and weediness.

Part 2 Intelligent weed control technologies

Part 2 opens with a chapter that reviews modelling the effects of cropping systems on weed dynamics, focusing on the how best to manage the transition from process analysis to practical decision support. Chapter 6 first assesses three contrasting models which quantify the effect of a cropping system on weed dynamics: a single-equation static model, matrix-based models and a model built from process-based sub-models. The chapter moves on to discuss ways of limiting the modelled system for more practical applications, focusing on temporal, spatial and species scales. It then reviews modelling approaches, first focusing on empirical versus mechanistic models, then discussing stochastic versus deterministic models. It also considers how to bridge the gap between process analysis and decision support before concluding with an overview of why models are essential in managing weeds and selecting the optimum approach to IWM.

Chapter 7 discusses developing decision support systems (DSS) for weed management. The chapter begins by reviewing how DSS can be used in weed management to set thresholds for implementing an IWM strategy. It then examines the role of decision support systems in reducing herbicide use, as well as how these systems can be used to prevent herbicide resistance for effective, low-cost weed control. The chapter also highlights how DSS can be used for long-term management of a wide range of weed species and how the adoption of weed management DSS by farmers is slowly increasing. The chapter concludes by highlighting how research into using DSS for weed management is developing.

The next chapter focuses on advanced detection technologies for weed scouting. Chapter 8 starts by highlighting the current techniques that can be used to make weed management more efficient, such as on-ground and remote-sensing methods for weed detection. The chapter then goes on to show how more precise weed scouting can contribute to implementing and assessing the effects of different IWM techniques and the ways they can be combined. These methods range from more targeted spraying, use of cultural techniques such as more competitive crop cultivars, tillage and rotation practices, through to better assessment of weed competitiveness and resistance in response to IWM strategies. The chapter concludes by highlighting the importance of improving detection technologies for weed scouting in the future.

The subject of Chapter 9 is advances in precision application technologies for weed management. The chapter begins by reviewing advances in precision weed control systems, including more precise herbicide application techniques (such as off and online patch spraying) for site-specific weed management. It also looks at advances in areas such as camera-guided mechanical weed control and robotic weeding. The chapter then examines emerging technologies such as improvements in image processing and weed identification, the use of genetic modification, signalling compounds, topical and systematic markers to help distinguish crops more easily from weeds. It also assesses the potential of nanotechnology in such areas as non-markers and sensors. A section on herbigation – the application of herbicides through an irrigation system – is also provided, followed by a discussion on tracking spatial distribution patterns of weeds for improved pre-emergence management. A summary on why new developments in precision weed management are essential to improving IWM practices closes the chapter.

Expanding on topics previously touched upon in Chapter 9, Chapter 10 focuses on advances in mechanical weed control technologies. The chapter first discusses the principles of mechanical weed control, then goes on to examine the three main types of mechanical weed control, starting with full-width cultivators then discussing inter-row and intra-row cultivation. The chapter looks, for example, at how vision and global navigation satellite system (GNSS) technologies can improve guidance systems for mechanical intra-row weed control possible, opening the possibility of automatic intra-row weeding to revolutionize weed management in direct-sown row crops

Part 3 Case studies

The first chapter of Part 3 assesses on-farm implementation of integrated weed management. Chapter 11 reviews the cognitive, social and individual dispositional factors which help to explain the lack of IWM adoption by farmers. It assesses factors such as lack of available knowledge on IWM, limited evidence for its efficacy, reliability and cost-effectiveness of IWM. The chapter also discusses the challenges associated with trade-offs against other attributes of cropping systems and the increased complexity involved in implementing an IWM strategy. The chapter reviews the infrastructure needed to support learning by farmers to change existing beliefs of farmers and resistance to change. The chapter includes a case study on understanding the decision-making processes for on-farm IWM amongst European farmers.

Chapter 12 looks at optimising integrated weed management in narrow-row crops. The chapter uses the IWMPRAISE framework which focuses on the five pillars of IWM. It first discusses cropping system diversification, then moves on to examine cultivar choice and establishment, field and soil management and direct control tactics. The chapter includes four separate case studies on IWM programmes for cereals in the United Kingdom, France, Slovenia and Denmark. The chapter then assesses the relative success of each programme to identify those approaches worth exploring in future research.

The next chapter reviews the current status of integrated weed management for grasslands. Chapter 13 first describes the weed management toolbox for grasslands, focusing on prevention, cultural, physical and biological control. It then moves on to review how weed management practices can be integrated in grasslands, supported by case study. The chapter also addresses how multiple transitions in the weed's life cycle can be dealt with, looks at the vertical and horizontal integration of weed management practices and the integration of grazing and mowing practices. A section on use of invertebrates and pathogens for weed control in combination with other management practices is also provided. The chapter concludes with an outlook for further improving IWM in grasslands.

Chapter 14 focuses on integrated weed management in perennial woody crops. The chapter discusses two case studies. The first of these is on olive orchards in Spain, focusing on strategies such as the use of soil management systems, tillage, no tillage with chemical control, inert cover with plant residue mulches, as well as use of spontaneous and cultivated cover crops. The second case study focuses on vineyards in the UK. The case study reviews soil management systems and, in particular, a NIAB EMR integrated weed management experiment, as well as the influence of weed management on canopy development, yield and grape quality. The chapter concludes by highlighting how the most suitable integrated weed management strategy can be influenced by factors such as location, topography, soil type, crop features, farmer preferences and climatic conditions.

The final chapter of the book reviews evaluating the economics of integrated weed management. Chapter 15 first looks at the various approaches to economic evaluation, then moves on to provide a case study on the economic performance of IWM for winter wheat production in Denmark. It focuses on comparing current weed management practices using crop rotations with alternative IWM strategies. The chapter compares the economics of different IWM strategies and describes the different approaches that can be used to assess the economics of IWM.

Preface

Weeds are ubiquitous and cause substantial yield and quality losses across all arable and horticultural systems and are thus a major concern to farmers. In many countries, weeds outnumber pests and disease in terms of potential impact on crop production. Some weeds are toxic and their presence in grassland may be a threat to grazing animals. Weeds also creates problems in recreational areas and the pollen of some weeds can cause allergenic reactions in humans.

Since the introduction of organic chemical herbicides shortly after World War 2, farmers in the developed world have relied heavily on the use of chemical herbicides. Mechanical weed control and cultural practices, which can prevent or reduce weed infestation, and which were widely practiced before the introduction of chemical herbicides, were given up. This change was perhaps most clearly reflected in the adoption of less diverse crop rotations. The blanket use of chemical herbicides became a standard practice in many crops even when the use of insecticides and fungicides against pests and disease was, at least partly, based on reaching certain thresholds for use and more targeted application. One reason why many farmers have been unwilling to skip the use of herbicides, even in fields with low weed infestations, is the long-term implications of surviving weeds on the soil seed bank.

In recent years, the intensive use of chemical pesticides has come under increased scrutiny and interest in alternative control measures has increased. In conventional farming, this renewed interest in non-chemical weed control measures has very much been triggered by the steadily increasing cases of herbicide resistance. At the same time, particularly in the EU, pesticide legislation has been tightened, and the criteria required for a pesticide to receive authorization have become stricter than ever. This is expected to lead to a reduction in the number of pesticides (including herbicides) available to EU farmers. The 2009 Sustainable Use of Pesticides Directive (SUD) sought to further reduce reliance on chemical control in favour of integrated pest management (IPM). Recently, the EU agreed on the 'Green Deal', at the heart of which is the Farm to Fork strategy that includes a 50% reduction in the use of pesticides by 2030.

One of the requirements of the SUD is that EU farmers should adopt IPM and follow the eight principles laid out in one of its annexes. IPM in entomology can be traced back to the 1900s while integrated weed management (IWM) is more recent. The backbone of IWM is more diverse crop rotations, requiring the trend towards less diverse crop rotation associated with the introduction of effective chemical herbicides to be reversed. Furthermore, non-chemical methods and biological control methods need to be developed, optimized and implemented to reduce the reliance on herbicides. However, most non-chemical tools are less effective or less reliable than herbicides. They cannot be considered stand-alone methods but need to be combined with other methods to provide an IWM strategy, making effective weed control more complex. The high level of complexity of IWM partly explains why it has not received the same attention as integrated management of pests and diseases. On the other hand, if the complexity of IWM can be resolved successfully, it could inspire others to proceed and develop integrated crop management solutions, which should be the final goal.

The present book addresses some of the issues that need to be resolved to reach this goal. This book complements the book 'Integrated weed management for sustainable agriculture' edited by Prof. Bob Zimdahl but also present results from the EU Horizon 2020 project 'IWMPRAISE', the first EU research and innovation project focusing solely on IWM. Hopefully the book will be of inspiration to the reader and promote both IWM research and uptake by end-users.

Chapter 1

Advances in understanding the contribution of weeds to the functioning of agroecosystems

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1 Introduction

Weeds are an essential component of the agroecosystem. They are one of the main biotic factors limiting crop productivity (Oerke, 2006), as they compete with the crop for sunlight, water and nutrients (Bastiaans et al., 2000). Their primary producer status also places them at the base of the agroecosystem food web (Pocock et al., 2012). The vast array of interactions weeds have with diverse biotic components found in cultivated fields can modulate ecological processes occurring above and below the ground in the agroecosystem (Marshall et al., 2003; Petit et al., 2011). As such, weeds are part of the functional biodiversity, defined as the biotic components that stimulate the ecological processes driving the agroecosystem and that provide ecosystem services (Blaix et al., 2018).

Research describing the functional role of plants in driving ecological processes is well developed in many ecosystems (e.g. grasslands, see Manning et al., 2015), but it is relatively recent in arable ecosystems where the focus has mostly been on processes underpinning food production (Moonen and Barberi, 2008; Martin and Isaac, 2015). However, over the last two decades, a number of studies have attempted to quantify the contribution of individual weed species and weed communities to a wide range of processes. One of the

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rationales was to assess the potential ecological consequences of the general decline in weed diversity observed in many parts of the world (Storkey and Neve, 2018). Another objective was to enhance our capacity to identify farming management strategies that can ensure crop productivity and enhance weed biodiversity and associated ecological processes, while being economically sustainable (Petit et al., 2015; Adeux et al., 2019a).

Weeds are primarily considered as pests (e.g. Shennan, 2008) and the outcome of weed–crop competition has been the topic of numerous studies and syntheses (Oerke, 2006). Losses in crop yield due to weeds are highly variable and affected by (i) the characteristics of the crop and of the species composing the weed community (Adeux et al., 2019b), (ii) the environmental conditions and crop management (Milberg and Hallgren, 2004), and (iii) the methodological approach implemented to relate weeds to crop yield (Colbach et al., 2020). The contribution of weeds to other agroecosystem services has received much less attention, although their role as trophic resource providers has been highlighted early on (Palmer and Maurer, 1997; Norris and Kogan, 2000; Marshall et al., 2003). In a recent review, Blaix et al. (2018) identified 129 studies describing weed contribution to ecological processes underpinning regulation services. Weeds were found to contribute to nutrient cycling and were shown to improve the soil's physical properties. The review highlighted knowledge gaps concerning the benefits of weeds for crop pollination and natural pest control. In the latter case, many studies only provided evidence that the presence of weeds increases the abundance or diversity of natural pest enemies, with no quantification of the positive feedback on crop yield.

Several key issues need to be addressed in order to improve our ability to predict the potential services and disservices provided by weeds and to identify farming management strategies that could reconcile crop productivity and the provision of regulation services. We need to better understand the role of weed diversity in the functioning of the agroecosystem. Some advances are also required in the development of functional approaches, that is, identifying key functional traits and accounting for their intraspecific variability. There is also an urgent need to implement functional approaches linking farming management to weed traits and to the multiple functions provided by weeds.

2 How key issues of weeds are addressed

2.1 The role of weed diversity

Agricultural intensification, including increased use of tillage, fertilisers and herbicides, on top of the simplification of crop rotations, has led to a widespread decline of weed diversity in many parts of the world over the last decades (e.g. Sutcliffe and Kay, 2000; Fried et al., 2009; Cirujeda et al., 2011). Although field edges (Fig. 1) still harbour higher weed diversity than field interiors (e.g. Fried

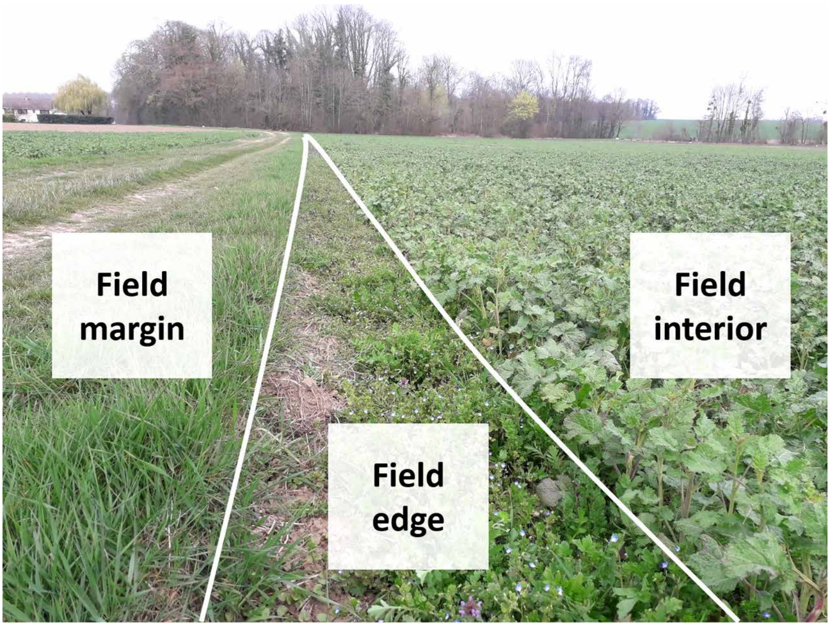

Figure 1 Field edges and field interiors harbour different weed communities.

et al., 2009), this loss of weed diversity is a concern, because it threatens the delivery of multiple functions and services in agroecosystems. The consequences of weed decline on higher trophic levels are quite easy to grasp. For example, at the national scale in UK, the decline in the population of farmland birds was partly explained by a reduction in the frequency and cover of bird food plants in arable fields (Smart et al., 2000). Similarly, the decline of bumblebee forage plants at a national scale over the last decades was identified as the likely principal cause of decline in bumblebee species across the UK (Carvell et al., 2006).

It is also increasingly suggested that in-field weed diversity could alleviate weed–crop competition, notably because it could protect the weed community from being dominated by a few highly competitive and/or herbicide-resistant weeds (Storkey and Neve, 2018). The idea that a diverse weed community will be less competitive is supported by several studies (Poggio and Ghersa, 2011; Cierjacks et al., 2016). More recently, through a detailed analysis of the effect of weed communities on several components of crop yield in a multi-year and multi-site field experiment, Adeux et al. (2019b) demonstrated that high levels of weed diversity were always associated with low weed biomass and reduced interference with the crop. The authors observed a positive relationship between the evenness of weed communities (evenness represents the similarity of contribution of the different weed species to the community and ranges from 0 to 1, a value of 1 meaning that all species in the community have an equal contribution) and crop productivity at all the critical crop stages, that is, stem elongation, heading, grain filling and maturity (Fig. 2). Besides the effect of weed diversity/evenness, the composition of weed communities was also a main factor explaining the variations in the degree of interference with the crop, with higher yield losses when competitive trait values were high at the community level.

2.2 Adopting weed functional approaches

Approaches based on functional traits have allowed a shift in perspective that better reflects the ecological processes that drive weed communities. Similarly, functional trait diversity, rather than the diversity of species *per se*, is the dimension of biodiversity most directly related to ecosystem functioning. Relevant functional traits can inform our understanding of plant responses to environmental and management factors (response traits). They can also have an effect on ecosystem processes underlying ecosystem service delivery (effect traits). Trait-based approaches have been widely applied in semi-natural ecosystems, yet their application to agriculture could help better identify the mechanisms underlying the role of agrobiodiversity in providing services. In agricultural systems, research on effect traits has initially focused on grasslands (e.g. see Manning et al., 2015). Lately, much effort has been devoted to arable systems and the identification of weed traits that are key for processes underlying the provision of agroecosystem services (Navas, 2012; Gaba et al., 2017; Cordeau et al., 2017). In parallel, weed mean trait values have become increasingly accessible in databases such as TRY (Kättge et al., 2011), LEDA Traitbase (Kleyer et al., 2008) or BiolFlor (Klotz et al., 2002).

Functional approaches accounting for the pattern of weed productivity and weed competitive ability and the resulting impact on crop yield have been the focus of several studies (Storkey, 2006; Adeux et al., 2019b). A low

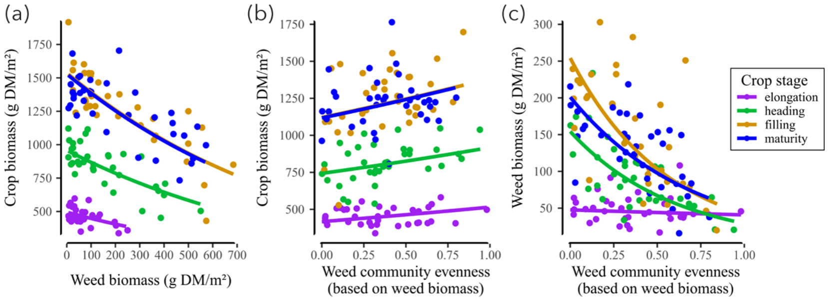

Figure 2 Relationships between (a) weed and crop dry biomass (b) weed community evenness (calculated from biomass data and crop biomass) and (c) weed community evenness (calculated from biomass data) and weed biomass at four crop stages in un-weeded winter cereals (Source: Adeux et al., 2019b).

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