Universitat de Lleida

Adapting the Decision Support System CPOWeeds to optimize weed control in northern Spanish conditions

José María Montull Daniel

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Universitat de Lleida

Departament d'Hortofructicultura, Botánica i Jardinería

Adapting the Decision Support System CPOWeeds to optimize weed control in northern Spanish conditions

Adaptación del Sistema de Ayuda a la Decisión CPOWeeds para optimizar el control de malas hierbas en las condiciones del norte de España

Programa de Doctorado en Ciencia y Tecnología Agroalimentaria

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Adapting the DSS CPOWeeds to optimize weed control in northern Spanish conditions

Doctoral Thesis Memory presented by José María Montull Daniel to obtain the Doctor degree by the Universitat de Lleida

This research has been performed at the Departament de Hortofruticultura, Botànica i Jardineria, Universitat de Lleida under the supervision and tutorage of Dr. Andreu Taberner Palou, professor of the Universitat de Lleida

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Sine agricultura nihil

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Agradecimientos

Quizá esta sea la parte que siempre dejamos al final, puede que por el miedo a dejarnos a alguien o porque ya dejamos de sentir la presión por el trabajo a realizar.

En primer lugar dar las gracias al Dr. Andreu Taberner. Esta tesis no deja de ser un paso mas en aquel camino que empezó en el año 2007 cuando se reportaron los primero casos de vallico resistente a glifosato en Castellón y Cáceres. Hay ocasiones en los que una tesis doctoral es un punto y final pero esta no deja de ser un punto y seguido en el complejo mundo de la malherbología donde los nuevos desafíos exigen que demos lo mejor de nosotros mismos.

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Summary

Integrated weed control is required in the current legislative framework for sustainable Plant Protection Products use. The advent of synthetic pesticides at the 50’s allowed simplifying cropping systems and forego more complicated crop protection strategies, especially in cereal production with more than 6M hectares cropped in Spain. But, the awareness of the decrease in the amount of pesticides applied is increasing since the mid 80’s in Europe.

In this work, a Decision Support System (DSS) is developed to make a Site-Specific Crop Management (SSCM). The advantages of the use of DSS are both economical and environmental because, by optimising plant protection products, it is in some cases possible to reduce the applied doses.

The Danish decision support system Crop Protection Online (CPO) optimizes herbicide weed control because it recommends specific herbicide solutions to achieve a required level of control. It has been developed since 1980's. CPOWeeds is a version of CPO adjusted to the conditions in Spain.

The first objective was to determine the *A*-parameter of the dose-response curve for relevant species.

The second objective was to calculate the shift of the dose-response curve according to the phenological stage for the main species of weeds because is the main factor that varies herbicide efficacy.

The final objective was to validate the CPOWeeds in field. The predicted efficacies and the yield obtained with CPOWeeds were checked in winter cereal field trials from 2010 to 2013.

For achieve that objectives, dose-response curves for each species and herbicides were parameterized. These parameters are the basis for the development of CPOWeeds. It was also noted that *B*-parameter is similar to that obtained for the same herbicides in conditions of Northern Europe. It may simplify in the future the process to obtain the parameters for new herbicides.

All CPOWeeds treatments were compared to the efficacies obtained with standard herbicide treatments decided by local advisors. The predictions from

CPOWeeds were compared to the achieved efficacies in the field trials for nine weed species at different developmental stages. In 84.2% of the comparisons the obtained efficacies were equal to or higher than the predicted ones Moreover, CPOWeeds achieved a satisfactory control level. In all five tests carried out in commercial wheat and barley fields, yield tended to be higher using the CPOWeeds.

It was concluded that the use of CPOWeeds allowed the optimisation of the herbicide application with a very high robustness. The recommendations were satisfactorily for the conditions of Spain and have the potential to decrease the amount of applied herbicides by at least 30%. Therefore, CPOWeeds can be an important tool in Integrated Weed Management.

Resumen

El Control Integrado de malas hierbas es obligado en el actual contexto legislativo de Uso Sostenible de Fitosanitarios. La llegada de los fitosanitarios en los años 50 permitió simplificar los sistemas de cultivo y prescindir de estrategias de protección de cultivos más complejas, sobre todo en el cultivo de los cereales, con más de 6 millones de hectáreas sembradas en España. Sin embargo, la preocupación por la disminución de la cantidad de fitosanitarios utilizados está aumentando en Europa desde mediados de la década de los 80.

En este trabajo, se pone a punto un Sistema de Ayuda a la Decisión (SAD) y se plantea un manejo campo a campo. Las ventajas del uso de los SAD son económicas y medioambientales porque optimizando el uso de herbicidas es posible, en algún caso, disminuir las dosis aplicadas.

El Crop Protection Online (CPO) es un SAD danés que optimiza el control de malas hierbas recomendando soluciones específicas concretas para cada situación que se viene desarrollando desde la década de 1980. CPOWeeds es una versión del CPO ajustada para las condiciones del Nordeste de España.

El primer objetivo del trabajo fue determinar el parámetro *A* de la curva dosis-respuesta para las principales especies de malas hierbas, este parámetro indica la eficacia de cada herbicida para cada especie en condiciones estándar.

El segundo objetivo fue calcular el desplazamiento de la curva dosis-respuesta según el estado fenológico para las principales especies de malas hierbas porque este es el factor principal que afecta la respuesta a los herbicidas.

Finalmente, se validó el CPOWeeds en campo. Se comprobaron las eficacias y el rendimiento obtenido utilizando el CPOWeeds en campos de ensayo entre 2010 y 2013.

Para conseguir estos objetivos, se determinaron las curvas dosis-respuesta de las diferentes especies y sus parámetros, que son la base para el desarrollo del CPOWeeds. Asimismo, se observó como el parámetro *B*, la pendiente de la curva es similar al obtenido para herbicidas similares en el norte de Europa, lo

que en el futuro puede simplificar el cálculo de los parámetros para nuevos herbicidas.

Todos los tratamientos del CPOWeeds se compararon con tratamientos Estándar, recomendados por técnicos de cada zona. En el 84,2% de los casos, las eficacias obtenidas fueron iguales o mayores que las predichas y se alcanzó siempre un nivel de control satisfactorio. En los cinco ensayos en campo, los rendimientos tendieron a ser superiores utilizando el CPOWeeds.

Por tanto, se concluye que el CPOWeeds permite optimizar la aplicación de herbicidas con una gran robustez para las condiciones agroclimáticas del noreste de España, con un potencial de reducción de uso de herbicidas de al menos un 30%. Por tanto, este SAD puede ser una herramienta muy importante dentro del Control Integrado de Malas hierbas.

Resum

El Control Integrat de males herbes és obligat en l'actual context legislatiu d'Ús Sostenible de Fitosanitaris. L'arribada dels fitosanitaris als anys 50 va fer possible simplificar els sistemes de cultiu i prescindir d'estratègies de protecció de cultius més complexes, sobre tot, en el conreu dels cereals, que ocupen una superfície de 6millions d'hectàrees a Espanya. Però, la preocupació per la disminució de la quantitat de fitosanitaris utilitzats està augmentant a Europa des de mitjans de la dècada dels 80.

En aquest treball, es posa a punt un Sistema d'Ajuda a la Decisió (SAD) i es planteja un maneig específic per a cada parcel·la. Els avantatges de l'ús del SAD son econòmiques i mediambientals perquè optimitzant l'ús d'herbicides, en algun cas, és possible reduir les dosis aplicades.

El Crop Protection Online (CPO) és un SAD danès que optimitza el control de males herbes recomanant solucions específiques concretes per a cada situació, ha estat desenvolupat des de mitjans de la dècada de 1980. CPOWeeds és una versió del CPO ajustada per les condicions del Nord-est d'Espanya.

El primer objectiu va ser determinar el paràmetre *A* de la corba dosi-resposta per a les principals espècies de males herbes.

El segon objectiu va ser calcular el desplaçament de la corba dosi-resposta segons l'estat fenològic de les males herbes per a les principals espècies.

Finalment, es va validar el CPOWeeds en assajos de camp. Les eficàcies i el rendiment obtingut amb el CPOWeeds van ser validats en camps d'assajos entre 2010 i 2013.

Per assolir aquests objectius, es van determinar les corbes dosi-resposta per a les diferents espècies de forma estadística. Així mateix, es va veure com el paràmetre *B* es similar al obtingut per els mateixos herbicides al nord d'Europa, la qual cosa pot simplificar el càlcul dels paràmetres per nous herbicides.

Tots els tractaments del CPOWeeds es van comparar amb tractaments Estàndard recomanats per tècnics de cada zona. Es van comparar les prediccions del CPOWeeds amb les obtingudes en camp per a les 9 principals espècies en diferents estats fenològics i, en el 84,2% dels casos, les eficàcies van ser iguals o més grans que les predites i es va aconseguir sempre un nivell de control satisfactori . Als cinc assajos en camps de blat i ordi, els rendiments van tendir a ser superiors utilitzant el CPOWeeds.

Es conclou que el CPOWeeds permet optimitzar l'aplicació d'herbicides amb una gran robustesa. Les recomanacions han estat satisfactòries per a les condicions agroclimàtiques del Nord-est d'Espanya, amb un potencial de reducció d'ús d'herbicides d’ almenys un 30%. Per tant, aquest SAD pot ser una eina molt important dins el Control Integrat de Males herbes.

General Introduction

General Introduction

Preamble

Agriculture and livestock farming require continuous evolution towards more efficient production processes. This is applicable for all inputs, but due to various reasons as social acceptance and economics, it is especially applicable for pesticide use.

Pesticide use has increased exponentially due to its excellent cost-benefit relationship compared to other agricultural practices since its appearance in the market since the 50’s. For example, herbicide consumption in Spain was 6326tm in 1995 and it was increased until to 14179tm in 2013 (FAOSTAT, 2016) and the majority of this consumption was in winter cereal, the main arable crops in Spain. In 2014, grain area was about 6.15 million hectares.

This excellent cost-benefit relationship in economic terms has led to an overuse of pesticides in some crops that may have negative impacts on non-target organisms and contamination of groundwater or surface water. However, the use of herbicides for nearly sixty years has allowed a deep knowledge of their advantages and disadvantages. For example, it is known that the effect of herbicides can be modulated more easily than other weed control methods. Thus, optimising their use should consider both improving the economic efficiency of farms and also decreasing the environmental impacts of their widespread use.

In addition, the evolution of society entails a greater awareness of environmental issues which has resulted in various Directives and Regulations in Europe. Within this legal framework various initiatives such as the Network of Excellence ENDURE and the PURE-IPM Project have been developed in order to promote tools such as decision support systems to be available for farmers throughout Europe with the objective of a more sustainable use of pesticides.

This thesis is integrated in this philosophy, where a Decision Support System (DSS) used in northern Europe is tuned to the southern European conditions.

It is remarkable the fact that in Northern Europe, cereals stop their growth due to the frost. In Aarhus, as an example of Danish conditions, there are two months with average temperatures under 0ºC, January and February.

In Spain, agroclimatical conditions vary a lot within the different parts of the country. Spanish Group to evaluate new cereal varieties (GENVCE) has defined nine agroclimatical conditions in order to facilitate the interpretation of data taking into account the rainfall and temperature values of each locality (GENVCE, 2015). Regarding the temperature, the following categories have been established:

-Cold areas. Areas with an average temperature below 11°C on April.

-Temperate zones. Areas with an average temperature between 11ºC and 13ºC on April.

- Warm areas. Areas with an average temperature above 13 °C on April.

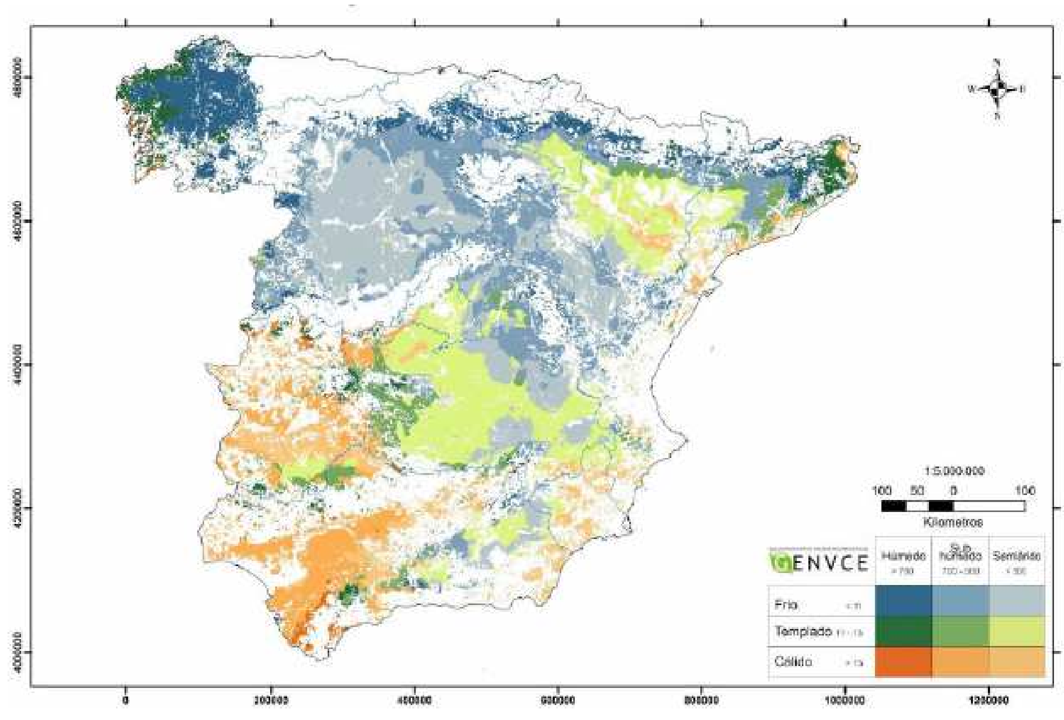

Figure 1. Spanish agroclimatical conditions regarding on annual rainfall and average temperature on April (GENVCE, 2015)

Regarding rainfall, created categories are:

-Semiarid zones: Areas where annual rainfall is less than 500mm

-Subhumid zones: Areas with an annual rainfall above 500 mm and less than 700 mm.

-Humid zones: Areas with an annual rainfall higher than 700 mm.

Taking into account this classification, Danish agroclimatical conditions are very cold, with an average temperature in April under 7ºC and among subhumid and humid, depending on the distance to the sea.

For that reason, in this thesis it has been verified whether the assumptions calculated for Northern Europe are also valid in the Southern climatic conditions with different herbicides and weed species.

Legal aspects: Directive 2009/128 on sustainable use of plant protection products

Dependency on pesticides for crop protection is associated with undesirable effects on the environment, human health and the sustained efficacy of their use. The advent of synthetic pesticides has made it possible to simplify cropping systems and to forego more complicated crop protection strategies. But this process threatens even the future of crop protection (Barzman *et al.*, 2015) due to the pollution and the development of resistance cases.

The awareness for decreasing the amount of pesticides used is increasing since the mid 80's in Europe, and has also placed emphasis on reducing toxicity on animals and humans. Finally, this awareness has been translated into a series of regulatory documents written by the European Parliament and the European Council.

The first one was the Directive 91/414 / EEC concerning the placing of plant protection products on the market. This Directive primarily aimed to favour the control and harmonization of requirements for the approval of active substances within the scope of the EEC. This would facilitate the exchange of plant products within the EEC and, therefore, improve its functioning. Furthermore, this Directive granted the efficacy of plant protection products and focused on toxicological and environmental aspects. That is, it focused on the toxicity to the applicator, non-target residues of plant protection and conditions on undertakings.

The main consequence of the application of Directive 91/414 was the decline of permitted active substances, from 984 active ingredients authorized in 1993 to 451 active ingredients usable in 2007. So, farmers, for some crops, began to use techniques of integrated pest, disease and weed control because they had run out of chemical solutions for some problems (Haza, 2008).

Later, in 2009, the Directive 2009/128 on Sustainable use of Plant Protection Products entered in force. This Directive no longer refers to the cutting criteria for authorization of new active ingredients but the use of plant protection products by itself. It also makes special reference to integrated pest, disease and weed management. The use of these techniques is mandatory since

January 1, 2014 and advocating the preferential use of non-chemical control methods: crop rotations, mechanical control, etc. at the expense of traditional chemical control (European Parliament, 2009).

Furthermore, this Directive requires the State Members to make available to advisors and farmers the necessary tools for the implementation of the Integrated Pest Management like Decision Support Systems to optimize and make a more sustainable and rational use of pesticides. This Directive has been transposed into Spanish law by the Royal Decree 1311/2012 which establishes the policy framework to achieve a sustainable use of plant protection products.

Towards a sustainable use of pesticides using Precision Agriculture techniques

Precision Agriculture (PA) is a farming management concept based upon observing, measuring and responding to inter and intra-field variability in crops, or to aspects of animal rearing.

The benefits to be obtained are chiefly due to increased yields and/or increased profitability of production to the farmer. Other benefits come from better working conditions, increased animal welfare and the potential to improve various aspects of environmental stewardship. Thus, PA contributes to the wider goal concerning sustainability of agricultural production (Zarco-Tejada *et al.*, 2014).

In this work, a Decision Support System (DSS) is developed. In this case, the DSS is used to make a Site-Specific Crop Management (SSCM); its approach is a form of PA whereby decisions on resource application and agronomic practices are improved to better match soil and crop requirements as they vary in the field. In this case, the differences in weed infestation for each field require different doses of herbicides or even different herbicides. There are other SSCM where the variations indicated in such a definition are not limited to spatial variations (i.e. within-field variability) but also comprise observations throughout a season or between seasons. Actual PA implementation in the 1980’s started when farmers integrated newly-developed fertilizers capable of deploying variable rate application (VRA) technology with maps that showed the spatial variability of soil chemical properties.

These techniques allow optimising herbicide application. Traditionally, herbicide application is made at crop level, not a field level within a farm, without monitoring the real infestation at field level.

The first step to a more sustainable use of herbicides would be to monitor the weed species in each plot in order to select the most suitable active ingredients. The second step would be to determine the phenological stages of each species in order to refine the selection of those active substances and the third step is the optimization, which refer to the adjustment of the required dose to comply with the basic definition of Precision Agriculture: to apply the right treatment in the right place at the right time (Gebbers & Adamchuk, 2010), or as mentioned in the area of crop protection: application should be as much as necessary, but as little as possible (Been *et al.*, 2009).The next step, which is more difficult to achieve with current technology, would be also to apply the required amount of herbicide plant by plant, to centimeter accuracy.

However, and although it seems relatively simple, optimising the application of plant protection products is a complex decision and it is affected by many variables: crop, growth stage of the weeds and crop, weather and soil conditions, treatment cost, expected return, expected sales price and also, long-term profitability.

That is why since 30 years ago there are being developed various DSS in the area of crop protection, and in particular in weed management trying to optimize the use of herbicides or other control methods as it is shown in the next section.

Decision Support Systems developed in Europe for weed management

Decision support systems (DSS) are computer technology solutions that can be used to support complex decision making and problem solving (Shim *et al.*, 2002).DSS have evolved significantly since their early development in the 1970s. Over the past three decades, DSS have taken on both a narrower or broader definition, while other systems have emerged to assist specific types of decision-makers faced with specific kinds of problems. Research in this area has typically focused on how information technology can improve the efficiency with which a user makes a decision, and can improve the effectiveness of that decision (Pearson & Shim, 1995).

Early in the development of the DSS, they ran based on the operating systems DOS or UNIX, and then at the beginning of the decade of the90's, they were upgraded to the Windows platform. Finally, DSS developers have taken advantage that gives the Worldwide Web, especially in applications designed to be used when you are out of the office, such as DSS to use in the agricultural area, where it is very important to use these tools from tablets or smartphones with internet connection. Their use from tablets or smartphones has been the key that has facilitated large-scale use.

It is important to clarify that the DSS are unable to think by their own, they are mere information managers. There an intense job in setting up and validation of the data has to be made in different circumstances to ensure its robustness. In fact, a DSS can be considered as a good DSS when it is capable to respond to different and changing circumstances. For this, initial data introduced into program is essential.

Usually, mathematical models are used. They are able to read data from various databases and generate with these parameters one or more responses which can be chosen by the user. They never intend to eliminate technical work but rather facilitate decision-making processes. Therefore, in some cases, the output consists in several alternatives and user makes the final choice based on his criteria.

On European level, 9 different DSS have been developed in the area of weed management (Been *et al.*, 2009), and the main characteristics that describe them are shown in Table 1. A more robust and with better performance DSS has been created taking the best parts from the previous DSS developed in Europe as a result of the creation of the ENDURE consortium in 2007, which has been continued by the PURE project (Pesticide Use-and-risk Reduction in European farming systems with Integrated Pest Management) (Rydahl *et al.,* 2015).

Table 1. Main characteristics of the DSS for Weed management existing in Europe. Adapted from Been *et al.*(2009).

	Sweden (DoseKey)	**Italy (Gestinf)**	**Poland (IPMDSS)**	**Holland (MLHD)**	**Denmark (CPOWeeds)**	**France (Phytochoix)**	**UK (Weedmanager)**	**France (Decidherb)**	**France (OptherbClim)**
Short-term decision	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Operated by the farmer	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Suggestion of treatment option	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Evaluation of environmental impact	No	Yes	No	Yes	Yes	Yes	Yes	Yes	No
Instructions relating to weather conditions	Yes	No	No	Yes	Yes	No	Yes	No	Yes
Long-term decision	No	No	No	Yes	Yes	No	Yes	Yes	No
Weed identification	No	No	Yes	Yes	Yes	No	Yes	No	No
Use of economic thresholds	No	Yes	Yes	Yes	Yes	No	No	No	no
Instructions on treatment implementation	No	No	No	Yes	No	Yes	Yes	Yes	No
Resistance management	No	No	Yes/no	Yes	No	No	Yes	Yes	No
Use of cost-benefit analyses	No	Yes	No	Yes	No	No	Yes	No	No
Pest monitoring	No	No	No	Yes	Yes	No	Yes	No	No
First publication	1990	1997	2002	2002	1986	2003	2003	2005	2007
Nº of crops	2	3	1	4	30	1	11	12	3
Nº of weed species	100	20	20	-	105	All species	12	250	All species
Interface	Web	CD	Web	Web	Web	CD	CD	Web	Web

The objective for that DSS is to increase its use in maize crop because on more than 90% of the maize production area weeds were controlled with herbicides, mainly in post-emergence (INRA, 2010).

As said previously, DSS are only information managers, so, in most cases a good technical background is needed to use them. For that reason, new systems are tried to be designed in a more user-friendly way to increase its potential use by farmers (Rydahl *et al.*, 2014).

However, there are several aspects to be considered since the DSS are not as widely used as expected. The first aspect is that for an adequate response given by a DSS accurate information should be provided and this information is both time and money consuming (Jorgensen *et al*., 2007), moreover the expected response should be given in a short time frame.

Another drawback is that the solutions given by a DSS sometimes is a mixture of several herbicides, a tank-mix. Tank-mixes are used in agriculture to achieve, for example, a broader spectrum of activity, reduce the number of working steps or because products can only be mixed shortly before application due to certain physico-chemical properties. In sum, tank-mixing is a good way to optimize the use of plant protection products and other inputs such as labor, machinery and fuel.

These mixtures are regulated in Spain with the *Guide of best practices for mixing plant protection products in field applications* (MAGRAMA, 2015).This guide gives guidelines to make plant protection product tank-mixes adequately taking into account the Regulation (EC) 1272/2008 on classification, labeling and packaging of substances and mixtures.

In other countries like UK, it is only illegal to mix two or more pesticides which are anticholinesterase compounds (this will be shown on the product labels), unless the mixture is allowed under the approved conditions of use (as shown on the product label of at least one of the pesticides); or use a pesticide with an adjuvant (a substance that makes the pesticide more effective) unless the adjuvant appears on the authorized list and using the pesticide with the adjuvant is in line with both the approved conditions of use for the pesticide and the authorised use of the adjuvant with that pesticide (DEFRA, 2006).

In Germany, for example, tested and untested tank-mixes are differenced. Untested tank-mixes are used in practice, for example due to advice which has been given or based on the operator's own experience, without having been tested in the context of the authorisation procedure. The instructions for use often state such mixes (German Federal Office of Consumer Protection and Food Safety, 2012).

In the case of DSS, the recommendations could be considered as untested tank-mixes and moreover, the product mixture restrictions could be implemented in the DSS database to prevent the program recommend those risk mixtures.

Another aspect to be taken into account is the human factor. The fast visual effect of herbicides still has more strength than the economics. For that reason, farmers like contact herbicides, as bromoxynil. Farmers don’t buy a chemical called tris (2-hydroxy-ethyl) ammonium salt of 2,4-dichlorophenoxyacetic acid, they buy a cost-effective tool for broad-leaf weed control in cereals. Hence, its biological effect is a commercial advantage that determines whether a compound launch will be successful (Copping, 2002). Historically, a good farmer is considered the one who has no weed in the field, even though the cost of treatment or loss of yield due to the herbicide application is greater than the losses caused by weeds present in the plot. Farmers have the feeling that the costs of implementing a monitoring and an adjustment of the herbicide doses by a DSS will be greater than the costs of applying herbicides in excess (Jorgensen *et al.*, 2007). So, the adoption of glyphosate tolerant crops has been much faster than the innovations to mitigate the side-effects of this technology (Doohan *et al.*, 2010). In fact, 91% of soybeans planted in the US is GM after 13 years from the initial authorization, because it enormously simplifies weed control. Farmers consider herbicides as insurance. In addition, this demonstrated that farmers tend to be reluctant to changes; in fact, the adoption of new techniques follows a sigmoid curve, with a minority of early adopters, a majority slowly accessing new technology and minority that will never adopt it (Doohan *et al.*, 2010).

Despite the widespread adoption of herbicides by farmers, there is ever-increasing interest in reducing herbicide use. Growers cite low commodity prices, crop injury, and herbicide carryover concerns, the escalating problem of herbicide-resistant weeds, and rising unease with the environmental and human health effects of pesticides as issues forcing them to reconsider how they manage weeds (Blackshaw *et al.*, 2006).

As said previously, although several farmers retrying to optimize herbicide use as much as possible from the economic point of view, there are various factors that make it a difficult decision to optimize economically.

One factor is the competitiveness of each crop. For example there are competitive crops such as barley where reductions in the use of herbicides maintain or even increase the economic return. However, there are little competitive crops such as lentils that increase yield and profitability as the spending on herbicides is increased (Blackshaw *et al.*, 2006). A good weed management mainly relies on crop competitive ability that minimizes the herbicide cost/reliance and reduces environmental contamination (Asif *et al.*, 2014).

It also depends on the initial density of weeds, the use of reduced herbicide dose was sufficient to achieve the same level of control that the full dose, if the density of weeds is low (Navarrete *et al.,* 1999) (Belles *et al.*, 2009) and always maintaining acceptable crop yields.

It is on these and other areas where the economic advantages of using DSS are clear since they are able to give the economically optimal solution taking into account all the variables, the question is no longer just to spray or not to spray but through linear programming or other techniques DSS can give an answer for the best active/s substance/s and dosage/s for each case.

Another advantage of the use of DSS is environmental because, by optimising the use of all control methods, including plant protection products, it is possible, in some cases, to reduce their use or the applied doses (Sønderskov *et al.*, 2014).

The lower doses of applied pesticides means less risk of potential contamination to surface water bodies or leaching because the factors that significantly affect the leaching of pesticides are:

-Dosage applied
- Water solubility of the active ingredient
-Mobility in soil solution
- Rate of degradation in soil

Therefore, the optimization of the applied dose is ensuring the best rate between efficacy and polluting potential.

In addition, DSS can also help to improve application techniques of crop protection products, giving recommendations regarding nozzles, spray volumes, speed, etc. so that the potential for drift is reduced and thus, no contamination outside the sprayed area occur.

The Danish Crop Protection Online (CPO)-Weeds

The challenge, in order to achieve a better use of herbicides, is that in some way the need of weed control and also predicting their efficacy could be integrated in a simple and quick way.

To achieve this goal, since the 1980's scientists from Aarhus University began to develop what it is now the most widely used DSS of weed science in Europe, the Crop Protection Online-Weeds (Rydahl, 2003). It was initially designed only for spring cereals in their agro-climatic conditions, such as spring barley (Rydahl & Pedersen, 2003) and it was commercialized since 1991 (Rydahl, 2003; Kudsk, 2008). Basically CPOWeeds optimizes herbicide combinations and dosages in relation to the actual crop and weed infestation either by lowest dose or lowest price.

Target efficacies in CPOWeeds are estimated based upon densities and growth stages of both crop and weed species. The general principle is that high competitiveness and density of the weed species induces high target efficacies, while the less competitive weed species and low densities calls for lower target efficacies. The aim is to set a target efficacy level, which insures yield and prevent excessive build-up of the soil seed bank, but still enables reduced doses. In the user-interface eleven criteria are integrated to define the weed scenario in a particular field. These criteria are: season, crop, potential yield, weed species, phenological stage and crop and weed densities, temperature and water stress. When the user has provided this information the program calculates the level of control required for every species.

The last update in CPOWeeds has been the integration of herbicide resistance management because herbicide resistance is of major concern in weed control. In this case, resistant weed biotypes are incorporated in CPOWeeds by creating separate weed biotypes with very low sensitivity towards herbicides with the mode of action for which they are resistant.

In the current Danish version, it is estimated that herbicides inputs in cereal crops can be reduced by over 40% without enriching soil seed bank for the succeeding crops (Sønderskov *et al.*, 2014). The biggest qualitative leap gave it at the beginning of the Internet age when CPOWeeds was improved. Currently, only in Denmark, 1500 farmers use it. In addition CPO is implemented to varying degrees in Norway, Estonia, Poland and Germany in one or more crops. In these countries the validation tests have showed that the recommendations were robust (Sønderskov, 2015, unpublished results). However, the potential of herbicide reductions varies between countries and depends on the weed species present in the fields and management done to date (Been *et al.*, 2009). Furthermore, an ongoing project develops CPO for weed control in maize in Germany, Italy and Slovenia with a module for mechanical measures included (Rydahl *et al.*, 2015).

The statistical modeling of the effect of herbicides. The basis of CPOWeeds

Herbicide performance is influenced by a number of biotic and physicochemical factors and knowledge of the key factors affecting herbicide efficacy is a pre-requisite for optimising herbicide dose (Kudsk, 2008).

Within these key factors there are some that depend on agro-climatic conditions such as light intensity, temperature, humidity, rainfall, soil moisture and texture, etc (Kudsk & Kristensen, 1992; Kudsk, 2008). However, others depend on intrinsic factors to the weed as its growth stage (Kudsk, 1989; Kudsk, 2008).

All these factors cause a variation in the response to herbicides. In this case, the dose is the amount of active ingredient that reaches the site of action, not the applied dose. Therefore, all the above factors may change the efficacy of each particular herbicide applied to a known dose because they can cause variations in the efficiency of the process,

As an example, the efficacy of many herbicides is positively correlated with the temperature at spraying as long as the temperature is not high enough to cause stress to plants (Kudsk & Kristensen, 1992; Mathiassen *et al.*, 1995). This is because temperature influence herbicide uptake of some foliage-applied herbicides (Kudsk, 2008). Several factors affecting herbicide efficacy are shown at figure 2. The fact that all herbicides are chemical compounds that have different chemical composition and hence different behaviour on the environment and at the plant, should not be forgotten.

The chemical parameters which define and affect the soil-efficacy of a particular herbicide are: Solubility in water, soil-organic carbon-water partitioning (K_{oc}), distribution coefficient (Kd), dalf-life time ($t_{1/2}$) and its mode of action.

Therefore, herbicides don´t have the same behaviour against dose adjustments.

For example, root absorption herbicides, applied directly to the soil, need to be dissolved in the aqueous phase of the soil to be activated. In these cases it is necessary to ensure a minimum concentration to be effective which depends on the above parameters, thus increasing or diminishing the applied dose is varied both efficacy as its persistence. However, this is an aspect that does not affect foliar absorption herbicides, which makes the response to an applied reduced dose lower.

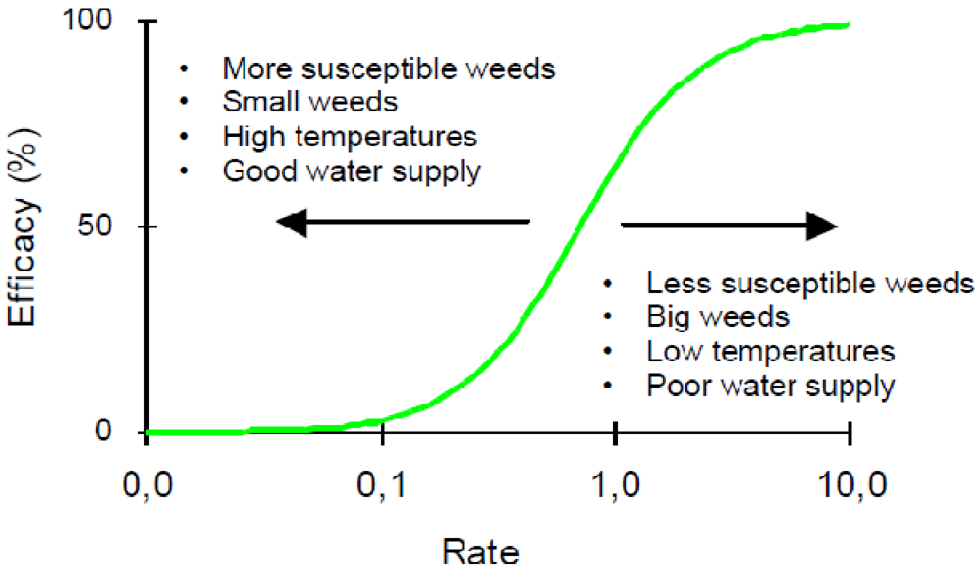

Figure 2. Factors affecting herbicide efficacy (Rydahl *et al.*, 2014)

The important fact is to quantify numerically the variation of the herbicide efficacy in different conditions and different doses to allow modeling.

In fact, modeling is nothing but a mathematical simplification of reality. Therefore, in toxicology the dose-response curves are used because a dose-response curve is a modeling of a biological process that assumes two criteria: firstly, the greater the dose, the greater the effect and secondly, the susceptibility to the dose is distributed normally, i.e., following a Gaussian distribution (Price *et al.,* 2012). An example of a log-logistic dose response curve is shown at figure 3.

The dose-response curve, essentially, relates a measurable variable generally mortality or plant biomass to the dose of the applied product.

Despite the fact that there are several dose-response models, in weed science, the most used equation is that proposed by Seefeldt *et al.* (1995),

$$Y = f(x) = C + \frac{D-C}{1+\left(x/A\right)^{b}}$$

In this equation, *Y* is the survival expressed as a percentage of the untreated control, *C* and *D* are the lower and upper asymptotes, respectively, *b* is proportional to the slope of the curve, A is the dose of herbicide at the point of inflection, and *x*, the independent variable, is the applied dose of herbicide. This is a logistic growth curve implying exact symmetry around *A*, the Effective Dose 50 (ED50) (Price *et al.,* 2012). This is the value of the dose that causes the 50% effect.

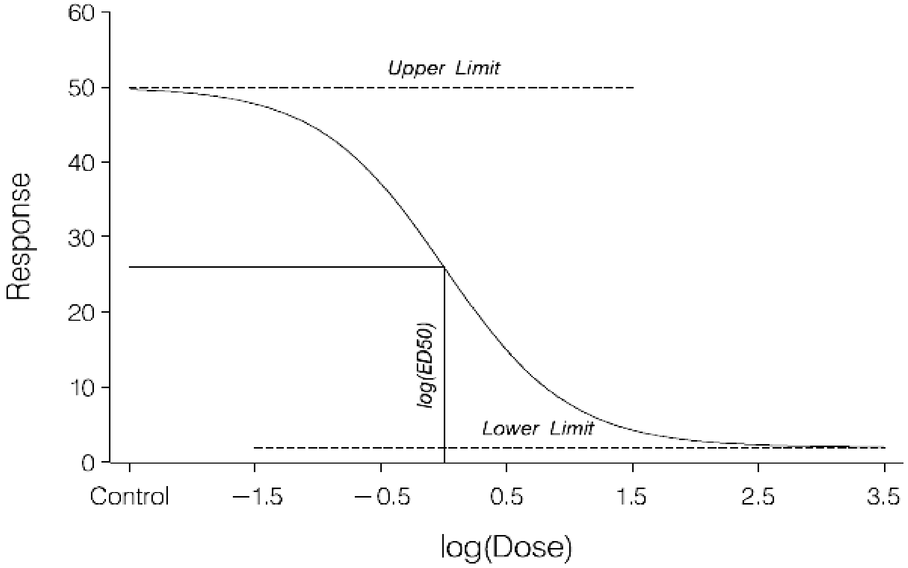

Figure 3. An example of log-logistic dose-response curve describing plant response, e.g. dry biomass, against logarithm of the dose of a hypothetical herbicide applied (Streibig, 2003)

If the maximum available response is assumed at an infinite dose as 100%, and the minimum response is equal to 0 at dose=0, then the modified equation used is the following:

$$Y = f(x) = \frac{100}{1 + \left(x / Ed50 \right)^{b}}$$

When using the logarithm of the dose, the also called the log-logistic curve is given:

$$Y = f(x) = \frac{100}{1 + \exp\left[\left(b\left(\log(x)\right) - \log\left(Ed50\right)\right)\right]}$$

This last model offers certain advantages over the linear regression (Seefeldt *et al.,* 2011):

- Biologically meaningful parameters
- Less squares summary statistics
- Confidence intervals
- Better response estimation at high and low doses
- Tests for differences in *ED50* or slope
- Still errors at extremes of doses

Knowing this relationship for each combination species-active ingredient and at every moment, with a given confidence interval, the dose of herbicide to apply for a required efficacy is known.

The shape of the dose-response curve clearly shows that there is a zone in which herbicides have greater efficacies than the increasing of dose applied when they are applied at low rate and then, at higher doses the increasing in the obtained efficacy is lower than the increasing in the applied dose.

This last feature is what justifies finding the balance between the desired effect and sustainability of the system, both environmentally and economically by using dose-response curves.

For example, it may be necessary to double the active ingredient applied per hectare to increase the efficacy from 90% to a 99%. Therefore, if an efficacy of 90% is enough to have proper control of weeds, it does not make sense to use twice the amount of active ingredient taking into account the negative environmental or economic implications.

The advantage of using dose-response curves is that one concrete curve can be calculated for a specific spraying condition. Moreover, how each factor affects the efficacy of herbicides can be parameterized (Rydahl 2003).

When comparing several dose-response curves from an experiment, the equation can be extended to:

$$Y = f(x) = \frac{100}{1 + \exp[(b(\log(Rx)) - \log(Ed50))]}$$

where *R* is the relative potency between the two curves having the same D, C, and *b* parameters i.e. the curves are similar, also called parallel (Streibig, 2003). Parallel dose response curves could also be used to compare the effect of different factors on herbicide performance. For that, the relative herbicide potency (R-parameter) could be used because *R*-parameter is constant at any one response level.

$$R_i = \frac{ED50_1}{E50_i}$$

$ED50_1$ and $ED50_i$ are the values of the parameters calculated in different conditions as can be seen in figure 4.

Another aspect to be taken into account is that if the herbicides have the same site of action, their response curves should be theoretically similar (parallel) with a relative horizontal displacement (Jensen & Kudsk, 1988). On the other hand, the assumption of similar curves is a necessary but not a sufficient condition for assuming similar mode of action of compounds (Streibig *et al.*, 1998). For those reasons, ***b*** only depends on the mode of action of herbicide and that parameter is known for all compounds (Kudsk, 1989).

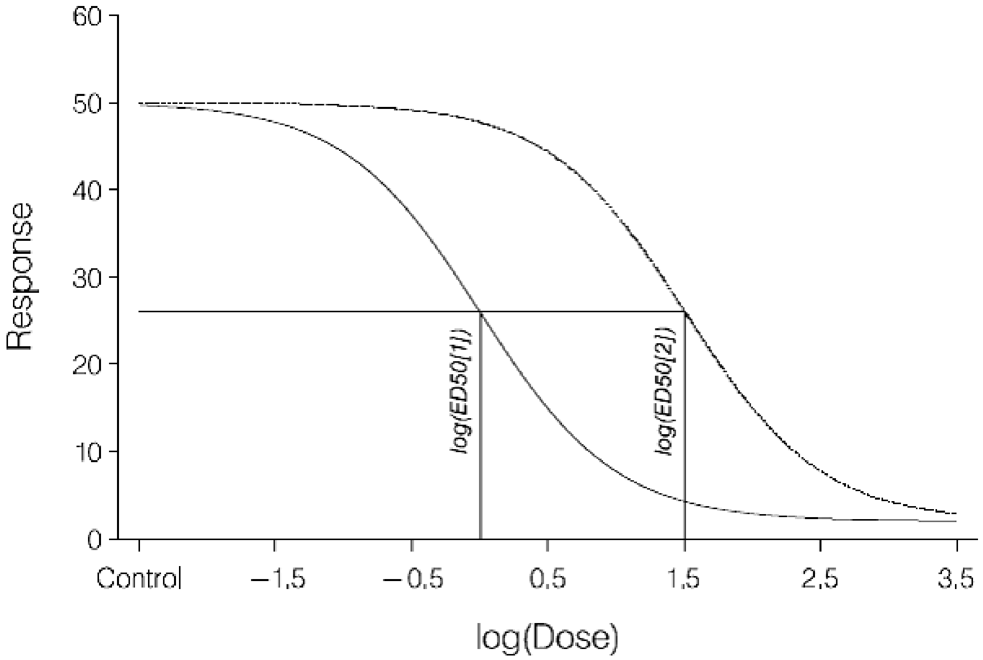

Figure 4. Comparison of two dose-response curves ([1] and [2]) at the ED50 value, which is the dose required to affect the response, e.g. biomass, by 50% (Streibig, 2003)

Therefore, for one done weed species, for a known compound and at defined standard conditions, the unique unknown parameter is the parameter **ED50**.

An herbicide dose model estimates the required dose of the available herbicides and rank them according to either price or herbicide amount. The herbicide dose model contains dose response curves, which are based on experimental data from scientific work and more practical approaches from herbicide efficacy testing.

Since all weed species are not equally susceptible against all herbicides, the Additive Dose Model (ADM) is used (Streibig *et al.,* 1998). The program will automatically calculate mixtures of herbicides, if such are advantageous in terms of costs or Treatment Frequency Index (Rydahl, 2003), particularly when in a plot there are more than one species. In those cases, CPOWeeds is able to determine the best herbicide solutions determining tank-mix if necessary until four different herbicides (Kudsk & Mathiassen, 2004; Kudsk, 1999).

The ADM assumes that, at a defined response level, the effect of a mixture of two or more herbicides can be expressed by the relative potency of the herbicides applied separately (Figure 5) (Streibig *et al.*, 1998). A widely known characteristic of the ADM is that, for mixtures of two components, when the response surface predicted by the model is plotted against arithmetic scales of the component doses, the contours of equal response (i.e.isobols) are straight lines. More fundamentally, the predicted dose-response relationship for the mixture is as follows. At any particular level of response, the relative potency of the components when acting alone establishes scales of equivalent doses. In terms of these effective-dose scales, if one component of the mixture is replaced, wholly or in part by the other, the predicted response is unchanged (Morse, 1978).

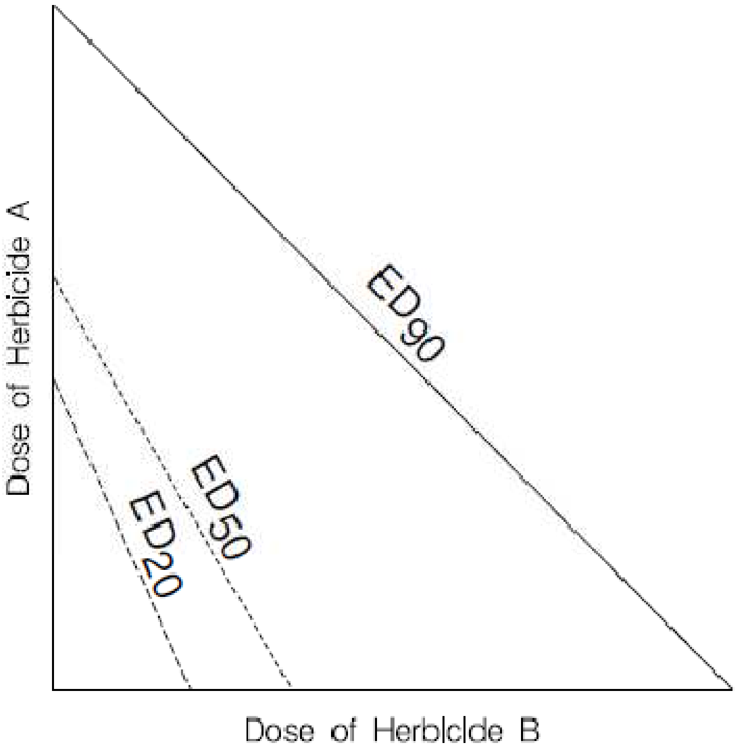

Figure 5. ADM isoboles at different response levels when the response curves are not similar for two species (Streibig, 2003)

Therefore, taking into account all of these parameters herbicide efficacy can be predicted properly whatever the herbicides and treatment conditions and thus define the optimum dosage and active ingredient for given conditions.

The open debate of the high doses vs. low doses in the development of resistance cases

Technically, the greatest controversy on the development and large-scale use of DSS is that there are occasions when the recommended doses are lower than the maximum indicated on the label. In these cases loss of yield or increase of the seed bank density in the long term can occur (Kudsk, 2014).

It should not be forgotten that unfortunately the bulk of herbicide efficacy data available to farmers merely classifies weed species as ‘controlled’, ‘partly controlled’ or ‘not controlled’ using the dose recommended by the manufacturer. For most herbicides the group of weed species classified as ‘controlled’ consist of species easily controlled with doses considerably lower than the recommended and species only controlled satisfactorily if the full recommended dose is applied (Kudsk, 1989; Kudsk, 2008). Information available on the dose response of weeds to even the most commonly used herbicides is very rarely although such information would greatly improve decision making on herbicides and their doses.

The other part of the open debate between supporters of the use of high rates and low rates of herbicides is based on the possibility of development of resistant biotypes.

It seems clear that the recurrent selection using low herbicide doses tends to generate Non Target Site Resistance (NTSR) (Yu *et al.*, 2012; Busi *et al.,* 2012; Neve & Powles, 2005a) due to the accumulation of minor genes with smaller additive effects while the recurrent selection at high doses tends to develop Target Site Resistance (TSR) biotypes due the relative contribution to adaptation of genetic variation at major genes with a large phenotypic effect (Darmency, 1994; Jasieniuk *et al.,* 1996; Neve & Powles, 2005a; Powles & Yu, 2010; Neve & Powles, 2005b; Renton *et al.,* 2011).

A conceptual model for high-dose vs. low-dose herbicide resistance selection is shown at figure 6. The model assumes that unselected weed populations possess standing genetic variation for response to herbicides. This variation is represented by a normally distributed resistance phenotype (the resistance phenotype of an individual within a population being the minimum dose of herbicide that will cause mortality of that individual). The mean resistance phenotype is equivalent to the LD50 value for the population. Applied herbicide doses are shown with broken arrows. Where a high herbicide dose is applied (a), selection acts beyond the range of standing genetic variation and resistance can only evolve via selection of major resistance mutations that result in an extreme resistance phenotype. Where a low dose is applied (b), selection occurs within the range of standing variation. In outcrossing species, surviving individuals (grey shading) cross with one another, resulting in the selection and recombination of standing variation at minor resistance alleles (Neve *et al.*, 2014).

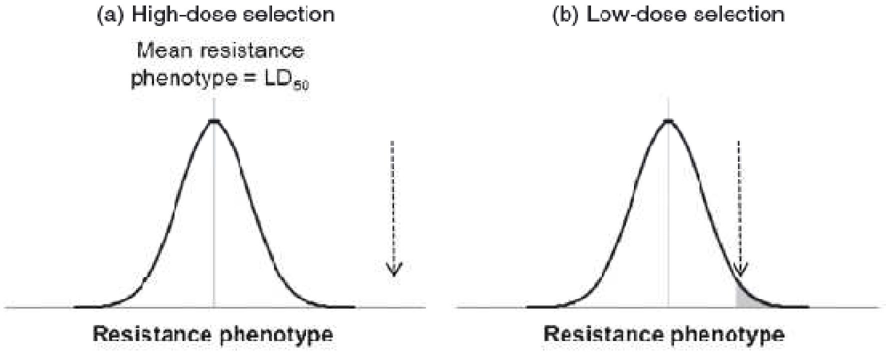

Figure 6. A conceptual model for (a) high-dose versus (b) low-dose herbicide resistance selection (Neve *et al.,* 2014).

There is no logical relationship between dose and efficacy although this may seem to be obvious, for that reason, the question of talking about doses or efficacies must be wondered. For a given dose, depending on the application time and the weed species we can have very different efficacies. Therefore, in this case, the right thing would be to talk about efficacy. In fact, when in the scientific articles researchers write about resistant weed biotypes selected after low doses application, the results show biotypes selected using individuals who have survived at doses that cause about 30% mortality (Busi *et al.,* 2012; Yu *et al.*, 2012). These works hence are about low dose selection but also are low efficacies; in no case they are acceptable from an agronomic point of view.

Also, when in a scientific paper it is discussed about high doses or low doses it is in relation to maximum authorized dose in each country. But, for example, the maximum amount authorized for diclofop-methyl in Australia is 375 g/ha of active ingredient while in Spain the maximum authorized rate is 630 g/ha or 900 g/ha in France. Other example is the herbicide prosulfocarb, in Australia the maximum authorized rate is 2000 g/ha of active ingredient while in Spain is 4800 g/ha. This fact also depends on the registration criteria and active dose for each country, for that reason; there are fewer differences for the new authorized herbicides. However, herbicide efficacy varies between environments due to factors such as crop density and weed characteristics, so it is unclear whether and to what extent these differences in regulated rates can be translated into real differences in effective application rate at the level of individual weeds and thus into real differences in levels of control (Renton *et al.*, 2011).Hence, globally, there are countries with greater potential than others to optimize the use of pesticides when having a high maximum authorized rate.

Here again, the DSS play an important role because they allow the adjustment of the applied dose to obtain a particular efficacy without increasing the selection pressure that can generate resistance of TSR or NTSR type because the goal is always achieve appropriate efficacies since an agronomic point of view.

Finally, Decision Support Systems can be able to offer the selection of one or another group of herbicides related to their mode of action if they have the information of the resistance mechanism that has a concrete weed biotype because they are merely information managers.

Objectives

The general objective is to develop a CPOWeeds version for its use in Spanish agroclimatical conditions, herbicides and main weed species. The existing algorithms are used to tune up a version for Spanish weed species and for the most used herbicides in the north of Spain.

To achieve this general objective, four partial goals have been raised, corresponding one goal to each chapter.

The first aim, corresponding to chapter 1, is to determine the A-parameters of the dose-response curves for the most relevant weed species. A-parameter has been calculated for thirty-five herbicides and up to twelve species per herbicide but only the results for herbicide Herbaflex are presented at as example. The A-parameter for the rest of herbicides and species is shown as an annex.

The second aim, corresponding to chapter 2, is to quantify the efficacy variation of several herbicides depending on key-weeds growth stage, the R-parameter. In a similar way than the previous objective, only four herbicides are showed as an example.

The third objective is to validate the CPO concept under climatic conditions different from northern Europe with a CPO version developed for Spain. It corresponds to chapters 3 and 4. The ability to preserve yield and the robustness of the obtained efficacies were validated in field conditions.

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Chapter 1

Obtaining the dose-response parameters for key weeds

Obtaining the dose-response parameters for key weeds

Abstract: In Spain, the maximum authorized field rate for herbicides is higher than in other countries for many herbicides. Herbicide use can be improved but it is difficult to have enough data to know the behaviour of plant protection products at doses different than the maximum. That is an issue when optimising herbicide use. The objective consist on determining the A-parameter of the dose-response curve for relevant species for the herbicide IPU50%+beflubutamid 8.5% as an example of all the parameters calculated for the herbicides. With this aim, raw data from 122 Official field tests in six years has been statistically studied based on dose-response curves for each species. Results show that this raw data has been proved very useful to achieve an optimization of herbicide use via the development of Decision Support Systems.

Introduction

In Spain, the maximum authorized field rate for many herbicides is higher than in other countries as detailed in the previous chapter. One reason comes from the fact that the authorized rate is not always the minimum effective one. In many cases, the maximum authorized rate is based on environmental parameters or in the safety for the farmer. Companies need to demonstrate that their products are safe for the workers and the environment at the suggested maximum rate. A secondary aspect is related to efficacy. For these reasons, if there are specific cases in which the amount of applied product can be diminished, the evaluation is not done. This occurs since it is difficult to have enough data to know the behaviour of plant protection products at doses different than the maximum. This is an important issue for optimising herbicide use given that efficacy can vary a lot depending on weed species and other conditions (Minkey & Moore, 1996).

In the article 14 of the Directive 2009/128/CE it is said that *Member States shall establish or support the establishment of necessary conditions for the implementation of integrated pest management. In particular, they shall ensure that professional users have at their disposal information and tools for pest monitoring and decision making, as well as advisory services on integrated pest management*. The use of DSS allows advisors to make an adjusted recommendation, not only in relation with the environmental aspects but also about economics. To build proper DSS it is necessary to know enough data as the efficacy of each product versus every weed species in all possible field conditions (climate, soil, growth stage, etc.). One way to model all this data is using dose-response curves, which are the basis of CPOWeeds (Soenderskov *et al.*, 2014).The use of these dose-response curves allows applying the optimal herbicide solution, since as it is said previously, efficacy is affected by weed species composition, weed growth stage and the required control level (Kudsk, 2008).

The first step to develop CPOWeeds is related with the determination of dose-response curves for relevant herbicide-weed species combinations in standard conditions. The second step consists in determining the magnitude of the parallel displacement which is specific for each herbicide and is based on experimental data (Rydahl, 2003).The efficacy response on dose is assumed to be well-explained by the logistic model proposed by (Seefeldt *et al.,* 1995):

$$y = f(x) = C + \frac{D - C}{1 + \left(x / Ed50 \right)^{b}}$$

In this case, it is assumed that the maximum response available for an infinite dose is 100%, and the minimum response is equal to 0 at dose=0. So, the modified equation used is the following:

$$Y = f(x) = \frac{100}{1 + \left(x / Ed50 \right)^{b}}$$

In this model, **Y** is the efficacy expressed as percentage versus untreated control. ***B*** is the slope of the curve; **ED50** is the dose at the point of inflection and **x** is the actual dose rate.

Theoretically, if herbicides have the same site of action, then all other parameters should be equal; their response curves should be similar (parallel) with a relative horizontal displacement. On the other hand, the assumption of similar curves is a necessary but not a sufficient condition for assuming similar mode of action of compounds (Streibig *et al.,* 1998). For these reasons, **b** only depends on the mode of action of herbicide and that parameter is known for all compounds (Kudsk, 1989).

Therefore, for a given weed species and a known compound, the unique unknown parameter is parameter **ED50**. But, in this case, CPOWeeds doesn't run using ED50 but needs the estimated efficacy at maximum authorized rate; this value is the **A-parameter**. Performing the curves is the best way to manage the big data generated after running field tests done for registering a new compound. This is due to the fact that all tests weren´t made with exactly the same dosages for each product. Moreover, using a lot of tests made in different climatic conditions allow us to better estimate the behaviour of herbicides and after that, the CPOWeeds is expected to be more robust.

In this work, the objective deals with determining the A-parameter of the dose-response curve for relevant species in the case of the herbicide IPU 50%+beflubutamid 8.5%, commercial name Herbaflex, provided by Cheminova. This is a cereal herbicide in Spain taken as an example within the thirty-five herbicides parameterized to develop the program.

Materials and methods

The process of generating the dose-response curves for CPO Weeds has three steps: First of all, generating efficacy data at different herbicide doses, then performing dose-response curves and finally determining the A-parameter based on each dose-response curve.

The first step is made in field-conditions. Efficacy data for each weed species and herbicide at different doses is needed. In this case, as an example of one of the thirty-five herbicides data introduced in the program, data has been obtained from official field trials conducted by Cheminova, a company who is interested in the CPOWeeds development in Spanish conditions for winter cereals. Company provided the raw efficacy data from their official field tests to perform the statistical studies. Number of year tested, weed species and number of Official Field tests per species could be seen at table 1. It is important to have these raw data to check outliers and the variability that herbicide efficacy can exert in field conditions.

Table 1. Number of years tested, weed species and number of Official field tests per species.

Years tested	Weed species	Official field tests
2	*Alopecurus myosuroides*	5
1	*Anagallis arvensis*	1
2	*Atriplex patula*	4
4	*Avena sterilis*	7
2	*Bromus diandrus*	7
2	*Capsella bursa-pastoris*	4
1	*Chenopodium album*	1
5	*Fumaria officinalis*	5
3	*Galium aparine*	6
1	*Lamium amplexicaule*	1
5	*Lolium rigidum*	11
2	*Matricaria chamomilla*	2
6	*Papaver rhoeas*	15
1	*Poa annua*	1
5	*Polygonum spp.*	16
2	*Ranunculus muricatus*	2
1	*Scandix pecten-veneris*	1
3	*Sinapis arvensis*	6
4	*Stellaria media*	7
6	*Veronica hederifolia*	17
2	*Veronica persica*	2
1	*Viola arvensis*	1
		122

In this case, field tests have been conducted all over the northern half of Spain. Thus, the aim is reduce the effect of the different soil types and moisture differences on the efficacy.

As CPOWeeds calculates the herbicide dosage for the desired control level based on dose-response, all trials should be conducted with a minimum of 4 replicates. Dosages used were 3, 2.5 and 2l/ha of commercial product and an untreated control for all tests.

At the moment of spraying, weeds phenological stage should be the standard moment for each herbicide. In the case of herbicide IPU50%+beflubutamid 8.5%, for grass weeds, tests were made between 10 and 12 BBCH, and for broadleaved weeds, from 10 to 14 BBCH.

The phenological stages defined for the model are: 0-2 leaves, 3-4leaves, 5-6 leaves and >6leaves. It is always referred to the phenological stage of weeds.

Efficacy is determined using the Abbott method (Abbott, 1925) counting surviving plants using a 1 m^2 square 50 days after spraying.

The second step consists on performing the dose-response curves for each species using the data obtained in the field tests. These data is adjusted to the logistic model proposed by (Seefeldt *et al.*, 1995) which has been showed previously.

In this case, all statistical analyses were performed using the Dose-Response Curve (DRC) Package from XLSTAT 2012 software for Microsoft Excel.

Finally, A-parameter is the value of the mean corresponding to the estimated efficacy at maximum authorized rate for the herbicide.

$$A = \frac{100}{1 + \left(x/Ed50 \right)^{b}}$$

Being *b* the slope of the curve and *ED50* the LD50 value, both statistically calculated.

Results and discussion

The data generated by Cheminova field tests during the registration phase of the herbicide has proved to be very useful because generating this information in such a short time would have been virtually impossible. The trials made to register new herbicides are very useful to extract very valuable data to optimize herbicide use. Usually, these trials are performed in several places, versus different weed infestations and in different climatic conditions. All this helps to know how different factors affect herbicide efficacy in each weed species. And for the same reason and by using proper statistical tools, it is possible to predict herbicide efficacy in a wide range of situations, which is one of the objectives of a DSS. In the present study, the data used was only the taken under standard conditions for each herbicide. Thus the ones, previously commented, mainly related to the weed growth stage.

Major monocot weeds in Spain are *Avena sterilis*, *Bromus diandrus* and *Lolium rigidum* (Cirujeda *et al.,* 2011). *Alopecurus myosuroides* is much less frequent.

L. rigidum and *A. sterilis* biotypes resistant to phenylurea herbicides like Chlortoluron (CTU) or Isoproturon (IPU) are common in the North of Spain. In these cases, the efficacy of herbicides affected by resistance is assumed to be 1% for CPO calculations. These kinds of biotypes are showed as UR-R (Urea resistant) in the tables. This means that CPOWeeds not consider those products in case of resistance. Moreover, *B. diandrus* is known for never being well controlled with this kind of herbicides and it is also known that there are herbicide resistant populations via CYP450 (Menendez & Bastida, 2006; Park & Mallory-Smith, 2004; Owen *et al.,* 2012).

Efficacy for each grass weed species is shown at table 2.

Based on LD50 parameters, it can be said that *A. myosuroides* is the most susceptible grass species versus this herbicide, with an estimated efficacy of 94.36% at the maximum authorized field rate, which is the starting value for CPOWeeds calculation. Moreover, if there is any case where an efficacy under that value is needed, herbicide dose can be lowered to the maximum authorized rate since CPOWeeds is able to calculate the estimated efficacy for each dose rate based on the A-parameter and the slope of the curve. In these cases

CPOWeeds will recommend the exact dose to achieve the expected efficacy in the field, optimising herbicide use.

Table 2. Tested grass weed species. Coefficient of determination, Lethal Dose 50, slope (B-parameter) of the curve for each species and estimated A-Parameter for CPOWeeds calculation. In brackets, the standard deviation for each parameter.

Species	r^2	LD50	Slope (B-parameter)	A-parameter
Alopecurus myosuroides	0,998	0,98 (0,08)	3,01 (0,37)	94,36
Avena sterilis	0,996	1,79 (0,09)	2,75 (0,45)	71,45
***Avena sterilis* UR-R**				1
Bromus diandrus	0,969	1,92(0,11)	2,20(0,60)	64,10
Lolium rigidum	0,991	1,34(0,06)	3,11 (0,26)	87,40
***Lolium rigidum* UR-R**				1

In the other three key species, the estimated efficacy at maximum field rate could not be sufficient to have enough efficacies to achieve the maximum yields. When needed, CPOWeeds can recommend a tank-mix of two or more herbicides depending on the infestation of each particular field. Thus it makes the calculation required to determine the exact dose for each herbicide to reach the required efficacy.

As expected, *B. diandrus* has been the worst controlled species when applying this herbicide getting a 64.1% of estimated efficacy. This suppression effect could be interesting in barley crops where no selective herbicides are available for its control.

In all species B-parameter, the slope of the curve, is around 3 and without statistical differences between them. This parameter depends on the mode of action of the herbicide (Kudsk, 1989). For this reason, this parameter should be statistically equal for all species if there are no changes in the mode of action, i.e. in case of herbicide resistance or natural tolerance. So, the slope of the curve for *B. diandrus* tends to be lower than the one obtained for the other species due to the previously mentioned natural tolerance.

Following the same scheme, table 3 shows seen the data obtained for broadleaved weeds treated with the herbicide. The most common broadleaved weed species in the North of Spain are *P. rhoeas*, *G. aparine* and *Brasicaceae* like *S.arvensis*. There are no resistant cases to this herbicide in this species.

Table 3. Tested broadleaved weed species. Coefficient of determination, Lethal Dose 50, slopes of the curve (B-parameter) for each species and estimated A-Parameter for CPOWeeds calculation. In brackets, the standard deviation for each parameter.

Species	**r^2**	**LD50**	**Slope (B-parameter)**	**A-parameter**
Fumaria officinalis	0,998	1,09 (0,03)	3,12 (0,26)	93,05
Galium aparine	0,991	1,82 (0,08)	3,20 (0,45)	73,53
Papaver rhoeas	0,998	0,92 (0,01)	3,20 (0,16)	96,08
Polygonum spp.	0,977	1,34 (0,08)	3,28 (0,52)	88,57
Sinapis arvensis	0,991	1,39 (0,05)	3,34 (0,38)	87,65
Stellaria media	0,999	1,13 (0,02)	3,13 (0,19)	92,36
Veronica hederifolia	0,945	1,45 (0,15)	3,27 (1,09)	85,49

The most susceptible broadleaved weed species has been *P. rhoeas* with an estimated efficacy higher than 96% followed by *F. officinalis* and *S. media*. Assuming that for certain fields, efficacies upper 85% are enough to achieve the maximum possible yield, only with *G. aparine* the maximum field rate is not enough to achieve this efficacy. For this reason, based on the previous parameters, could be cases where CPOWeeds recommends a dose below the maximum authorized rate.

When in a field there is a complex infestation is when a DSS like CPOWeeds gives the best of itself given that it is capable to perform the best option in terms of his cost or environmental safety. Another situation in which is able to improve the performance of a treatment is in fields with less usual weeds in our conditions like *S. media* or *F. officinalis.* This is due to the fact that, for most of advisors the performance of herbicides versus these weeds is not sufficiently well known. In these cases the use of CPOWeeds allows to use the minimum necessary dose.

Most farmers or advisors don’t know all the performance of this kind of herbicides given that most of these compounds have a broad-spectrum exerting a certain control in a big number of species but not reaching an enough effect. In these cases, a tank mix with some one of these products with a relatively low dose of other herbicide is able to have a very good performance with a relatively low cost. In this case is when farmer or advisors can see the ability of DSS to optimize weed control. Especially if it is necessary to prevent or manage resistance cases because DSS will only show the herbicides to solve the problem.

B-parameter in grass weeds is around 3. This was expected due to the mode of action of the herbicide, and without differences between species. It is remarkable the fact that there are not known resistant broadleaved species to phenylurea herbicides in this moment. Thus the slope of the curve has not to change.

Moreover, since the parameter B does not vary regardless of the treatment conditions but only by the herbicide, speed up the development of the DSS could be possible using only two instead of four doses when determining the dose-response curves.

The correlation between the dose-response curves and the values is very good ($R^2>0,945$) in all species. Therefore, it is proved that there is a high correlation between the applied dose and the obtained efficacy regardless of location of the test and the soil type.

As a summary, in the tables 1, 2.1 and 2.2 of the annex it can be seen the A-parameter for all the herbicides parameterized to develop CPOWeeds in Spanish conditions.

The A-parameter for grass weeds is shown in table 1 and the A-parameter for broadleaved weeds is shown in tables 2.1 and 2.2. As there are herbicides effective against both grass and broadleaved weeds, they are included in both tables. For that reason, there are 52 rows within the three tables.

Conclusions

This is the first step to get started on the CPO model for Spanish growing conditions. To know herbicide performance in its standard conditions is essential to establish bases for future work to learn how the performance varies for each product under different conditions.

The main conclusions are:

-Alopecurus myosuroides has been the most susceptible grass species with an A-parameter of 94,36.

-Papaver rhoeas is the most susceptible species to the herbicide. It has an A-parameter equal to 96,08.

-B-parameter is around 3 as it was expected by the mode of action of the herbicide, and without differences between species.

In summary, the efficacy at standard conditions of one authorized herbicide to control major cereal weeds in the North of Spain is shown in this work.

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Annex: A-parameter for all parameterized herbicides and weeds

Table 1. Grass weed species, herbicides tested and estimated A-Parameter for CPOWeeds calculation.

Composition	Maximum authorized rate	*Alopecurus myosuroides*	*Avena sterilis*	*Avena sterilis* FOP-R	*Bromus diandrus*	*Phalaris minor*	*Lolium rigidum*	*Lolium rigidum* FOP-R	*Lolium rigidum* SU-R	*Lolium rigidum* UR-R
Bifenox 17% + IPU 30%	4500	99,0	75,0	75,0	15,0		83,4	83,4	83,4	20,0
Chlorsulfuron 75%	20		1,0	1,0	20,0		70,3	70,3	1,0	
Chlortoluron (CTU) 50%	5000	95,4	78,6	78,6	20,0		99,1	99,1	99,1	1,0
Clodinafop 24%	350	97,5	99,9			96,4	94,0	1,0		
DFF 50%	250		1,0	1,0	1,0		70,0	70,0	70,0	70,0
Diclofop 24% + Fenoxaprop 2%	2500		99,6	1,0	1,0	1,0	98,7	1,0	98,7	79,0
Diclofop 36%	2500	75,2	94,8	1,0			99,5	1,0	99,5	79,6
Diflufenican (DFF) 4,2% + IPU 45%	2400		78,9	65,0	25,0		87,7	87,7	87,7	1,0
Fenoxaprop 6,9%	1200	98,6	98,4			98,2				
Iodosulfuron 0,6%+ mesosulfuron3%	500	98,5	99,0	99,0	88,8	95,3	98,0	98,0	1,0	98,0
Iodosulfuron 1% + propoxycarbazone 16,8%	265	99,1	94,0	94,0	84,4	87,3	92,0	92,0	1,0	92,0
Iodosulfuron 5%	200		85,0	85,0	20,0		96,4	96,4	1,0	96,4
IPU 50%	3000	97,0	84,4	84,4	30,0		80,5	80,5	80,5	1,0
Pendimethalin 33%	6000		1,0	1,0			45,9	45,9	45,9	45,9
Pinoxaden 6%	1000	96,8	99,5	10,0	1,0	98,0	96,5	1,0	96,5	96,5
Pinoxaden 9,8%	600	96,7	99,3	10,0	1,0	98,0	96,3	1,0	96,3	96,3
Prosulfocarb 80%	6000	80,8	25,0	25,0		82,1	99,2	99,2	99,2	99,2
Tralkoxidim 25%	1600		98,9				97,0	1,0	97,0	1,0
Tralkoxidim 40%	1000		98,9				97,0	1,0	97,0	97,0
Triasulfuron 20%	75	92,4	10,0	10,0	30,0		77,2	77,2	1,0	

Table 2.1. Broadleaved weed species, herbicides tested and estimated A-Parameter for CPOWeeds calculation.

Composition	Maximum authorized rate	*Anthemis arvensis*	*Fumaria officinalis*	*Galium aparine*	*Matricaria chamomilla*	*Papaver rhoeas*	*Papaver rhoeas 2,4D+SU-R*	*Papaver rhoeas 2,4D-R*	*Papaver rhoeas SU-R*	*Polygonum spp.*	*Sherardia arvensis*	*Sinapis arvensis*	*Stellaria media*	*Veronica hederifolia*
2,4-D 60%	1000	91,4		60,0		94,1	1,0	1,0	94,0			95,6		
Aminopiralid 30%+ 15% florasulam	33	98,5		97,0		99,0	50,0	99,0	99,0		96,0	95,9		60,0
Bifenox 17% + IPU 30%	4500	98,0		60,9		98,0	98,0	98,0	98,0			94,9		97,0
Bromoxynil 12% + ioxinyl 12% + MCPP 36%	1,8	99,2		88,9		99,3	99,3	99,3	99,3		93,4	99,0		99,7
Bromoxynil 24%	1000	96,8		97,2		99,1	99,1	99,1	99,1			99,7		97,9
Carfentrazone 40%	50	80,1		97,5		81,4	81,4	81,4	81,4		70,8			99,2
Chlorsulfuron 75%	20			89,0		87,3	1,0	87,3	1,0			99,7		
CTU 50%	5000	70,0		40,2		72,6	72,6	72,6	72,6			84,8		69,3
DFF 4,2% + IPU 45%	2400	99,0		72,0		99,9	99,9	99,9	99,9			99,5		98,4
DFF 50%	250	95,2		78,3		99,8	99,8	99,8	99,8			98,1		93,8
IMS 0,6% + mesosulfuron 3%	500	92,8		74,1		85,1	1,0	85,1	1,0			99,3		71,7
IMS 1% + propoxycarbazone sodium 16,8%	265	97,9		82,5	98,9	72,9	1,0	72,9	1,0	74,2		99,9		60,8
IMS 5%	200	94,9		81,1		89,6	1,0	89,6	1,0			95,4		
IPU 50%	3000	82,0		49,1		70,5	70,5	70,5	70,5			73,2		
Pendimethalin 33%	6000	97,8		90,4		99,7	99,7	99,7	99,7	99,2		99,0		97,0
Prosulfocarb 80%	6000	74,7	91,3	96,5	66,9	58,5	58,5	58,5	58,5	83,7		63,4	99,0	99,7
Tifensulfuron 33,3% + tribenuron 16,7%	67,5	90,8		80,0		96,1	1,0	96,1	1,0			98,3		60,5
Triasulfuron 20%	75	90,1		91,7		88,0	1,0	88,0	1,0			99,2		63,2
Tribenuron-metil 50%	37,5	94,8		67,5		99,9	1,0	99,9	1,0			94,1		35,9
Tribenuron-metil 75%	20	94,3		67,4		99,7	1,0	99,7	1,0					

Table 2.2. Broadleaved weed species, herbicides tested and estimated A-Parameter for CPOWeeds calculation.

Composition	Maximum authorized rate	*Anthemis arvensis*	*Fumaria officinalis*	*Galium aparine*	*Matricaria chamomilla*	*Papaver rhoeas*	*Papaver rhoeas 2,4D+SU-R*	*Papaver rhoeas 2,4D-R*	*Papaver rhoeas SU-R*	*Polygonum spp.*	*Sherardia arvensis*	*Sinapis arvensis*	*Stellaria media*	*Veronica hederifolia*
Beflubutamid 50%	500	99,9	66,6	68,6	81,8	87,4	87,4	87,4	87,4	91,7		94,8	99,9	80,8
Fluroxypir 50%	1000	70,9		99,0		78,9	78,9		78,9					70,9
Isoxaben 50%	250	99,7	96,0	85,0		96,0	96,0	96,0	96,0	85,4		92,0		90,6
Metsulfuron 20%	30	99,0				98,0	1,0	98,0	1,0	96,9		97,3		75,0
Metsulfuron 7% + tifensulfuron 68%	75	96,2		82,0		98,8	1,0	98,8	1,0	92,0	92,0	97,3		90,8
Tifensulfuron-metil 50%	75	96,5	87,5	72,0		85,7	1,0	85,7	1,0			97,9		79,6

Chapter 2

Effect of weeds growth stage in four herbicides performance

Effect of weeds growth stage in four herbicides performance

Abstract: Herbicide use can be optimized if its behaviour is previously established. This may result in an improving of decision making since there are several biotic and non-biotic factors affecting herbicide performance. Weed growth stage is one of the main factors affecting herbicide performance. To quantify this effect in the efficacy parameter, parallel dose-response curves have been used. In this work, four herbicides and four species are shown as an example of the thirty-five parameterized herbicides.

As expected, in all of these cases, weeds have been less susceptible to herbicides when sprayed at later growth stages. The quantification of this effect allows users to make a more reasoned use of herbicides since the knowledge of the previously described parameters could be used in a DSS to optimize herbicide dose in each situation.

Introduction

The optimization of herbicide performance is a key factor to diminish the possible adverse effects due to the use of plant protection products. Indeed, it is possible to maintain the efficacy using a lower quantity of herbicides (Blackshaw *et al,.* 2006) when knowing their behaviour inside the plant.

To kill weeds, herbicides have to play a complex task, they should be intercepted, absorbed and translocated, should enter inside the cells, and finally they should arrive to the target site in a sufficient quantity to kill the plant. All these steps can modify the amount of active ingredient that reaches the target-site. Therefore, all these steps can change the final efficacy obtained.

Optimising herbicide use requires the improvement of decision making (Kudsk, 2008b). This is due to the fact that there is not much information about the efficacy of herbicides in different conditions although it is known that there are several biotic and non-biotic factors affecting herbicide performance. Thus, a basic understanding of the influence of some key factors is a pre-requisite to optimize herbicide performance (Kudsk, 2008a).The main factor playing a role on the variation of the global herbicide efficacy in a field is weed flora, given that different species are not controlled by the same herbicides.

The variation of efficacy obtained in different fields or situations for the same species could be explained given that growth stage, climate conditions or weed resistance to herbicides are other aspects that can modify herbicide efficacy. Climatic conditions change the performance of herbicides since they can affect herbicides uptake and translocation as Kudsk and Kristensen (1992) detailed. Moreover, in a study carried out by the EWRS Herbicide Dose Optimisation WG (2013), no single climatic factor can explain differences in herbicide efficacy because in natural conditions the parameters interact between them and any benefits of increasing temperatures may be counteracted by the adverse effect of increased water vapor pressure deficit following a temperature rise (Mathiassen *et al*., 1995). Weed resistance to herbicides is another factor to be taken into account, even if resistant biotypes could be considered as different species with respect to susceptible biotypes as they show a different well-established behaviour when compared with susceptible ones.

In this study, the attention is only focused on the growth stage effect in relation with the performance of four herbicides in Spain. This is important since it is known that annual weed species are generally more susceptible to herbicides at early growth stages although there are exceptions such as the control of *Galium aparine* by mecoprop and fluroxypyr and the control of wild oats by some of specific wild oat herbicides (Kudsk, 2008b).

Moreover, this efficacy differs between herbicides. For example, one conclusion extracted from the previously cited study carried out by the EWRS Herbicide optimization Working Group, stated that growth stage affects the performance of clodinafop but not mesosulfuron+iodosulfuron (EWRS Herbicide Dose Optimisation WG, 2013).

The performance of an herbicide is assumed to be well-explained by the logistic model proposed by Seefeldt *et al.* (1995).

$$y = f(x) = C + \frac{D - C}{1 + \left(x / ED50 \right)^{b}}$$

In this model, **Y** is the efficacy expressed as percentage versus untreated control. ***b*** is the slope of the curve; **ED50** is the dose at the point of inflection and **x**, is the actual dose rate. If we assume that the maximum response available at an infinite dose is D= 100%, and the minimum response is equal to C= 0 at dose=0, the modified equation used is the following:

$$y = f(x) = \frac{100}{1 + \left(x \middle/ ED50 \right)^{b}}$$

Another aspect to be taken into account is related to the herbicides having the same site of action. Their response curves should be similar (parallel) with a relative horizontal displacement (Jensen and Kudsk, 1988). On the other hand, the assumption of curve similarity is a necessary but not a sufficient condition for assuming similar mode of action of compounds (Streibig *et al.*, 1998). For these reasons, ***b*** only depends on the herbicide mode of action and this parameter is known for all compounds (Kudsk, 1989).

Therefore, for one given weed species, a known compound and a defined growth stage, the unique unknown parameter is the parameter **ED50**.

Parallel dose response curves could also be used to compare the effect of climate factors or the growth stage on herbicide performance. With this aim, the relative herbicide potency (R-parameter) could be used (Streibig, 2003):

$$R_i = \frac{ED50_1}{ED50_i}$$

being $ED50_1$ the parameter value calculated at standard growth stage and $ED50_i$ the parameter value for the other growth stages.

In conclusion, CPOWeeds development in Spain requires quantifying the efficacy variation of herbicides (R-parameter) depending on four key-weed growth stage. For this reason, the main objective consists in generating the local R-parameters for the dose-response function described by Seefeldt *et al.* (1995). This has been carried out for four herbicides and four key weeds present in winter cereal fields in the north of Spain as an example of the work done in all thirty five herbicides parameterized.

Materials and methods

All trials were performed in commercial field crops. In all cases winter cereals, wheat or barley, were cultivated following each region standard farm practices: soil management, fertilization, sowing time, sowing density, etc. Characteristics of each field test are shown at table 1.

With this aim, the experiments were designed as completely randomized blocks, with 4 replicates each one. The measures of the experimental plots were 4x5 or 2x10 m depending on locations.

Table 1. Location of field tests, years tested, agroclimatical classification, weed species and herbicides tested.

Location	Agroclimatical classification	Weed species	Herbicides tested
Tarroja de Segarra (LLeida)	Semiarid temperated	Bromus diandrus	Iodosulfuron methyl sodium (IMS) 0,6% + mesosulfuron methyl 3%; IMS1% + Propoxycarbazone sodium 16,8% (2012)
Castellnou d'Oluges (Lleida)	Semiarid temperated	Bromus diandrus	IMS1% + propoxycarbazone sodium 16,8% (2012, 2013 & 2014)
Verdú (Lleida)	Semiarid temperated	Lolium rigidium & papaver rhoeas	Beflubutamid 8,5% + IPU 50% (2011, 2 field tests & 2012, 2 field tests)
Lleida	Irrigated temperated	Avena sterilis	Fenoxaprop-p 6,9% (2011, 2 field tests & 2012, 2 field tests)

Herbicides were applied using a precision sprayer propelled by compressed nitrogen. The boom had four Hardi ISOLD-110-02 flat fan 110º opening nozzles operating at a forward speed of 0.9 m s^{-1}, and 300 l ha^{-1} of spray solution. The boom was 50 cm above the target. As a minimum, 3 doses for achieve since 0% until 100% efficacy were necessary.

Weed species, herbicides, doses and spraying growth stages are shown at table 2.

Treatment efficacy was assessed 35 days after the treatment by taking four random counts per experimental plot, using a square of 0.1 m^2. Abbott method (Abbott, 1925) was used to calculate the efficacy observed in the field trials.

The second step consisted in determining the dose-response curves by taking into account the previous data obtained for each situation.

Table 2. Weed species, herbicides, doses and weed growth stages tested.

Weed species	Herbicide	Number of tests	Doses applied (g commercial product/ha)	Growth stage 1	Other growth stages tested
Bromus diandrus	Iodosulfuron methyl sodium (IMS) 0,6% + mesosulfuron methyl 3%	2	0-250-500-1000	13BBCH	16BBCH
Bromus diandrus	IMS1% + mropoxycarbazone sodium 16,8%	5	0-125- 250-330-660	13BBCH	16BBCH
Lolium rigidum	Beflubutamid 8,5% + IPU 50%	4	0-2000- 2500-3000	11BBCH	14BBCH
Papaver rhoeas	Beflubutamid 8,5% + IPU 50%	4	0-1000-2000-2500-3000	11BBCH	14BBCH
Avena sterilis	Fenoxaprop-p 6,9%	4	0-750-1000-1300	13BBCH	16BBCH

To check parallelism, Fisher's F-test was performed.

If the curves obtained were parallel, the model writes:

$$Y = f(x) = \frac{100}{1+\left(S_0 \times {}^{x}\!/_{Ed50_1} + S_i \times {}^{x}\!/_{Ed50_i}\right)^b}$$

S_0 is 1 if the observation comes from the standard sample and 0 if it is not the case. S_i is 1 if the observation is from the sample of interest, and 0 if not. This is a constrained model since the observations corresponding to the standard sample influence the optimization of ED50 and *b* values. From the model above, one can deduce that this model generates two parallel curves, which only differ on the positioning of the curve, being the shift given by ($ED50_1$-$ED50_i$). If $ED50_i$ is greater than $ED50_1$, the curve corresponding to the sample of interest is shifted to the right in relation to the standard sample curve, and vice-versa.

All statistical analyses were performed using the XLSTAT Dose 2012 software for Microsoft Excel.

Finally, if curves for each herbicide and species are parallel, the relative potency R_i is calculated as shown previously and in Streibig (2003).

Results and discussion

Effect of **Bromus diandrus** *growth stage in the performance of the herbicides iodosulfuron methyl sodium 0.6% + mesosulfuron methyl 3% and iodosulfuron methyl sodium 1% + propoxycarbazone sodium 16.8%*

Brome grass behaviour in front of herbicides iodosulfuron methyl sodium 0.6% + mesosulfuron methyl 3% and iodosulfuron methyl sodium 1% + propoxycarbazone sodium 16.8% can be seen at figures 1 and 2 respectively. Dose response curve parameters are shown at table 2. R^2 values obtained are remarkably good. As expected, brome grass is less susceptible to herbicides when sprayed at bigger growth stages, showing about 10% less herbicide efficacy at standard dose for both herbicides. Dose response curve at 16BBCH is shifted to the right in both cases. This means that the susceptibility to herbicides is lower when weeds are bigger. This agrees with the results obtained by (Barros *et al.*, 2009) about studies performed with the same herbicide versus *L. rigidum* in Portugal.

Theoretically, all two herbicides should have the same slope because both are ALS inhibitors. Instead at this, they are different since propoxicarbazone sodium is taken up predominantly via roots (Amman & Wellman, 2002), but iodosulfuron and mesosulfuron methyl are absorbed by the leaves (Hacker *et al.*, 2001). For this reason, the slopes of the curves could be different when comparing the two herbicides given that root absorption depends on the concentration of herbicide in the soil. So, the slope for soil applied herbicides tends to be higher. In this case, the higher slope was for iodosulfuron 1% + propoxycarbazone sodium 16.8% due to its root absorption.

As mentioned previously, if we model dose-response curve for a compound, the slope has to be constant and the curve shifts to the left or right direction depending on growth stage or climatic factors (Streibig *et al*., 1998). This fact accomplishes with the two herbicides, as shown at table 2, since dose-response curves are parallel for the two studied growth stages 13BBCH and 16BBCH for both herbicides analyzed.

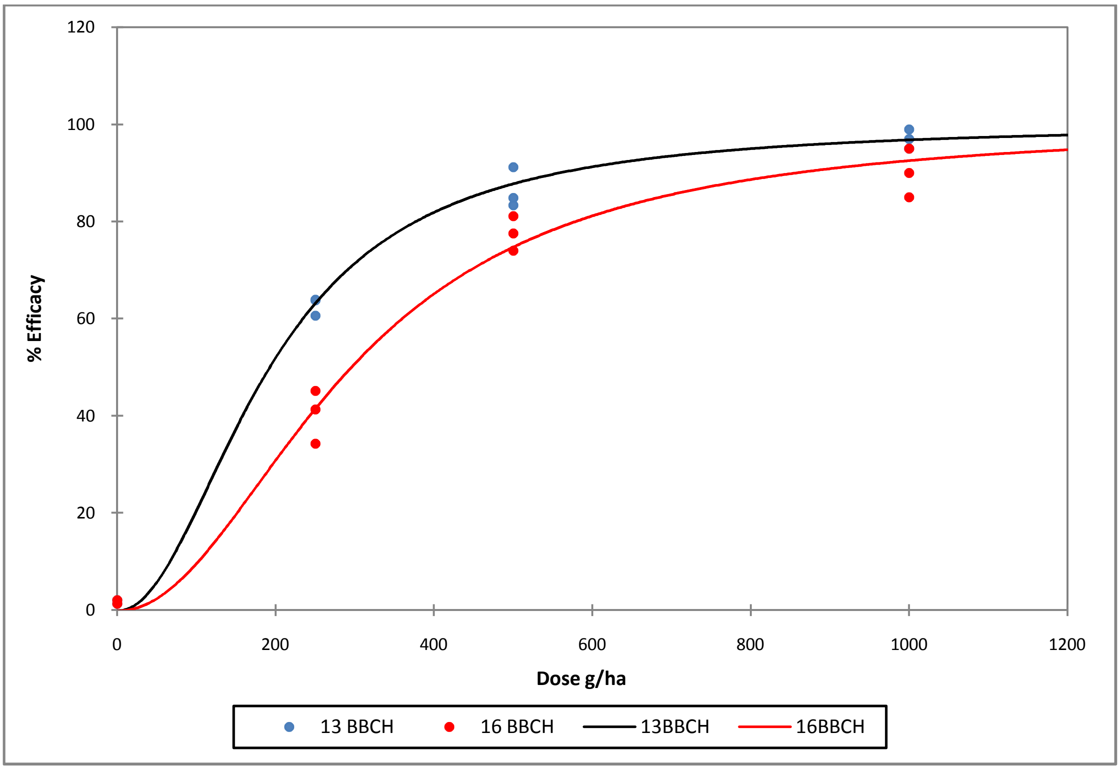

Figure 1. Estimated percentage of efficacy of iodosulfuron methyl sodium 0.6% + mesosulfuron methyl sodium 3% at 13BBCH in black and 16BBCH in red of brome grass. Dose is expressed as grams of commercial product per hectare.

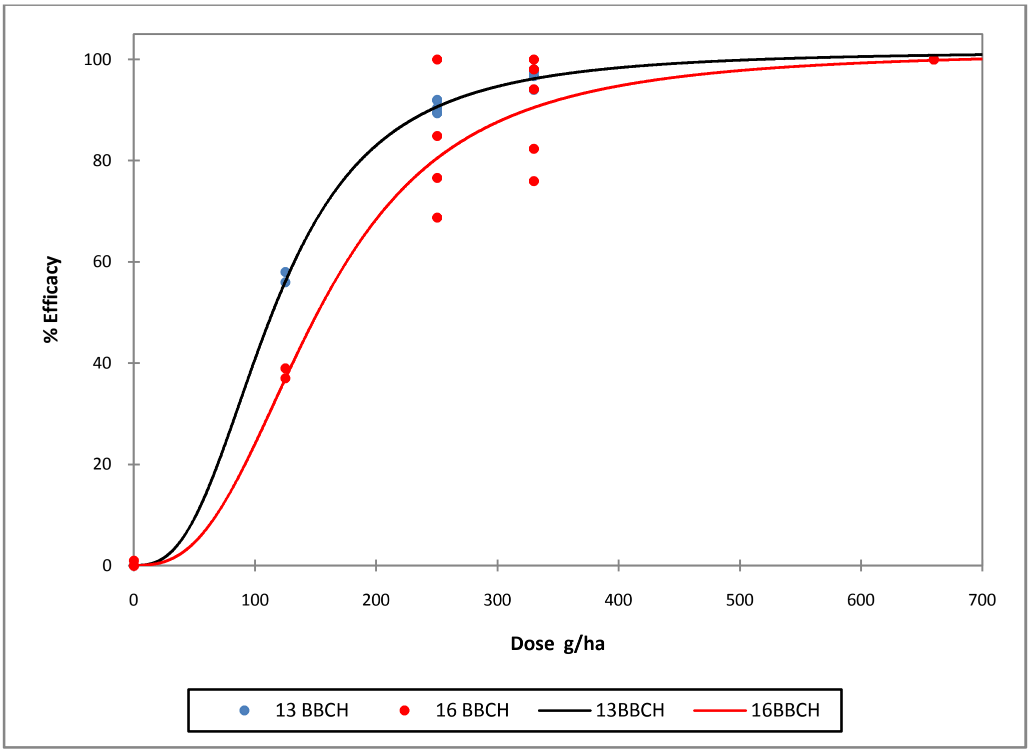

Figure 2. Estimated percentage of efficacy of iodosulfuron methyl sodium1% + propoxycarbazone sodium 16,8% at 13BBCH in black and 16BBCH in red of brome grass. Dose is expressed as grams of commercial product per hectare.

Table 2. Dose-response parameters for the herbicides iodosulfuron methyl sodium 0.6% + mesosulfuron methyl sodium 3% and iodosulfuron methyl sodium 1% + Propoxycarbazone sodium 16.8%, relative potency R in the two compared growth stages.

Herbicide	**R^2**	**ED50-13BBCH**	**ED50-16BBCH**	**Mean slope (B)**	**p-value Parallelism F-test**	**Relative herbicide potency-R**
iodosulfuron methyl sodium0,6% + mesosulfuron methyl sodium3%	0,995	192,5	295,5	2,06	0,569	1,53
iodosulfuron methyl sodium 1% + Propoxycarbazone sodium 16,8%	0,981	115,8	153,6	2,73	0,993	1,33

Relative potency for iodosulfuron methyl sodium 0,6% + mesosulfuron methyl 3% is higher than the one for iodosulfuron methyl sodium 1% + propoxycarbazone sodium 16,8%, which means that iodosulfuron methyl sodium 0,6% + mesosulfuron methyl 3% is more affected than iodosulfuron methyl sodium 1% + propoxycarbazone sodium 16,8% when brome grass grows from 3 leaves to 6 leaves. In this case, 53% of iodosulfuron methyl sodium 0,6% + mesosulfuron methyl 3% is needed to achieve the same efficacy in 6 leaves than in 3 leaves versus a 33% in case of iodosulfuron methyl sodium 1% + propoxycarbazone sodium 16,8% for the same weed stages.

Effect of Lolium rigidum *and* Papaver rhoeas *growth stage in the performance of the herbicide Beflubutamid 8.5% + IPU50%*

Dose-response curves obtained after beflubutamid 8.5% + IPU50% treatments are shown at figure 3. These results corroborate field observation that indicates that efficacy for this herbicide, is less affected by growth stage in corn poppy than in rigid ryegrass. At 2500 g of herbicide per hectare, the maximum authorized rate in Spain, efficacy drops from 99% to 94.8% in corn poppy and from 86.3% to 36.8% in ryegrass when weeds grow from 11 BBCH to 14 BBCH.

As expected, the slope of the curve was the same for both species, as it can be seen at table 3, since the compound tested is the same. Moreover, dose response curves are parallel at the two moments studied for both herbicides, as observed for the brome grass sprayed with the herbicides mentioned before.

It should be highlighted that in *L. rigidum* the efficacy resulted much more affected than in *P. rhoeas* when different growth stages were tested. In this case, the differences in the response to the IPU could be due to the fact that this herbicide is one of the herbicides that have been suggested to undergo P450-mediated metabolism in vitro (Siminszky, 2006) and *L. rigidum* is one species that is known to metabolize that herbicide (Prado *et al.*, 1997) but not *P. rhoeas*. Another important aspect could be dilution effect because broadleaved weeds such as *P. rhoeas* has a more prostrated growth habit than grass weeds like *L. rigidum.* So, herbicide uptake at different growth stages could be much different given that the herbicide droplets interception in a prostate plant is higher when the growth stage is more advanced. In contrast, in an erect foliar architecture, target surface increases in a lower rate compared with the total biomass of the plant (Massinon, *et al*. 2015).

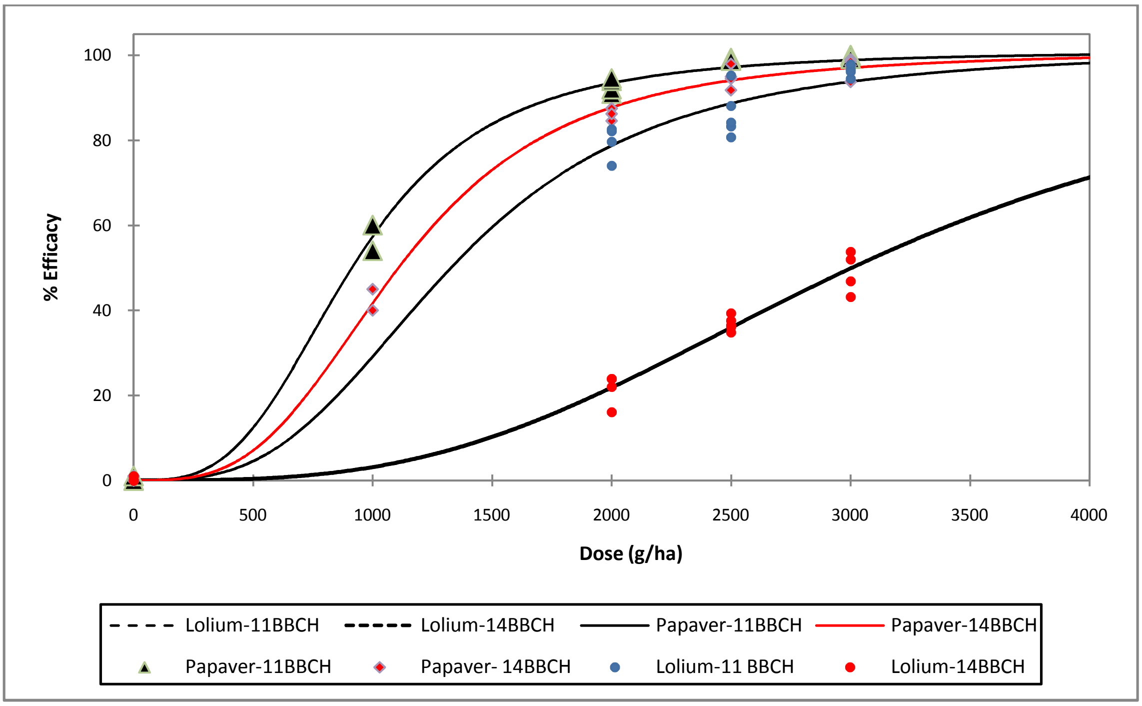

Figure 3. Estimated percentage of efficacy of beflubutamid 8.5% + IPU50% herbicide at 11BBCH and 14 BBCH of *Papaver rhoeas* and *Lolium rigidum.* Dose is expressed as grams of commercial product per hectare.

Another feature that can explain these differences is related to the fact that the effect of soil-applied herbicides is usually more affected than non-systemic foliage-applied herbicides, while systemic foliage-applied herbicides tend to perform better on later weed growth stages (Kudsk, 2008b). In this case, IPU, a soil-applied herbicide is the main active ingredient to kill *L. rigidum*, and beflubutamid, a non-systemic herbicide applied to soil but absorbed by cotyledons and coleoptiles of weeds, mainly kills broadleaved weeds such *P. rhoeas*. These reasons can explain that the variation in efficacy within the two growth stage tested for *L. rigidum* is higher than in the case of *P. rhoeas*.

Table 3. Dose-response parameters for the herbicide beflubutamid 8.5% + IPU 50% at 11 BBCH and 14 BBCH of *Papaver rhoeas* and *Lolium rigidum,* relative potency R in the two growth stages compared**.**

Weed species	**R^2**	**ED50-11 BBCH**	**ED50-14 BBCH**	**Mean slope (B)**	**p-value Parallelism F-test**	**Relative herbicide potency-R**
Lolium rigidum	0,994	1340,0	3033,5	3,10	0,892	2,26
Papaver rhoeas	0,998	918,9	1115,3	3,23	0,993	1,21

Effect of* Avena sterilis *growth stage in the performance of the herbicide fenoxaprop

Dose-response curves obtained after the treatments made with fenoxaprop 6.9% herbicide in *A. sterilis* are shown in figure 4. The high efficacy of this herbicide versus this weed reaching 90% efficacy when applied at less than one half of the maximum authorized rate at 13 BBCH is remarkable and also 90% efficacy at 60% of the maximum authorized rate in the later growth stage tested. This high efficacy allows advisors to recommend doses below the labeled while maintaining efficacies near 100%. This is possible if they have tools like CPOWeeds that are able to know the behaviour of herbicides in a wide range of conditions.

Moreover, the high R^2 values (0,997) obtained suggest that the model is able to explain the efficacy changes and therefore can make the CPOWeeds more robust. Indeed, if the model explains quite well the variation in efficacy, CPOWeeds can predict the final efficacy very accurately, as it was seen at Montull *et al.* (2014), the third chapter of this thesis.

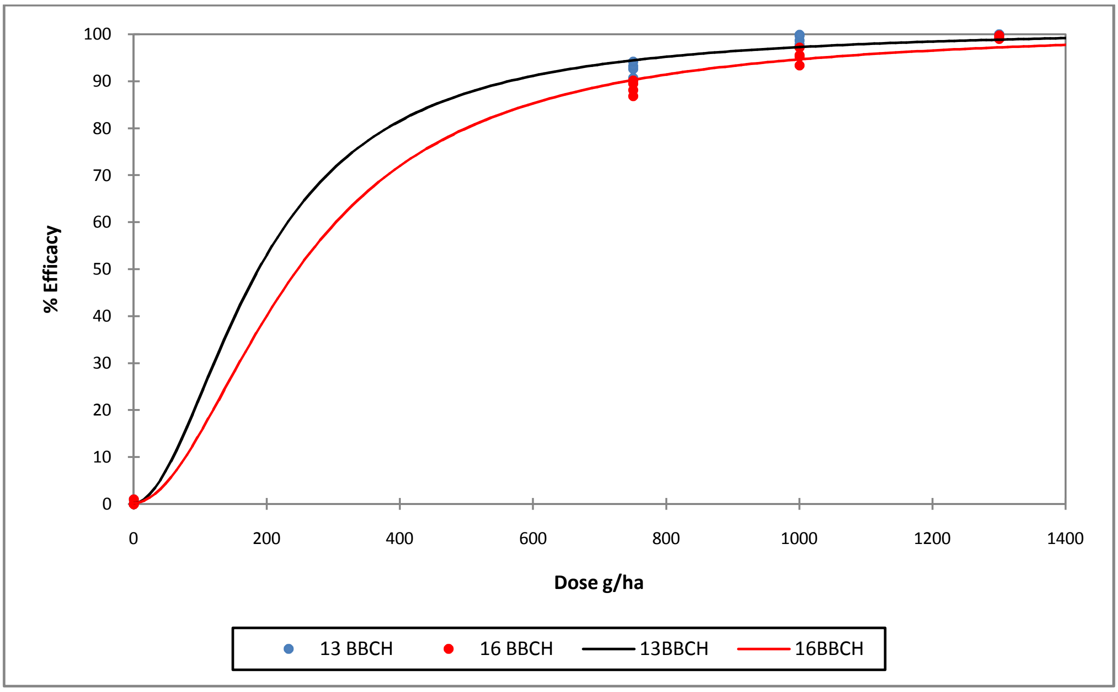

Figure 4. Estimated efficacy of fenoxaprop 6.9% herbicide at 13 BBCH in black and 16 BBCH in red for *A. sterilis.* Dose is expressed as grams of commercial product per hectare. Fine line for 11 BBCH and thicker line for 14 BBCH.

Fenoxaprop herbicide is absorbed mainly through the leaves and also inhibits an enzyme, like propoxycarbazone, iodosulfuron methyl sodium or mesosulfuron methyl. But, unless these herbicides, fenoxaprop belongs to ACCase inhibitors group. For this reason, the behaviour of this herbicide in front of weed species parameters has similar effect.

Indeed, the curve is shifted to the right, showing a lower efficacy when the growth stage is advanced. As expected, curves are parallel, since it is the same compound and therefore, its mode of action is the same.

Table 4. Dose-response curve parameters for the herbicide fenoxaprop 6.9%, relative potency R in *Avena sterilis* two growth stages.

R^2	ED50-13BBCH	ED50- 16BBCH	Mean slope (B)	p-value F-test Parallelism	Relative herbicide potency-R
0,997	190,800	250,420	1,906	0,994	1,31

The mean of the slope is around 2, as it can be seen at table 4. This value is expected for foliar-applied herbicides affecting enzymes, as seen previously in the case of iodosulfuron methyl sodium 0.6% + mesosulfuron methyl sodium

3%. Moreover, in this work, slopes of foliar-applied herbicides have been lower than soil-applied herbicides like beflubutamid 8.5% + IPU50% and iodosulfuron methyl sodium 1% + propoxycarbazone sodium 16.8%.

Relative potency has been similar to the one observed for the previous herbicides absorbed by leaves or cotyledons like beflubutamid, iodosulfuron methyl sodium or mesosulfuron methyl sodium. These results agree with those obtained by Per Kudsk in (2008a) and (2008b).

Conclusions

The main conclusions to be drawn after this research are the following ones:

-R-parameter for *B. diandrus* vary from 1.53 for iodosulfuron methyl sodium 0.6% + mesosulfuron methyl sodium 3% to 1.33 for iodosulfuron methyl sodim 1% + propoxycarbazone sodium 16,8%.

- *P. rhoeas* and *L. rigidum* showed different behaviour when sprayed with the herbicide beflubutamid 8.5% + IPU 50% since it is composed by two different active ingredients.

-In this work dose-response curve slope tended to be lower in foliar-applied herbicides, around 2, than in soil-applied ones, around 3.

-The efficacy of root-absorbed herbicides was more affected by growth stage compared to foliar-absorbed herbicides.

-All the studied species have been less susceptible to herbicides when later growth stages were tested.

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Chapter 3

Four years validation of decision support optimising herbicide dose in cereals under Spanish conditions

Montull, J. M., Soenderskov, M., Rydahl, P., Boejer, O. M., & Taberner, A. (2014). Four years validation of decision support optimising herbicide dose in cereals under Spanish conditions. *Crop Protection*, *64*, 110–114. doi:10.1016/j.cropro.2014.06.012

Four years validation of a decision support optimising herbicide dose in cereals under Spanish conditions.

Abstract: The Danish decision support system Crop Protection Online (CPO) optimises herbicide weed control. CPO recommends specific herbicide solutions to achieve a required level of control. The aim is to apply herbicides as little as possible but as much as necessary. CPOWeeds is a version of CPO adjusted to conditions in Spain. The predicted efficacies and the yield obtained with CPOWeeds were validated in winter cereal field trials from 2010 to 2013. All CPOWeeds treatments were related to the efficacies obtained with standard herbicide treatments decided upon by local advisors. The predictions from CPOWeeds were compared to the actually achieved efficacies in the field trials for the nine weed species at different developmental stages and for 84.2% of the comparisons the obtained efficacies were equal to or higher than predicted. The average difference between predicted and observed efficacies was 2.35 percentage points. Yield was measured in three trials and the recommendations from CPOWeeds were maintaining yield. There were two situations where CPOWeeds were performing suboptimal. One is in the early weed growth stages, as the model is not yet prepared to account for water stress on root action herbicides applied at 10-11 BBCH. The second situation was in fields with a prior unidentified population of resistant *Alopecurus myosuroides*. For key species in winter cereals in Spain, such as *Avena sterilis, Lolium rigidum* and *Papaver rhoeas*, CPOWeeds achieved a satisfactory control level. It was concluded that the use of CPOWeeds allowed optimisation of the herbicide application with a very high robustness. The recommendations were satisfactorily for the conditions of the north of Spain and have the potential to decrease the amount of applied herbicides by at least 30%. Therefore, it can be an important tool in Integrated Weed Management.

Introduction

Decreasing the dependence on chemical pest control is a primary objective for agricultural legislation and environmental initiatives, based on the experiences from a long period of agricultural intensification. The principle for Plant Protection Products (PPP) application should be as much as necessary, but as little as possible (Rydahl *et al.*, 2009).In practice, however, this is rarely the case. Reality is that advisors often make treatment recommendations for worst case scenarios of each major crop and use these solutions on large areas regardless of the actual weed flora. In order to reduce the applied amount of pesticides the spraying solutions have to be chosen based on specific observations for individual fields. Weed species composition, crop developmental stage and climatic conditions all play a role in the assessment of the optimal spraying solution (Kudsk and Kristensen, 1992; Lundkvist, 1997). For example, glyphosate ED90 for certain species varies between 70 and 1350 g.a.i./ha under different treatment conditions (Minkey & Moore, 1996). The potential for dose reductions are large as the label recommended dose has to be efficient under a variety of conditions and it is therefore higher than necessary when optimal conditions prevail.

Decision Support Systems (DSS) play an important role in the selection of optimal PPP's and dosages. Such systems can specify the relevant herbicides and dosages to reflect the actual weed infestation in a field under actual spraying conditions and thus ensure proper weed control. Currently, in Europe, there are 9 DSS for weed control decisions (Rydahl *et al.,* 2009), most of them have demonstrated a potential for reducing inputs within an appropriate crop rotation, while maintaining a high level of weed control.

Even though, these DSS's have good potentials for reducing herbicide use, there are relatively few farmers and advisors using them on European scale. The two main reasons for the low adoption of DSS are the low incentives to use them due to the relatively low cost of generalized treatments and the lack of resources or interest by farmers to make weed registrations in individual fields prior to herbicide sprayings (Rydahl et al., 2009). Moreover, farmers prefer high control every year, especially in a crop preceding another in which weed control is more expensive or difficult. By using a DSS they are sometimes advised to accept small amounts of weeds remaining after spraying. Integrated pest management (IPM) is, however, gaining interest and the annex of 2009/128/EU Directive explicitly demands the member states to implement IPM, which imply a decreased reliance on PPPs. Another reason for adoption of a DSS is economical, because despite the low price of PPP's, a reasoned use of pesticides is more efficient than an indiscriminate use.

CPOWeeds (Crop Protection Online - Weeds)

Crop protection Online (CPO) is a DSS developed and managed by Aarhus University, which was commercialised in 1991 (Rydahl, 2003; Rydahl, 2004; Kudsk, 2008). CPOWeeds optimises herbicide combinations and dosages in relation to the actual crop and weed infestation either by lowest dose or lowest price. As one herbicide rarely controls all weeds in a field, the model also includes calculation of herbicide mixtures by use of the additive dose model (ADM) (Streibig, 1981).

An important factor in CPOWeeds is the required level of control (target efficacy), which has been decided upon by expert weed scientist and advisors. A 100% control level is not realistic, even with label rates, as some plants will always survive treatment. Furthermore, sublethal doses can inhibit weed plants for a long time after spraying without killing them, thus reducing the weed competitiveness in favour of the crop (Boutin *et al.*, 2000; Terra *et al.*, 2007). Target efficacies in CPOWeeds are estimated based upon densities and growth stages of both crop and weed species. The general principle is that high competitiveness and density of the weed species induces high target efficacies, while the less competitive weed species and low densities calls for lower target efficacies. The aim is to set a target efficacy level, which insures yield and prevent excessive build-up of the soil seed bank, but still enables reduced doses.

In the user-interface eleven criteria are integrated to define the weed scenario in a particular field. These criteria are: season, crop, crop density, potential yield, weed species, phenological stage and densities of crop and weeds, temperature and water stress. When the user has provided this information the program calculates the level of control required for every species. An herbicide dose model estimates the required dose of the available herbicides and rank them according to either price or herbicide amount. The herbicide dose model contains dose response curves, which are based on experimental data from scientific work and more practical approaches from herbicide efficacy testing. Herbicide resistance is of major concern in weed control and resistant weed biotypes are incorporated in CPO by creating separate weed biotypes with very low sensitivity towards herbicides with the mode of action for which they are resistant.

Different prototypes have been developed since the initial system was launched in Denmark and they have been validated in different crops where the weed coverage at harvest time and the yield was measured (Sonderskov *et al.*, 2014). In the current Danish version, it is estimated that herbicides inputs in cereal crops can be reduced by over 40% without enriching soil seedbank for the succeeding crops.

Presently, CPO is implemented to varying degrees in Norway, Estonia, Poland and Germany in one or more crops. In these countries the validation tests have showed that the recommendations were robust (Sønderskov *et al.* unpublished results). However, the potential of herbicide reductions varies between countries and depends on the weed species present in the fields and management done to date (Rydahl *et al.,* 2009). Furthermore, an ongoing project develops CPO for weed control in maize in Germany, Italy and Slovenia with a module for mechanical measures included.

Objectives

The objectives of this study were to validate the concept of CPO under climatic conditions different from northern Europe with a version of CPO developed for the north of Spain. The ability to preserve yield and the robustness of the obtained efficacies were validated.

Material and methods

Model description and adjustments made for conditions in the North of Spain

The aim of this work was to examine locally generated parameters and adjustments for the dose-response function described in (Rydahl, 2003) with regard to herbicides and weeds present in winter cereal fields in the North of Spain. The prototype was developed under the name CPOWeeds.

Table 1. Target efficacies (%) for each species and density.

Species	Efficacy required (%) for each density (plants/m^2)				
	½-1	2-10	11-40	41-150	>150
Alopecurus myosuroides, ALOMY	0	85	85	90	95
Anthemis arvensis, ANTAR	0	75	85	90	95
Avena sterilis, AVEST	0	75	85	90	95
Diplotaxis erucoides, DIPER	0	75	85	90	95
Galium aparine, GALAP	85	90	90	95	95
Lolium rigidum, LOLRI	0	85	85	90	95
Malcomia africana, MAMAF	0	80	85	90	95
Papaver rhoeas, PAPRH	0	80	85	90	95
Veronica hederifolia, VERHE	0	0	75	75	80

CPOWeeds is dependent upon parameterisations of dose-response curves for all relevant combinations of herbicides and weed species. Given the amount of existing herbicides and diversity of weed species it is a huge task to provide data for this amount of dose-response curves. Therefore, different approaches were used to collect the data. Dose-response curves were preferentially estimated based on field experiments. Ideally, at least three doses, representing different levels of efficacy, should be available for an herbicide in order to establish a dose-response curve. For some herbicide-weed species combinations this was not available and the dose-response curves were either based upon less data or borrowed from other European regions. For some herbicides with no existing data, semi-field tests were performed to substitute full field experiments. The available data was scarce for some species, but dose-response curves were estimated for twelve species commonly observed in winter cereal fields in the region, whereof nine was found in the field trials. A safety margin was added to the most uncertain dose-response curves and the higher the uncertainty was the higher safety margin was included for the herbicide efficacy. This was done by shifting the dose-response curve to the right. Some non-parameterised species were regarded equally susceptible to a herbicide as another species by local experts and similar dose-response curves were adopted in the system for those species.

Target efficacies were established by local expert evaluation (table 1). Although, at a practical level, only efficacies between 75 and 95% are recommended, lower efficacies were established for research purposes. CPOWeeds listed all possible solutions for a given weed composition in specific fields sorted by Treatment Frequency Index (TFI). TFI is a measure of the dose reductions, where TFI of 1 equals label rate and lower TFI indicates dose reductions.

Field trials

Two trial setups were conducted from 2010 to 2013. Trials on efficacy were performed over four years, whereas yield trials were all conducted in 2013. Trials were conducted with different types of winter cereals, but primarily barley for efficacy trials and all yield trials in wheat (table 2). Under the climatic conditions in the region no differences were expected between the weed species composition. The target efficacies required in the different crop types were considered equal.

Field trials were carried out in 2x10 or 4x5m plots, for efficacy and yield experiments, respectively with four replicates at each location. For each efficacy trial a number of recommendations from the prototype were tested (table 2). Furthermore, different application times were tested as some herbicides are most efficient or only legal when applied in early stages. The fields were surveyed at 10-11 BBCH of the weeds and a weed report was made to supply data for CPOWeeds. A solution for the early stage was calculated by CPOWeeds and applied at this stage as one treatment. The fields were surveyed again at the 12-14 and at 16 BBCH and again solutions were calculated and applied for each growth stage. For the yield trials the application was either at 12 BBCH for herbicides with root activity or 22 BBCH for herbicides with leaf activity. A standard treatment was chosen by local advisors for all fields to have a reference for the CPOWeeds solutions.

Herbicides were applied with a precision sprayer propelled by compressed nitrogen. The boom had four Hardi ISO LD-110-02 flat fan 110 degrees opening nozzles operating at a forward speed of 0.9ms^{-1}, and 300 lha^{-1} of spray solution. The boom was 50cm above the target.

Treatment efficacy was assessed 35 days after treatment by four random counts per experimental plot, throwing a square of 0.1m^2. Yield was estimated harvesting three randomly squares of 0.1 m^2 in each plot. It was not possible to measure yield in all trials as there were severe drought after the sampling at 35 days after spraying in some trials. Therefore, additional trials were conducted in 2013 to have evaluation of yield in CPOWeeds treatments.

Statistical analyse

Abbott method (Abbott, 1925) was used to calculate the efficacy observed in the field trial. In each treatment the efficacies predicted by the prototypes were compared to the efficacies obtained in the field on a species level.

Differences between predicted and observed efficacies were analysed using linear mixed models (fixed effects: species, growth stage at application and year; random effects: field and replicate) using R (R Development Core Team, 2013). Model fits were assessed by visual inspection of residual and normal probability plots. Pair wise differences between variables were evaluated using post hoc T-tests with adjustment for multiplicity (Hothorn, 2008). Analysis of variance (ANOVA) was performed to determine significant differences between the different obtained yields. The Duncan’s Multiple Range Test was used if necessary for separation of means with α=0.05. The analysis was performed for each field.

Table 2. Efficacy and yield trials. TFI for CPO treatment was calculated as an average of the different solutions applied in the fields. Standard TFI was the TFI of the reference treatments selected by local advisors. The reduction in TFI is the difference between the two TFI measures.

Trial purpose	Year	Location	Agroclimatical classification	Crop	Soil management	Fertiliser	Weeds found in field	Weed density (plants m^{-2})	Number of CPOWeeds treatments	Standard TFI	Average CPO TFI	% reduction on TFI
Efficacy	2010	Ballobar	Semiarid warm	Barley	Minimum till		AVEST, LOLRI, DIPER		10	2	1.41	29.5
Efficacy		Ballobar		Barley	Minimum till		LOLRI, ANTAR		10	1.8	1.11	38.3
Efficacy	2011	Verdú	Semiarid temperated	Barley	No till		LOLRI, VERHE		6	2	1.52	24
Efficacy		Verdú		Barley	No till		PAPRH, LOLRI		6	1	0.71	29
Efficacy		Verdú		Barley	No till		VERHE, PAPRH		6	1.3	1.01	22.3
Efficacy		Verdú		Triticale	No till		VERHE, PAPRH, AVEST		6	2	1.33	33.5
Efficacy	2012	Algerri	Semiarid temperated	Barley	No till		PAPRH, LOLRI, MAMAF		6	1.7	1.33	21.7
Efficacy		Algerri		Barley	No till		PAPRH, LOLRI, MAMAF		6	1.7	1.33	21.7
Efficacy		Verdú		Triticale	No till		LOLRI, AVEST, PAPRH		6	1.66	1.33	19.8
Efficacy		Penelles		Barley	No till		ANTAR		8	1	0.34	66
Efficacy		Penelles		Barley	No till		LOLRI, AVEST, PAPRH		8	1.66	0.85	48.8
Efficacy	2013	Vimbodí 1	Subhumid temperated	Wheat	No till	40m3 pig slurry	ANTAR, AVEST, LOLRI		5	2	0.95	52
Efficacy		Vimbodí 2		Wheat	No till	60m3 pig slurry	GALAP, LOLRI, VERHE		6	2	1.09	45.5
Efficacy		Termens	Irrigated temperated	Wheat	Irrigated	180-50-150 NPK	ALOMY		7	1	0.68	32
Yield		Termens		Wheat	Ploughing + rotary harrow	180-50-150 NPK	ALOMY	503	6	1	0.71	29
Yield		Vimbodí 1	Subhumid temperate	Wheat	No till	40m3 pig slurry	ANTAR, AVEST, LOLRI	75	4	2	0.95	52.5
Yield		Vimbodí 2		Wheat	No till	60m3 pig slurry	GALAP, LOLRI, VERHE	207	6	2	0.99	50.5

Results

TFI of the trials ranged between 1 and 2 for the standard treatments and between 0.34 and 1.52 for the average CPOWeeds treatment. This equals herbicide use reductions between 19.8 and 66 % with a weighted average of 36%. These reductions did not result in generally lower weed control and yield was preserved.

The accuracy of the CPOWeeds predictions was estimated based upon weed counting 35 days after spraying in the efficacy trials. The observed values were equal to or higher than predicted for 84.2% of the samplings. . Also, 88% of results are included in the range -5%to 10%, with an average value of 2.35% difference between the observed and predicted values. That is, the efficacy values observed in the field are higher than predicted by the model, with a mean difference of 2.35%.

Nine different species were used in the analyses and there were some differences in the accuracy among the species (figure 1). The average difference between predicted and observed efficacies for *Avena sterilis, Lolium rigidum* and *Papaver rhoeas*, which are key species in this region, showed a difference just above 2%. This was similar to that obtained with *Anthemis arvensis*, which is less commonly found in this region. For *Malcomia africana* and *Alopecurus myosuroides*, differences between observed and predicted values were as low as 0.7% and 0.151%. The relationship between predicted and observed efficacies for *Malcomia africana* was smaller than for most other species ($< 0.0001 < p < 0.97178$ for pairwise comparisons among other species and *M. africana*). This species, however, was only found at two locations in 2012. The largest differences between predicted and observed efficacies were found for *Lolium rigidum* and *Papaver rhoeas* in 2011, but the differences were not consistently positive or negative. Generally, the negative differences for *L. rigidum* were found for plants sprayed at the earliest stage (BBCH 10-13), whereas there was no tendency for *P. rhoeas* for dependence on growth stage.

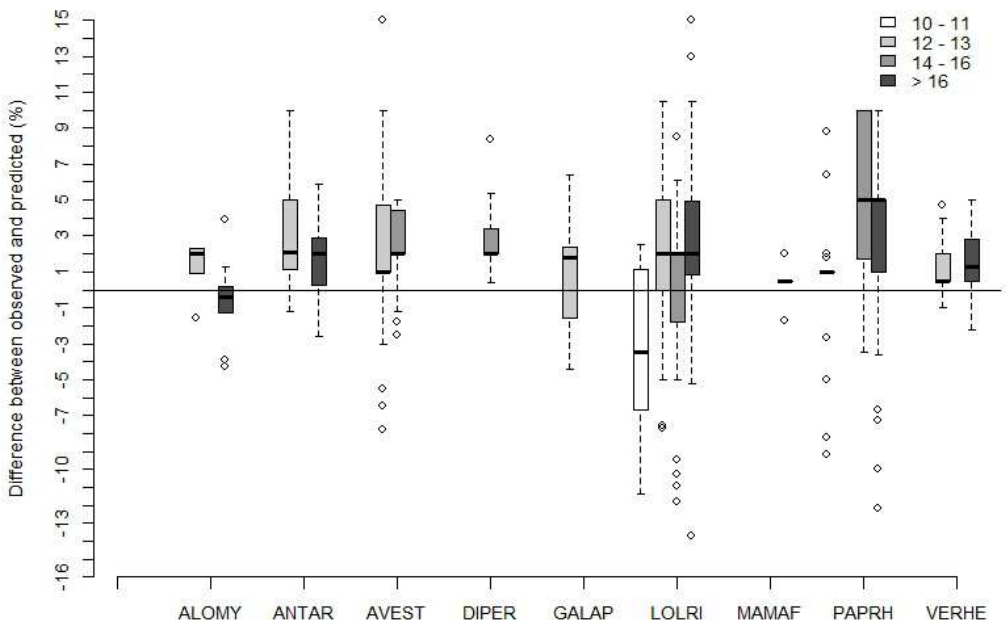

Figure 1, Difference between observed and predicted values for the different species and growth stages (legend indicate growth stages.).

The growth stage of the weed plants at the time of application did not influence the robustness of the model recommendations, as the difference between predicted and observed efficacies did not differ among growth stage (p = 0.4151, n= 4). The model was designed to account for the developmental stage at the time of application and CPOWeeds was observed to adequately adjust the doses. There was some variation in the magnitude of the difference between predicted and observed efficacies among years (p = 0.0116, n = 4). The observed efficacies were less consistent with the predicted efficacies in 2011 than in the other three years (<0.0001 < p < 0.0288 for pairwise comparisons). During that year, the rainfall was only 33.7mm in compared to an average rainfall slightly above 110mm in the period when the field tests were carried out (December 2010 to February 2011).

The yield trials support the results obtained in the efficacy trials, which shows that CPOWeeds provide robust advice that sufficiently control the weeds present in the validation trials (table 3). The yield of CPOWeeds treatment was equal to or even higher than the standard treatments. At Termens there were two CPOWeeds treatments that did not provide the same yield as the standard treatment. This was due to the presence of a resistant *A. myosuroides* population, which was unidentified at the establishment of the trial.

Table 3. Yield trials. Yields of CPOWeeds treatments are given as an interval as 4-6 different solutions were tested in each field. Lower case letters indicate differences between standard treatment and CPOWeeds treatments.

Location	**Treatment**	**Yield (kg ha^{-1})**
Termens	Standard	10450^{a}
	CPOWeeds	6403^{b} – 11006^{a}
Vimbodí 1	Standard	4082^{a}
	CPOWeeds	4168^{a} – 4793^{a}
Vimbodí 2	Standard	4763 ^{a}
	CPOWeeds	6286^{b} – 7103^{b}

Discussion

In 9 of 17 trials the herbicide reduction obtained was above 30% when the standard treatment was compared to the average TFI of the CPOWeeds treatment. In all cases the reduction was at least 20%. The yield trials supported the general impression from the efficacy trials that no yield loss was induced by following CPOWeeds recommendations. In some instances there was an increase in yield compared to standard advice.

The obtained results were accurate, with most of the values in the range 0-5% regardless of conditions, weed composition and phenological stages. There were, however, small differences between the growth stages indicating that the model performance was best between stage 12 and 16. Most post-emergence herbicides are recommended in this stage, which was reflected in the model performance. The herbicides with the highest root activity, is often applied before the actual weed composition can be determined. The application in stage 10-11 might be later than optimal for those herbicides. Another reason for the less efficient treatments in the early stages was that this version is not yet prepared to determine the effect of water stress on root action herbicides, which was an important factor, especially in 2011. The standard treatments, decided by the local advisors, in early stages also had lower effect that expected, the data is, however, not shown. Another aspect is, that the model does not account for the synergy between different active substances, so in cases where there is synergy, the observed efficacy will be higher than required, with obtained efficacies up to 15% larger than predicted. To avoid antagonism, the model does not recommend mixtures in which this phenomenon can occur to avoid losing strength because it is virtually impossible to model the antagonistic response. Species like *Avena sterilis, Papaver rhoeas* and *Lolium rigidum* are important species in winter cereals in the North-east of Spain and CPOWeeds recommendations provided sufficiently control of these species. There were some rare species in the cereal fields in this area, like *M. africana*, with limited information on the herbicide efficacy. Nevertheless, the dose-response curves were solid enough to provide control for these species, *i.e.* the built-in safety margin adequately accounted for the uncertainty. With few data available, it is better to underestimate the effectiveness of treatments to increase robustness.

In the future, improvement of the model with more efficacy data, increasing numbers of weed species and herbicides will provide even better estimates of the efficacy of the presently available herbicides and increase the ability to recommend specific solutions for individual fields. This is likely to increase the potential for herbicide reductions.

The validation trials showed that CPOWeeds gave robust advice, which sufficiently controlled the present weed species and maintained yields. There were a few fields with inadequate weed control, which were attributed to the lack of identification of a resistant *A. myosuroides* biotype. CPOWeeds are able to handle the identified resistant biotypes. Currently, a resistance prevention initiative is being developed in CPOWeeds, which aims at limiting the development of more resistant weed species by altering the mode of action of herbicides between weed generations.

In the future feedback from users will be important to adjust the target efficacies to levels that will provide sufficient control in all situations. The present target efficacies were estimated by experts, but experiences from Denmark has shown that adjustments are necessary through the initial implementation period as it is difficult to account for all factors. The final conclusion is that the use of this tool allowed an optimising of the application of herbicides, adjusting the applied herbicide rates with a very high robustness, its recommendations were very satisfactory for the conditions of the North of Spain and has a potential to decrease the amount of applied herbicides with more than 30%. This, potentially, makes CPOWeeds an important tool in Integrated Weed Management which is faced with the Directive 2009/128 / EC in 2014.

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Chapter 4

Evaluación del Sistema de Ayuda a la Decisión CPOWeeds en cereal de invierno en España

Evaluation of the Decision Support System CPOWeeds recommendations in winter cereals in Spain

Evaluación del Sistema Experto de Ayuda a la Decisión CPOWeeds en cereal de invierno en España

Resumen: El control integrado de malas hierbas es básico en el actual marco legislativo, donde se pretende realizar un uso sostenible de productos fitosanitarios. Los herbicidas se deben de utilizar conjuntamente con el resto de métodos de control de malas hierbas para que el impacto ambiental derivado de su uso sea el mínimo posible. Para conseguirlo, se han desarrollado durante los últimos 25 años varios Sistemas de ayuda a la Decisión. Se presentan los resultados de cinco ensayos en campo llevados a cabo en campos de trigo y cebada con el objetivo de demostrar que con la utilización del Sistema de Ayuda a la Decisión CPOWeeds en las condiciones agronómicas de España se obtienen, para los cereales de invierno, rendimientos iguales a los obtenidos con las recomendaciones dadas por los técnicos. En todos los casos, las recomendaciones dadas por el sistema de ayuda a la decisión CPOWeeds obtuvieron rendimientos similares o superiores con un ahorro de un 41,7% de materia activa herbicida comparado con las recomendaciones de los técnicos.

Evaluation of the Decision Support System CPOWeeds recommendations in winter cereals in Spain

Abstract: Integrated weed control is required in the current legislative framework for sustainable Plant Protection Products use. Herbicides must be employed as a tool together with the other weed control methods to reduce environmental impacts. Several Decision Suport Systems (DSS) have been developed in Europe during the last 25 years to achieve this goal. In this paper five tests are described. They were carried out in commercial fields of wheat and barley demonstrate that the use of the DSS CPOWeeds in Spanish conditions allows to obtain similar yields than those obtained after the recommendations made by advisors. In all tests the recommendations provided by the CPOWeeds gave similar or higher yields with 41.7% less use of active herbicide related compared with recommendations made by local advisors.

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Introducción

En Europa está aumentando la concienciación sobre el uso de productos para la protección de cultivos; esta es una de las razones por las cuales se implementó la Directiva 2009/128/CE de Uso Sostenible de Productos fitosanitarios. Se pretende mejorar el uso de estos productos con el objetivo de disminuir la contaminación a suelos, aguas y aumentar la seguridad del aplicador.

Sin embargo, Oerke (2006) estimó, a nivel global, unas pérdidas potenciales de rendimiento de un 43%, causadas solo por malas hierbas, en ausencia de medidas de control. Por esta razón, las malas hierbas deben ser controladas para evitar las pérdidas de rendimiento. Para conseguir este objetivo, se pueden utilizar varios métodos ya sean químicos, mecánicos o culturales. Dentro de los métodos químicos, los herbicidas son una más de las herramientas disponibles con la ventaja de que su uso es más modulable que otros métodos de control ya que se puede varíar la dosis de aplicación.

Los herbicidas pueden tener efectos medioambientales negativos, además, está aumentando la concienciación sobre el efecto de los residuos de fitosantarios tanto en el agua de boca como en los alimentos (Christensen *et al.*, 2009). Desde otro punto de vista, tanto la aplicación de herbicidas como el producto en sí representan un coste significativo en la producción de los cultivos (Christensen *et al.*, 2009). Generalmente, los herbicidas se aplican según recomendaciones a gran escala, sin determinar cuál es la flora presente en cada parcela. Por estas razones, el aplicar los herbicidas solo cuando está económicamente justificado ofrece una oportunidad para reducir costes innecesarios cuando la presión de malas hierbas es baja y reduce la presión negativa sobre el medio ambiente (Buhler, 1996)**.**

El principal problema que tienen los agricultores es que la optimización del manejo de malas hierbas es una labor compleja que requiere de la integración de la biología de las malas hierbas, los riesgos medioambientales, el rendimiento potencial esperado, la eficacia de cada método de control y los criterios económicos (Renner *et al.,* 1999).

Para conseguir dicha optimización se han desarrollado en los últimos 25 años varios Sistemas Expertos de Ayuda a la Decisión (SEAD) en el ámbito de la malherbología (Been *et al.*, 2009). Al principio de la década de los 90, los SEAD disponibles solo eran capaces de dar como respuesta intervenir o no con un tratamiento determinado para un campo en concreto. Pero actualmente los tratamientos herbicidas pueden ser ajustados basándose en todos los parámetros que pueden variar su eficacia (Mithila *et al.*, 2011; Been *et al.*, 2009) tales como estado fenológico de las malas hierbas, técnica de aplicación, condiciones climáticas, etc. Basándose en toda esta información, los SEAD son capaces de definir las materias activas y las dosis que deben utilizarse para conseguir un control de malas hierbas óptimo en cualquier condición.

Actualmente, los SEAD no son muy utilizados debido a que los agricultores o técnicos prefieren utilizar recomendaciones herbicidas en base a programas que son suficientemente efectivos en una región determinada. Otra razón es que el coste de los herbicidas es relativamente bajo en relación a la pérdida potencial de rendimiento por las malas hierbas y por ello, los agricultores prefieren la seguridad de no perder rendimiento antes que optimizar el coste de los herbicidas. La tercera razón es que no existen muchos ensayos demostrativos en campo donde los agricultores puedan comprobar la eficacia de estos sistemas (Been *et al.*, 2009).

Además, la reducción en las dosis aplicadas, normalmente, no es bien aceptada porque se le presupone que puede favorecer el desarrollo de resistencias. Con la utilización del CPOWeeds, las eficacias obtenidas son similares a las obtenidas a la dosis máxima autorizada y similares a las requeridas (Montull *et al.,* 2014) y por tanto, la presión de selección hacia una resistencia metabólica no se incrementa. Así, el riesgo de desarrollo de resistencias no se aumenta utilizando el CPOWeeds.

Las bondades del CPOWeeds se deben demostrar de dos formas: la primera que las eficacias obtenidas en campo se correspondan a las predichas por el sistema y que fueron publicadas en (Montull *et al.,* 2014); la segunda es que los rendimientos obtenidos en cosecha son similares a los que se obtienen con las recomendaciones de los técnicos asesores.

Por tanto, el principal objetivo de este estudio es demostrar que con la utilización del CPOWeeds en las condiciones agronómicas de España se obtienen, para los cereales de invierno, rendimientos iguales a los obtenidos con las recomendaciones dadas por los técnicos asesores de cada zona.

Material y métodos

Todos los experimentos se han llevado a cabo en parcelas comerciales del NE de España durante los años 2013 (3 ensayos) y 2014 (2 ensayos). Solo se han realizado durante dos años porque se asume que las diferencias climáticas entre las diferentes fincas donde se han llevado a cabo son mayores que la variación climática interanual.

Las prácticas de cultivo y la clasificación agroclimatica de cada finca se muestran en la tabla 1.

En todos los casos, se comparan las diferentes alternativas propuestas por el CPOWeeds para cada parcela en concreto con un tratamiento estándar por parcela, propuesto por el técnico que asesora el cultivo en cada una de las fincas.

La infestación de malas hierbas se evalúo el día previo a la ejecución del tratamiento con 4 conteos por parcela experimental, lanzando al azar un cuadrado de 0,1 m^2.Los datos requeridos se introducen en el CPOWeeds para obtener las diferentes recomendaciones. Estos datos se muestran, para cada parcela, en la tabla 2.

En 2013 los herbicidas se aplicaron utilizando un pulverizador manual de ensayos propulsado por nitrógeno comprimido. La barra dispone de cuatro boquillas Hardi ISO LD-110-02 de abanico plano. El volumen de aplicación fue de 300 l/ha. La barra estaba situada a 50cm por encima de las malas hierbas. Se definieron dos momentos de tratamiento, el primero en estado fenológico 12 BBCH, dos hojas verdaderas del cereal, con herbicidas de acción radicular y otro en 22 BBCH, inicio de ahijado del cereal con herbicidas de absorción foliar. Se realizó así para ensayar la respuesta del CPOWeeds en un rango mayor de situaciones. Los experimentos se diseñaron como bloques completos al azar, con 4 repeticiones. Cada parcela experimental medía 4x5 m y cada bloque estaba compuesto por una parcela para cada una de las 4-6 recomendaciones del CPOWeeds, la recomendación estándar propuesta por el técnico y un testigo sin tratar.

Tabla 1. Practicas de manejo del cultivo en cada ensayo.

Año	Localidad	Cultivo	Clasificación de la zona agrícola	Manejo del suelo	Fertilizante	Densidad de siembra (plantas/m^2)	Numero de variantes del CPOWeeds	TFI estándar	Promedio TFI CPO	% reducción en TFI
2013	Térmens	Trigo	Riego por inundación 3000m^3/ha	Laboreo convencional	180-50-150 NPK	500	6	1	0.71	29
	Vimbodí 1	Trigo	Secano semiarido templado	No laboreo	40m^3 purín porcino	450	4	2	0.95	52.5
	Vimbodí 2	Trigo	Secano semiarido templado	No laboreo	60m^3 purín porcino	450	6	2	0.99	50.5
2014	Briançó	Cebada	Secano subhumedo templado	No laboreo	60m*3* purín porcino	450	1	1.5	1.1	26.7
	Pancorbo	Trigo	Secano humedo frio	Laboreo convencional	210-70-120 NPK	500	1	2	1	50

Tabla 2. Infestación de malas hierbas en cada parcela. Las abreviaturas indican el nombre de la especie en código EPPO.

	Alopecurus myosuroides (ALOMY) (Plantas/m^2)	**Anthemis arvensis (ANTHAR) (Plantas/m^2)**	**Avena sterilis (AVEST) (Plantas/m^2)**	**Galium aparine (GALAP) (Plantas/m^2)**	**Lolium rigidum (LOLRI) (Plantas/m^2)**	**Veronica hederifolia (VERHED) (Plantas/m^2)**	**Papaver rhoeas (PAPRH) (Plantas/m^2)**	**Sinapis arvensis (SINAR) (Plantas/m^2)**
Térmens	503							
Vimbodi 1		35	10		30			
Vimbodi 2				140	42	25		
Briançó			150				15	
Pancorbo			70 (Resistente FOP)			3		75

En la campaña 2014, los herbicidas se aplicaron a parcelas comerciales completas con un tractor equipado con un pulverizador de barras de 24 m de anchura equipado con boquillas Hardi ISO LD-110-03 de abanico plano a 8 km/h, aplicando 200 l/ha de caldo. La aplicación se llevó a cabo en estado fenológico 22 BBCH con herbicidas de absorción foliar. La mitad de cada parcela se trató con la recomendación con menor Treatment Frecuency Index (TFI) (Soenderskov *et al.*, 2014; 2015) de las 4-6 recomendaciones dadas por el CPOWeeds para la parcela en cuestión y la otra mitad con el tratamiento estándar recomendado por el técnico. El TFI se calcula según indica la siguiente ecuación:

$$TFI = \sum_{i}^{j} \frac{Dosis\ aplicada_i}{Dosis\ máxima\ autorizada_i}$$

Los tratamientos realizados en cada parcela se muestran en las tablas 3, 4, 5 y 6.

La eficacia esperada la proporciona el CPOWeeds para cada tratamiento y especie de mala hierba en concreto y siempre es igual o superior a las eficacias requeridas presentadas en Montull *et al.* (2014).

La eficacia de los tratamientos se evaluó 35 días después de la aplicación con 4 conteos de plantas vivas por parcela experimental, lanzando al azar un cuadrado de 0,1 m^2. Se utilizó el método Abbott (Abbott, 1925) para calcular el porcentaje de eficacia de cada tratamiento.

El rendimiento se estimó cosechando y trillando de forma manual cuatro cuadros de 0,25 m^2 por parcela, lanzado al azar. El rendimiento se expresó en kilogramos por hectárea.

Se utilizó un modelo de regresión lineal para valorar el efecto de las malas hierbas supervivientes al tratamiento herbicida. La ecuación utilizada fue la siguiente: Rendimiento (kg/ha)= Parametro1*Ln (densidad de mala hierba)+Parametro2

Se plantearon Análisis de varianza (ANOVA) para determinar las diferencias significativas para las variables eficacia y rendimiento. En caso necesario, para la separación de medias se utilizó el Test de Duncan con α=0.05. El análisis se realizó para cada una de las parcelas y para las dos variables: eficacia herbicida y rendimiento. Se utilizó el paquete informático Xlstat 2012.

Tabla 3. Herbicidas y dosis utilizadas en el ensayo 1, Termens. Se muestran TFI, momento de tratamiento y eficacia esperada.

Tratamiento	Ingrediente activo	Dosis (g/ha de IA)	TFI	Momento de tratamiento (BBCH)	Eficacia esperada (%)
No tratado					ALOMY
Estándar	Clortoluron	2000	1	12	
CPO1.1	Iodosulfuron-metil+ mesosulfuron-metil	1.5+ 7.5	0,5	22	95
CPO2.1	Florasulam + piroxsulam	5.7+17.1	0,94	22	95
CPO3.1	Fenoxaprop-p	27.6	0,4	22	95
CPO4.1	Beflubutamida + isoproturon	191.25+1125	0,9	12	95
CPO5.1	Iodosulfuron-metil+ propoxicarbazona	2.4+163.2	0,96	22	95
CPO6.1	Clodinafop	42	0,54	22	95

Tabla 4. Herbicidas y dosis aplicados en el ensayo 2, Vimbodi 1. Se muestran TFI, momento de tratamiento y eficacia esperada.

Tratamiento	Ingrediente activo	Dosis (g/ha de IA)	TFI	Momento de aplicación (BBCH)	Eficacia esperada (%)		
					ANTHAR	LOLRI	AVEST
Estándar	Diclofop + tribenuron-metil	900+18.75	2	22			
CPO1.2	Diclofop+ bromoxynil	576+144	1,04	22	95	99	95
CPO2.2	CTU + clorsulfuron	1150+9.75	1,07	12	95	99	95
CPO3.2	(Iodosulfuron-metil + propoxicarbazona) + diclofop	2.5+42+324	1,12	22	88	95	99
CPO4.2	(Beflubutamida + isoproturon)+ diclofop	68+400+225	0,57	22	95	95	90

Tabla 5. Herbicidas y dosis aplicados en el ensayo 3, Vimbodi 2. Se muestran TFI, momento de tratamiento y eficacia esperada.

Tratamiento	Ingrediente activo	Dosis (g/ha de IA)	TFI	Momento de aplicación (BBCH)	Eficacia esperada (%)		
					GALAP	VERHED	LOLRI
Estándar	Isoproturon (IPU) +diflufenican	1500+ 50	2	12			
CPO 1.3	Diclofop + bromoxynil	230 + 240	0,92	22	95	97	90
CPO 2.3	Iodosulfuron-metil + propoxicarbazona	42 + 2,5	1	22	90	97	85
CPO 3.3	(Iodosulfuron-metil + propoxicarbazona)+ diclofop	(38,64 + 2.3) + 151,2	1,09	22	90	85	90
CPO 4.3	Carfentrazona + diclofop	16 + 230	1,06	22	90	97	90
CPO 5.3	(Beflubutamida + IPU) + carfentrazona	(165,75+975) +2	0,88	12	95	97	95
CPO 6.3	(Beflubutamida + IPU) + carfentrazona + diclofop	(165,75+975) +2 + 108	1	12	95	97	95

Tabla 6. Herbicidas y dosis aplicadas en los ensayo 4 y 5, Brianço y Pancorbo. Se muestran TFI, momento de tratamiento y eficacia esperada.

Tratamiento	Ingrediente activo	Dosis (g/ha de IA)	TFI	Momento de aplicación (BBCH)	Eficacia esperada (%)			
					AVEST	VERHED	PAPRH	SINAR
Estándar Brianço	Pinoxaden + bromoxynil	45+480	1,75	22				
CPO Brianço	Fenoxaprop-p+ bromoxynil	51,7+336	1,45	22	95		85	
Estándar Pancorbo	Pinoxaden + (florasulam+aminopiralida)	60+(4,95+9,9)	2	22				
CPO Pancorbo	Iodosulfuron-metil + mesosulfuron-metil	3+15	1	22	97	50	90	90

Resultados

Parcela 1: Térmens

La eficacia obtenida para cada uno de los tratamientos frente a *A. myosuroides* se muestra en la tabla 7. El tratamiento estándar recomendado por el técnico ha sido uno de los que ha tenido una eficacia más alta, pero sin diferencias estadísticas con las opciones propuestas por el CPOWeeds excepto en los tratamientos CPO3.1 (Fenoxaprop) y el CPO 6.1 (Clodinafop) que han tenido una eficacia mucho más baja de lo esperado.

Estas opciones están diseñadas para conseguir un 95% de eficacia, que se considera suficiente para alcanzar el rendimiento máximo. Al no buscar la eficacia máxima sino la óptima, se puede ver que las dosis recomendadas son inferiores a la máxima autorizada para estos herbicidas en España.

Tabla 7. Eficacia (%) obtenida 35 días después del tratamiento para ALOMY y rendimiento estimado (kg/ha) para cada tratamiento en la parcela 1-Termens.

Tratamiento	Eficacia obtenida (%)	Rendimiento estimado (kg/ha)
Estándar	99,1 a	10450 a
CPO 1.1	95,1 a	10956 a
CPO 2.1	95,7 a	9356 a
CPO 3.1	9,5 b	6403 b
CPO 4.1	97,5 a	11006 a
CPO 5.1	92,3 a	9656 a
CPO 6.1	29,1 b	6466 b
No tratado		6156 b

El rendimiento ha estado relacionado con la eficacia del tratamiento, el mejor ajuste para la regresión no lineal ($r^2=0,88$) lo da la expresión Rendimiento (kg/ha)=-1104,28*ln (plantas/m^2)+13233,67. El rendimiento más bajo obtenido ha sido en las parcelas no tratadas, sin diferencias estadísticas con los tratamientos CPO 3.1 y CPO 6.1. Por otra parte, el resto de recomendaciones del CPO han tenido rendimientos similares o superiores al estándar pero sin diferencias estadísticamente significativas entre ellos.

Parcela 2: Vimbodi 1

En esta parcela, todos los tratamientos han tenido una eficacia superior a la prevista por el CPOWeeds, los cuales se muestran en la tabla 8. Además, estas eficacias han sido estadísticamente igual para todos los tratamientos, tanto el estándar como los que se han realizado en los dos momentos fenológicos, 12 BBCH y 22 BBCH.

Tal y como ha ocurrido en la parcela anterior, el rendimiento ha estado condicionado por la eficacia herbicida. Por esto, no ha habido diferencias significativas en el rendimiento entre el tratamiento estándar y las recomendaciones del CPOWeeds y sí que las ha habido respecto al testigo no tratado.

Tabla 8. Eficacia (%) obtenida 35 días tras el tratamiento para cada especie de mala hierba y rendimiento estimado (kg/ha) para cada uno en el ensayo 2, Vimbodi 1.

	Eficacia obtenida (%)			**Rendimiento estimado (kg/ha)**
Tratamiento	ANTHAR	LOLRI	AVEST	
Estándar	100 a	100a	100 a	4082 a
CPO 1.2	100 a	100 a	100 a	4168 a
CPO 2.2	100 a	100 a	100 a	4543 a
CPO 3.2	88,9 a	93,3 a	100 a	4725 a
CPO 4.2	100 a	93,3 a	91,7 a	4793 a
No tratado				2296 b

Parcela 3: Vimbodi 2

En esta parcela, a diferencia de las dos anteriores, se han observado diferencias estadísticamente significativas entre la eficacia obtenida con el tratamiento estándar y las recomendaciones del CPOWeeds (Tabla 9). Esto ha sido así porque los dos tratamientos que contienen beflubutamida + isoproturon han sido más eficaces frente a *G. aparine* que el tratamiento propuesto por el técnico, lo cual indica que quizá el tratamiento estándar no era el más adecuado para la parcela. Además, solo estos dos tratamientos han tenido una eficacia superior a la requerida, 95% para esta mala hierba. Las eficacias obtenidas con el resto de recomendaciones del CPOWeeds han sido ligeramente inferiores a las esperadas, sin diferencias significativas entre ellos.

El comportamiento de los herbicidas frente a *V. hederifolia* ha sido diferente que el del *G. aparine*. En este caso, todos los herbicidas han tenido la misma eficacia estadísticamente hablando y esta ha sido ligeramente superior que la predicha por el CPOWeeds.

Frente a *L. rigidum*, todos los tratamientos ensayados han tenido un comportamiento similar, sin diferencias significativas. Solo dos tratamientos recomendados por el

CPOWeeds han tenido una eficacia ligeramente inferior a la prevista, son los dos que contienen iodosulfuron-metil + propoxicarbazona: CPO 2.3 y CPO 3.3.

Tabla 9. Eficacia (%) obtenida 35 días tras el tratamiento para cada especie de mala hierba y rendimiento estimado (kg/ha) para cada uno en el ensayo 3, Vimbodi 2.

	Eficacia obtenida (%)			**Rendimiento estimado (kg/ha)**
	GALAP	VERHED	LOLRI	
Estándar	79,3 b	100 a	86,5 a	4763 b
CPO 1.3	92,2 ab	100 a	100 a	6703 a
CPO 2.3	86,8 ab	100 a	80,7 a	6390 a
CPO 3.3	86,2 ab	91,7 a	88,2 a	6713 a
CPO 4.3	90, 5 ab	100 a	100 a	6286 a
CPO 5.3	97,3 a	100 a	97,4 a	6520 a
CPO 6.3	98,8 a	100 a	100 a	7103 a
No tratado				3683 b

Los rendimientos obtenidos han estado condicionados por la eficacia frente a *G. aparine,* la ecuación que mejor explica esta relación (r^2=0,75) es Rendimiento (kg/ha)= -787,26*Ln (*G. aparine* plantas/m^2)+6280,62. En esta parcela, todas las recomendaciones dadas por el CPOWeeds han tenido los rendimientos más altos, sin diferencias significativas entre ellas y siempre superiores estadísticamente al estándar.

Parcela 4: Brianço

En esta localidad, no ha habido diferencias estadísticas en la eficacia entre el tratamiento estándar recomendado por el técnico y el tratamiento recomendado por el CPOWeeds (Tabla 10) para ninguna de las dos especies presentes: *A. sterilis* y *P. rhoeas*.

Tabla 20. Eficacia (%) obtenida 35 días tras el tratamiento para cada especie de mala hierba y rendimiento estimado (kg/ha) para cada uno en el ensayo Brianço.

	Eficacia obtenida (%)		**Rendimiento estimado (kg/ha)**
	AVEST	PAPRH	
Estándar	95,2 a	92,1 a	5341 a
CPO	95,4 a	86,2 a	5481 a

Asimismo, no ha habido diferencias significativas en el rendimiento obtenido. Es de destacar que esto se ha conseguido con un 17,2% menos de herbicidas, expresado como TFI. Esta reducción se ha conseguido solo ajustado la dosis herbicida al estado fenológico de las malas hierbas, porque las dos soluciones han sido similares en término de soluciones herbicidas aplicadas, un antigramíneo inhibidor de la ACCasa complementado con bromoxynil para controlar *P. rhoeas*.

Parcela 5: Pancorbo

En esta parcela, la eficacia obtenida con la recomendación del CPOWeeds ha sido estadísticamente similar a la estándar (Tabla 11). Además, con una cantidad inferior de herbicida aplicada, expresado como TFI, la eficacia contra *A. sterilis* ha tendido a ser superior que el estándar.

Tabla 31. Eficacia (%) obtenida 35 días tras el tratamiento para cada especie de mala hierba y rendimiento estimado (kg/ha) para cada uno en el ensayo Pancorbo.

	Eficacia obtenida (%)			**Rendimiento esperado (kg/ha)**
	AVEST	PAPRH	SINAR	
Estándar	93,2 a	95,2 a	97,8 a	8117 a
CPO	97,4 a	94,3 a	94,7 a	8963 a

Discusión

En todos los casos, el rendimiento obtenido con los tratamientos recomendados por el CPOWeeds ha sido estadísticamente igual que en los tratamientos estándar recomendados por los técnicos asesores de cada una de las parcelas excepto en la parcela en la parcela 3: Vimbodi 2, donde las recomendaciones del CPOWeeds han sido superiores al tratamiento estándar. Este es otro punto a favor para utilizar el CPOWeeds porque se demuestra que las recomendaciones a gran escala no siempre son las mejores para conseguir el rendimiento más alto en todas las condiciones. Como ejemplo, en la parcela 3: Vimbodi 2, el tratamiento recomendado por el técnico no era el más adecuado para esa parcela en concreto. Sin embargo, las recomendaciones del CPOWeeds se determinan parcela a parcela según la infestación presente y entonces se determina la eficacia necesaria para obtener el máximo rendimiento.

En la mayor parte de parcelas, no ha habido diferencias significativas en la eficacia herbicida obtenida comparado con la recomendación del técnico. Además, se ha conseguido con una disminución de la aplicación de herbicidas de un 41,7% en promedio respecto las recomendaciones estándar en base al TFI aplicado. Esto está de acuerdo con los principios de la Directiva de Uso Sostenible de Productos Fitosanitarios (2009/128/CE).

El CPOWeeds permite facilitar el manejo de biotipos resistentes, en ese caso, se introduce la información al programa, indicando a que familias herbicidas es resistente la especie y el sistema ya no recomienda ninguno de los productos de esa familia para evitar problemas. La razón por la cual se obtuvo tan baja eficacia en dos tratamientos del ensayo 1: Térmens frente *A*. *myosuroides* es porque este biotipo ha mostrado resistencia a herbicidas del grupo A. Esta información se desconocía a principio del ensayo y por tanto, este dato no se le introdujo al CPOWeeds, por eso recomendó también dos herbicidas de dicha familia.

En las parcelas sin tratar del ensayo 1: Térmens, la densidad media de *A. myosuroides* fue de 503 plantas/m^2. Con esta infestación, las pérdidas de rendimiento pueden estar alrededor del 40% (Ingle *et al*., 1997) respecto a parcelas sin competencia de malas hierbas. En este ensayo, se han alcanzado perdidas de rendimiento de un 42% entre las parcelas no tratadas y las tratadas, lo cual está de acuerdo con el trabajo citado previamente.

Estos resultados permiten extraer otra conclusión y es que las eficacias del 95%, para estas infestaciones de *A. myosuroides* son suficientes para conseguir los máximos rendimientos porque con eficacias del 95% se ha conseguido el mismo rendimiento que con eficacias del 99%. Aunque, teóricamente, eficacias más altas deban estar relacionadas con rendimientos más altos, el efecto del herbicida sobre el cultivo debe tenerse también en cuenta. Este mismo efecto fue descrito en Montull (2011), en el que los rendimientos de las parcelas experimentales tratadas con clortoluron fueron inferiores a las parcelas sin tratar debido a que el efecto fitotóxico del herbicida fue superior al efecto de la competencia por malas hierbas. Por esta razón, los herbicidas deben ser utilizados solo cuando esté económica y técnicamente justificado y por esto, los sistemas expertos de ayuda a la decisión permiten mejorar la toma de decisiones. Resultados similares obtuvo (Gonzalez-Andujar *et al.*, 2010), donde con la aplicación de un DSS para control de *A. sterilis* se mejoraba el retorno económico de la aplicación herbicida.

En el ensayo 3, Vimbodi 2, *G. aparine* fue la especie que puede causar las mayores pérdidas de rendimiento, que pueden alcanzar hasta un 40% según trabajos de (Ingle *et al*., 1997) con la densidad presente en las parcelas no tratadas.

En esta parcela, la razón principal de la bajada de eficacia con los herbicidas aplicados en estadio 22 BBCH fue la alta densidad de malas hierbas en las parcelas. En post-emergencia precoz, en estadio 12 BBCH, debido al pequeño tamaño de las malas hierbas, es fácil que el herbicida alcance todas las plantas. Pero, en los tratamientos realizados en 22BBCH, con plantas más grandes, las plantas más altas cubren a las menos desarrolladas y es más difícil que el herbicida las alcance de forma suficiente y por tanto, la eficacia se reduce.

Como resumen, se puede decir que en estas parcelas, el CPOWeeds ha sido capaz de dar recomendaciones consiguiendo el mismo o incluso superior rendimiento que las recomendaciones estándar con una menor cantidad de herbicidas aplicado. La disminución de cantidad de materia activa herbicida conseguida se debe a que el sistema CPOWeeds es capaz de predecir la eficacia herbicida que se obtendrá en una parcela para todas las alternativas herbicidas disponibles.

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General discussion and conclusions

General discussion and conclusions

In this thesis the decision support system CPOWeeds has been adjusted for Spanish agro-climatic conditions. It is not the first DSS developed in Spain for weed management because during the last 90's and the first 2000's two DSS were developed. The first DSS was developed to optimize *A. sterilis* management (Gonzalez-Andujar *et al.*, 2010) and the second one was developed to manage *L. rigidum* (Gonzalez-Andujar *et al.*, 2011). Also, in the mid-2000's Papaver Integrated Management (PIM) model was tuned up (Torra, *et al.,* 2010), its objective was improving long-term management of *Papaver rhoeas* infestations.

However and in contrast to these DSS, the CPOWeeds is not focused only in one species and a specific herbicide to simulate what will happen in the mid-term or long-term. The CPOWeeds response is based specifically on the flora in the plot at the time prior to spraying and also most of authorized herbicides are available. The aim is not to predict what will happen with a particular management in the medium term but to generate several alternatives, based on specific aspects, that the advisor can choose. It is intended that the CPOWeeds makes work easier for advisors to improve weed management based on all the knowledge gained during the development of it.

The main advantage is that the CPOWeeds answers are based on parameters corresponding to aspects of the weed biology and the behaviour of herbicides (Rydahl, 2003). The optimization is based on mathematical models as shown in Streibig *et al.* (1998) and Jensen & Kudsk (1988). Therefore, the cost optimization models and TFI have been succeeded in adapting to our conditions despite being designed in Denmark, a priori, a country very different from an agroclimatological point of view to Spain.

The initial results leave the way open to try to adapt quickly the mathematical model in which the CPOWeeds is based on different countries. For these different prototypes of CPOWeeds for conditions in the Baltic countries, Germany and Poland have been developed which are shown in (Rydahl, 2008; Rydahl, 2014; Sønderskov *et al.*, 2015).

The development of this thesis has demonstrated that, according to (Jensen & Kudsk, 1988; Kudsk, 1989; Streibig *et al.*, 1998), the slope of the dose-response curve, the B parameter, depends exclusively on the mode of action of the herbicide for foliar absorbed herbicides and is independent of the spraying conditions. This allows to diminish the quantity and complexity of the tests required to introduce new herbicides in the CPOWeeds database. This is so because knowing the slope of the curve implies that the only unknown parameter is the A-parameter, the efficacy estimated at maximum authorized dose. Therefore, the enormous work that was done to parameterize all herbicides shown in the first chapter can be greatly simplified assuming that the B-parameter is known for each herbicide depending on its mode of action.

In this case, multiple doses tests would only be required with new or unknown herbicide mode of action.

In fact, a new herbicide, propoxycarbazone-sodium, which theoretically should have a B-parameter equal to 2 according to its mode of action, ALS inhibitor, tended to B = 3 since its absorption is primarily via roots. Thus, root-absorbed herbicides have behaviour independent to their mode of action and have a B-parameter equal to 3.

This work has also shown that the shift of the parallel dose-response curve must be calculated species by species, as seen in the case of *L. rigidum* and *P. rhoeas* with the herbicide named Herbaflex composed by isoproturon and beflubutamid. As it is a commercial product composed of two active ingredients, the behaviour in each species is different depending wich active ingredient affects each particular species. Aspects such as leaf architecture or the ability to detoxify the active ingredients can vary the herbicide efficacy in each case. For example, this has observed with *L. rigidum* which is able to degrade substituted urea herbicides urea such as the isoproturon herbicide by the CYP450 enzyme (Siminszky, 2006).

Determining properly the growth stage of each weed is a key aspect in optimising the doses of herbicides. An advanced growth stage means that the dose required to have a specific efficacy needs to be increased up to more than 30% or even the maximum authorized dose is not enough to reach an adequate efficacy as also occurred in Kieloch & Domaradzki (2011). This aspect highlights the value of technical advisers work as it shows that a good job of determining the different species and growth stages allows lower costs in herbicides. This is a basic aspect in the actual framework of Sustainable Pesticide Use.

The field validation has two complementary parts. In the first one, corresponding to Chapter 3 of this thesis, it has been proven that predictions of efficacy given by the program are satisfied in the field. The results show that the fit between observed and predicted values for the CPOWeeds is very good. It is important that the observed values are higher than those predicted ensuring the robustness of the model; this aspect has also been seen in other countries that have tried to develop versions of this DSS (Rydahl, 2003; Rydahl, 2014; Sønderskov *et al.*, 2015). However, the efficacy values obtained should not be much higher than necessary, i.e., an efficacy which ensure maximum yield. An efficacy higher than necessary indicate a waste of herbicide, losing some of the positive aspects that presents this DSS that is saving active ingredient and enhancing environmental and economic sustainability.

In semi-arid climatic conditions such as those typically found in the north of Spain it is important to focus future studies on modelling the effect of water stress on herbicide effectiveness. Thus the response provided by the CPOWeeds will be optimal in all agroclimatic conditions. In this case, the effect of water stress in the parallel displacement of the curve should be studied. Water stress causes a shift of the dose-response curve to the right, i.e., greater dose of herbicide required to achieve the same efficacy. This effect may be greater or smaller depending on the mode of absorption of the herbicide. In general, root absorbed herbicides, which need to be dissolved in the water contained in the soil, are more affected by the lack of moisture in the soil than foliar herbicides; they can even fail completely (Kudsk, 2008). This effect should be studied formulated by formulated because there are pre-emergent herbicides like pendimethalin which act through contact, inhibiting the growth of the roots (Hutson, 1998) making them more independent of soil moisture. However, the performance of pendimethalin would not necessarily be identical in case of application using microencapsulated or slow release formulations. This kind of formulations may affect the bioavailability as occurs for other herbicides such as mesotrione (Galán-Jimenez *et al.,* 2015) or flufenacet (Gómez-Pantoja *et al.,* 2015).

The second part of the field validation corresponds to Chapter 4 of the thesis. This deals with the cereal yields obtained after the practical implementation of CPOWeeds. The goal is clear, yields should be kept using less herbicide. The background of the CPO in Denmark indicates that it is a feasible target (Rydahl, 2003; Sønderskov *et al.,* 2014) and this has been achieved in most cases. In cases where it has not been achieved it has been due to ignorance of the characteristics of a particular weed biotypes. In this case, because a resistance to the ACCase inhibitor herbicides, which was unknown at the beginning of the test.

Keeping yields indicates that the efficacies required for herbicides have been sufficient. These efficacies required for each species and weed densities were determined by prior knowledge. Looking to further improve the CPOWeeds would be interesting to conduct studies with lower efficacies required, in order to further reduce the amount of herbicides applied, while maintaining the crop yield.

The main conclusions that can be taken from this work are:

- The parameters necessary to operate CPOWeeds can be generated using dose-response curves, although not many data is available.

-In this work the dose-response curve slope tended to be lower in foliar-applied herbicides than in soil-applied ones. Slope tended to depend on the mode of action for foliar-applied herbicides and tended to be equal to 3 in soil-applied ones.

-The efficacy of root-absorbed herbicides was more affected by growth stage than foliar-absorbed herbicides and all the studied species have been less susceptible to herbicides in later growth stages tested.

- CPOWeeds recommendations provided sufficiently control in field trials of species like *Avena sterilis, Papaver rhoeas* and *Lolium rigidum* that are important species in winter cereals in the North of Spain
-The dose-response curves were solid enough to provide control for rare species, *i.e.* the built-in safety margin adequately accounted for the uncertainty.
-With few data available, it was better to underestimate the effectiveness of treatments to increase robustness.
-The validation trials showed that CPOWeeds gave robust advice, which sufficiently controlled the present weed species and maintained yields.
-In all cases, yield tended to be higher using the CPOWeeds in spite statistically significant differences with standard recommendations did not exist.

- It has been possible to decrease herbicide application of about 50% over the standard recommendations based on the Treatment Frequency Index. This is in accordance with the principles of the Directive on Sustainable use of pesticides (2009/128/EC).

In summary, it can be said that in our agroclimatic conditions, the CPOWeeds has been able to give recommendations with similar or even higher yield than standard recommendations with a smaller amount of herbicide applied. In addition, it is intended that this Decision Support System could be integrated in the future into other DSS at a European level in order to exploit the synergies between different research groups.

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Annex

Annex

During the works that have allowed the realization of this doctoral thesis diverse technical need for farmers and advisors were detected. These needs tend to be different for the cereal areas where CPOWeeds has been validated.

To meet these needs several technical papers were raised in the four largest agricultural extension journals in the country. Not all are directly related to the subject at hand, optimising the use of herbicides, but also with other areas of weed science as prevention and management of herbicide resistance.

These papers are the following:

Montull JM, Llenes JM, Taberner A. (2015). El control de malas hierbas de cereal en el contexto de la rotación de cultivos. *Agricultura: Revista agropecuaria, 987.* pp. 632-634

Montull JM, Taberner A. (2015). Nuevas tecnologías en el control de malas hierbas. Empleo de sistemas expertos de ayuda a la decisión. *Tierras de CyL*, 218, pp 78-81

Montull JM, Llenes JM, Taberner A. (2015) El manejo de las resistencias a herbicidas en el contexto de la rotación de cultivos. *Vida rural*, 401, pp. 68-70

Cirujeda A, Mari A, Pardo G, Aibar J, Taberner A, Montull JM, Llenes JM (2014). Control de *Bromus*, *Papaver*, *Lolium* y *Avena* en cereal de invierno

Montull JM, Taberner A. (2014) Control Integrado de *Bromus diandrus*, segundo año de ensayos. *Tierras de CyL*, 218, pp 52-55

Rey J, Montull JM. (2014) Valoración económica de las resistencias de amapola y vallico. *Tierras de CyL*, 220, pp 60-68

Montull JM, Llenes JM, Taberner A. (2013) Cómo combinar los herbicidas en cultivos extensivos para prevenir las resistencias. *Vida rural*, 361, pp. 34-39

Taberner A, Montull JM, Llenes JM. (2012) Control de malas hierbas en cereales de invierno. *Agricultura: Revista agropecuaria, 954.* pp 592-597

Abbreviations used in the text

ADM: Additive Dose Model

CPO: Crop Protection Online

DRC: Dose Response Curve

DSS: Decision Support System

ENDURE: It was originally a Network of Excellence funded by the European Commission from 2007 to 2010. Network partners learned to work together as researchers and agricultural advisers tackled the complexities of helping European farmers meet the challenges of the new European regulatory framework regarding crop protection.

NTSR: Non Target Site Resistance

PA: Precision Agriculture

PURE: Pesticide Use-and-risk Reduction in European farming systems

SSCM: Site Specific Crop Management

TFI: Treatment Frequency Index

TSR: Target Site Resistance

VRA: Variable Rate Application