Reduced herbicide rates: present and future

Reduzierter Herbizidaufwand: heute und zukünftig

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Abstract

Applying herbicides at rates lower than the label recommendation has been the rule rather than the exception in Denmark since the late 1980's. Justifications for reducing herbicide rates can be 1) that the dominant weed species in the field are very susceptible to the herbicide, i.e. even reduced rates will result in maximum effects, 2) that the conditions at and around the time of application, e.g. growth stage of weeds, crop vigour and climatic condition are optimum promoting the activity of the herbicide and thus allows for the use of reduced herbicides rates, or 3) that less than maximum effects are accepted because the weed flora is not considered to have a significant effect on crop yield. "Crop Protection Online-Weed" (CPO-Weed) is a web-based decision support system that was developed to support farmers in their choice of herbicide and herbicide rate. CPO-Weed will, based on information on crop development and status and the composition of the weed flora, provide farmers with a list of herbicide solutions often recommending the use of reduced rates. The potential of CPO-Weed to reduced herbicide input has been proven in numerous validation trials. In recent years the use of reduced herbicide rates has been linked to the increasing number of cases of non-target resistance in outcrossing grass weed species like *Alopecurus myosuroides* and *Lolium* ssp. The underlying hypothesis is that the least susceptible individuals in the population will survive the use of reduced rates and that recombination will lead to a gradual increase in the resistance level in the weed population. This scenario is only valid if the use of reduced herbicide rates is prompted by acceptance of a lower effect but not if a high susceptibility of the weed species present in the field or optimum conditions are the reasons for reducing herbicide rates. This is an aspect that is often overlooked in the on-going discussion on herbicide rates and resistance. Large weed population increases the risk of selecting resistant weed biotypes because the likelihood that resistant plants are present in the population increases with population size. Preventing the build-up of large weed populations is a key objective in integrated pest management (IPM). If the use of herbicide is combined with non-chemical weed control methods the risk of resistance will be reduced further, i.e. in an IPM scenario the use of reduced herbicides rates will be less likely to promote herbicide resistance even if it is triggered by an acceptance of lower effects.

Keywords: Crop Protection Online, dose response curve, herbicide rate, herbicide resistance, integrated pest management, IPM

Zusammenfassung

Seit den späten 1980-er Jahren ist in Dänemark die Anwendung von Herbiziden mit geringeren Aufwandmengen als bei der Zulassung vorgesehen eher die Regel als die Ausnahme. Den Aufwand herabzusetzen kann begründet sein, indem 1) die dominierenden Unkrautarten gegenüber dem Herbizid sehr empfindlich sind, d. h., dass selbst mit verminderten Aufwandmengen eine vollständige Wirkung erreicht werden kann, 2) die Bedingungen zum Anwendungszeitpunkt, z. B. das Entwicklungsstadium der Unkräuter, die Entwicklung der Kultur und die Witterung für die Herbizidwirkung günstig sind und daher verringerte Aufwandmengen erlauben, oder 3) weil angenommen werden kann, dass die Verunkrautung keine signifikante Auswirkung auf den Ertrag haben wird.
"Crop Protection Online-Weed" (CPO-Weed) ist ein Internet-basiertes Beratungs-System, das dem Landwirt bei der Auswahl des Herbizids und der Aufwandmenge helfen soll. CPO-Weed wird aufgrund der Informationen über den Entwicklungsstand der Kulturpflanzen und der Zusammensetzung der Verunkrautung dem Landwirt eine Liste von Herbiziden, oft reduzierten Aufwand empfehlend, liefern. Das Potential von CPO-Weed hinsichtlich reduzierten Herbizidaufwands ist in zahlreichen Wirksamkeitsversuchen nachgewiesen worden. In letzter Zeit ist die Anwendung reduzierter Herbizidmengen mit den zunehmenden Fällen von Resistenz bei zum Outbreeding neigenden Unkrautarten wie *Alopecurus myosuroides* und *Lolium* ssp. in Verbindung gebracht worden. Die Hypothese ist, dass die am wenigsten empfindlichen Individuen der Population den reduzierten Herbizidaufwand überleben und allmählig das Resistenzniveau der Unkrautpopulation ansteigen lassen. Dieses Scenario trifft nur zu, wenn eine verringerte Herbizidmenge eine geringere Wirkung erzielt, aber nicht, wenn die hohe Empfindlichkeit einer vorkommenden Unkrautart oder optimale

Anwendungsbedingungen die Herabsetzung des Herbizidaufwands begründeten. Das ist ein Gesichtspunkt, der in der laufenden Diskussion über reduzierten Herbizidaufwand und Resistenz oft übersehen wird. Große Unkrautpopulationen erhöhen die Gefahr, resistente Biotypen zu selektieren, denn die Wahrscheinlichkeit des Vorkommens resistenter Pflanzen wächst mit der Populationsgröße. Die Entwicklung starker Verunkrautung zu verhindern ist ein Hauptanliegen des Integrierten Pflanzenschutzes (IPS). Wenn die Anwendung von Herbiziden mit nichtchemischen Methoden der Unkrautbekämpfung kombiniert wird, kann die Resistenz-Gefahr weiter herabgesetzt werden, d. h., im Rahmen des IPS ist es weniger wahrscheinlich, dass reduzierte Herbizid-Aufwandmengen Herbizidresistenz fördern, auch wenn dabei geringere Wirkungen hingenommen werden.

Stichwörter: Crop Protection Online, Dosis-Wirkungskurve, Herbizidaufwand, Herbizidresistenz, Integrierter Pflanzenschutz, IPS

Introduction

In 1986 the first pesticide action plan, calling for a 50% reduction in pesticide use expressed as the Treatment Frequency Index (TFI), was passed by the Danish Parliament. Denmark was the first EU country to adopt a pesticide action plan but soon after followed by The Netherlands and Sweden. The pesticide action plan of 1986 was the first of in total four action plans all with the aim of reducing pesticide use. Recently a fifth pesticide action plan was launch entitled "*Protect Water, Environment and Health*" in which the overall objective has been redefined, in accordance with EU Directive 2009/128, in order to reduce adverse effects on health and environment rather than the pesticide use *per se*. As a result the TFI has been replaced by a new indicator, the Pesticide Load Indicator (PLI).

In practice pesticide use can be reduced either by 1) replacing pesticides by non-chemical control measures, 2) reducing the number of applications, or 3) reducing the pesticide rate. The majority of the conventional farmers are not prepared for complete giving up the use of herbicides and run the risk of yield losses and seed shedding that could lead to a build-up of the soil seed bank. Thus, farmers have so far mainly made use of the last option namely reducing the rates. As a result the herbicide rates applied by Danish farmers are typically lower than the label recommendations. The widespread use of reduced rates has been supported by research and demonstration trials involving research institutes and the farmers' union advisory service. Research has focused on adjusting herbicide rates to the prevailing conditions, i.e. herbicide rates are optimized rather than just reduced.

The interest in reduced herbicide rates was stimulated by the pesticide action plans but actually the interest of Danish farmers in reduced herbicide rates date back to the 1970's. Herbicide trials in spring barley revealed that effective weed control could often be achieved with 25 to 50% of the label recommendation. Back then only few farmers adopted the concept of reduced rates but this changed significantly during the 1980's.

This paper will firstly discuss herbicide rates and variability in herbicide performance. Hereafter the parameters to be considered when optimizing herbicide use will be outlined. Finally the paper will focus on optimized herbicide rates in the context of integrated pest management (IPM).

Herbicide rate and variability in performance

Studying results from herbicide experiments it is obvious that variability in performance is inversely correlated to efficacy, i.e. the lower the efficacy the more variable the effect. In contrast, variability in performance is not always correlated to herbicide rate as rate and efficacy are not necessarily correlated. This can be easily understood by looking at the shape of a dose response curve (Fig. 1). The example in Figure 1 is generated using the widely adopted log-logistic dose response (Ritz, 2010). Due to the asymptotic properties, an increase or decrease in herbicide rate at very high or very low rates will only have a marginal effect on efficacy and variability. In contrast, on the linear part of the dose response curve even small changes in herbicide rate will have a pronounced effect on herbicide performance and consequently variability will be higher. The

example illustrates clearly that there exists no unequivocal relationship between reduction in herbicide rate and reduction in herbicide efficacy.

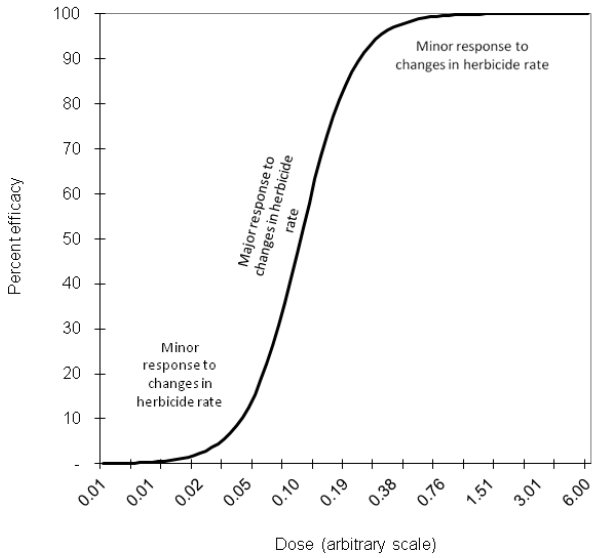

Fig. 1 A schematic dose-response curve.

Abb.1 *Eine schematische Dosis-Wirkungskurve.*

In practice it means that as long as the farmer is aiming at a high efficacy to reduce the rate this may not have any influence on variability in performance. On the contrary, if farmers are aiming at an efficacy lower than e.g. 85% variability becomes an issue and detailed knowledge about the influence of the variable parameters influencing herbicide performance becomes crucial. In the following section the most important parameters will be listed and their potential impact on herbicide performance will be shortly described.

Biotic and abiotic parameters influencing herbicide performance

Weed flora and growth stage

In contrast to disease and pest management, where often only one species is targeted at a time, in weed management one is nearly always targeting a population of species. Some weed species are more abundant than others and the lack of diversity in crop rotations in many fields has led to weed floras dominated by a few weed species but even in those fields more than just the dominating weed species will be present. It is well documented that the susceptibility of weed species to the herbicides varies profoundly. KUDSK (2002) reported that while application of 1/16 to 1/1 of the recommended rate of chlorsulfuron resulted in effects ranging from 38 to 96% on *Polygonum aviculare* L. the same rates produced effects ranging from 98 to 100% on *Veronica persica* L. A look at the dose-response data in the web-based decision support system "Crop Protection Online-Weed" (CPO-Weed), generated on basis of data from the official efficacy trials and data provided by the agrochemical companies, showed that 11 out of 56 weed species were controlled at 90% or higher with 50% of the maximum registered rate of tribenuron (KUDSK, 2014). For flurasulam the corresponding figures were 12 out of 38. Since weed management implies control of a population of species with different susceptibility to herbicides, it is basically not

consistent with the term "minimum effective dose" as it is known from herbicide efficacy evaluations. Typically the "minimum effective dose" is the minimum herbicide rate required to control the least susceptible weed species but this rate is often significantly higher than the rate required to control the more susceptible weed species, as illustrated by the above-mentioned data.

From both a crop yield loss perspective as well as a long-term weed management perspective, different levels of control of the weed species in the field are required. Besides the potential of a weed species to multiply and increase its abundance in the field, long-term management aspects should also consider the risk of selecting for herbicide resistant biotypes.

Another parameter to consider is the growth stage of the weeds at the time of herbicide application. For residual herbicides the window of application is often very narrow whereas it may be very wide for foliage-applied herbicides. The susceptibility of annual weeds, however, tend to decrease with increasing growth stage with non-systemic foliage-applied herbicides (contact herbicides) being more affected by growth stage than systemic foliage-applied herbicides (KUDSK, 2014). Exceptions from this rule of thumb do exist. POWELL *et al.* (2002) found that the susceptibility of two grass weed species *Alopecurus* myosuroides and *Lolium perenne* was higher when the plants had developed 2 to 4 leaves compared to the 1-leaf stage. The erect growth habit of grass weeds at the young growth stages may explain this deviation from the general rule.

Crop competition

The competitive ability of the crop can be increased e.g. by selecting competitive cultivars or by increasing crop density. In a competitive crop total weed biomass is lower than in a less competitive crop. In practice this means that a lower effect is required to reduce weed biomass below the threshold level causing yield reduction allowing for the use of reduced herbicide rates. Whether weeds exposed to a competitive crop are inherently more susceptible to herbicides remains unknown.

Soil type

Soil texture and not at least soil organic matter content can have a significant effect on the efficacy of residual herbicides (PEDERSEN *et al.,* 1995). Attempts to correlate herbicide performance to soil properties and adjusting herbicide rates to soil type have generally been unsuccessful probably because other parameters and most notable soil moisture will also influence the herbicide performance. Another aspect to consider is that although a reduced herbicide rate applied to a soil with a low content of organic matter may result in the same effect on emerging weeds as a higher rate applied to a soil with a high content of organic content, the residual effect will be lower which could lead to a lower overall effect later in the growing season. Thus in practice it is very difficult to include soil type considering in what would be the appropriate herbicide rate.

Climatic conditions

Weather conditions before, during and after application have been shown to affect herbicide performance (e.g. KUDSK, 2001). Light, temperature and air humidity are the climatic parameters to consider deciding on the herbicide rate.

Although light conditions do affect the activity of some herbicides it is a parameter that is difficult to take into account when deciding on herbicide rate because light conditions can play a role both prior to application (e.g. on cuticle development), at the time of application (e.g. on photosynthesis) and after application (e.g. assimilate production and translocation). The same is true for temperature but as temperature does have a direct effect on the passive diffusion of herbicides across the cuticle (e.g. BAUR *et al.*, 1997) effects of temperature at the time of application are often more profound than those of light conditions. Impact of temperature on herbicide performance varies between herbicides with bentazone being an example of a herbicide benefitting from high temperatures around the time of application while the sulfonylurea herbicides are generally less affected by temperature (KUDSK, 2001).

High air humidity promotes the uptake of hydrophilic herbicides like glyphosate and salt formulations of phenoxy alkanoic acid herbicides, while the activity of more lipophilic herbicides is generally unaffected by air humidity. In practice a better effect can be achieved if hydrophilic herbicides are applied during periods with high humidity like in the early morning.

Other parameters

Besides weed flora, growth stage of weeds and climatic conditions application technique, adjuvants and mixture with other pesticides may also influence the performance of a herbicide but the effects of these parameters are often herbicide specific and it is beyond the scope of this paper to discuss their influence on herbicide performance.

"Crop Protection Online" – a web-based decision support system compiling the available knowledge on herbicide performance

As a follow-up on the first pesticide action plan it was decided to initiate the development of a computer assisted decision support system that nowadays has become the web-based "Crop Protection Online" (RYDAHL, 1995). "Crop Protection Online" consists of two modules, one for weed management and one for disease and pest management. The two modules have evolved very differently since they were launched and in this presentation only the weed management module "Crop Protection Online-Weed" (CPO-Weed) will be covered.

CPO-Weed works as a three step model (RYDAHL, 2004). Firstly, the need for weed control is assessed based on evaluation of the economic impact of each of the weed species recorded in the field. In winter cereals, for example, competitive weed species like *Alopecurus myosuroides* and *Galium aparine* will be controlled irrespectively of their density while less competitive species such as *Veronica spp*. will only be controlled beyond a certain density. This part of CPO-Weed is based solely on expert knowledge and can be easily changed if new data suggest so.

Secondly, the level of control required is determined for each weed species. It depends on the weed species and its density. Competitive weed species will be controlled more effectively than less competitive species and the higher the density the higher the targeted level of control. The target levels of control are also largely based on expert knowledge and like the first step in CPO-Weed the values can easily be adjusted.

Finally the appropriate herbicide and herbicide rate is determined. This is possible because CPO-Weed contains information on the dose response curves of all registered herbicides on a wide range of weed species. The dose response curves were generated based on the data from official efficacy evaluation trials as well as data provided by the registration holders. The shape of the dose response curve is determined by the mode of action of the herbicide while the location on the x-axis (the dose axis) is determined by the weed species. Furthermore the dose-response curves are adjusted according to weed growth stage, weather conditions and crop cultivar. In CPO-Weed these adjustments are implemented as parallel displacements of the dose response curves.

CPO-Weed provides solutions not only for individual herbicides but also for herbicide mixtures. The composition of herbicide mixtures is calculated using the underlying principles of the Additive Dose Model (KUDSK, 1999). The composition of herbicide mixtures can be optimized according to either costs or TFI. In the future herbicide mixtures can also be optimized according to the new PLI. All potential herbicide solutions are listed and can be sorted according to either costs or TFI and in the future also to the PLI.

In summary, if CPO-Weed suggests the use of reduced herbicide rates it could be due to a high susceptibility of the weed species in the field, optimum conditions for applying the herbicide and/or a low target control level. For competitive weeds herbicide rate is primarily determined by the susceptibility of the weed species and the conditions at the time of application while susceptibility, conditions around application and a lower control level may explain low herbicide rates against less competitive weed species.

Field test of CPO-Weed have revealed a significant potential for reducing herbicide use compared to the current practice (JØRGENSEN and KUDSK, 2006). For more information on CPO-Weed see RYDAHL (2004) and SØNDERSKOV *et al.* (2013).

Potential long-term implications of reduced herbicide rates

Historically the dispute on reduced herbicide rates have centred on yield losses, problems at harvest and the risk of seed shedding from surviving weed plants and a gradual build-up of the soil seed bank. Recently, the discussion on reduced herbicide rates has focused more on the propensity of reduced herbicide rates to increase the rate of selection of resistant biotypes (e.g. NEVE and POWLES, 2005; RENTON *et al.*, 2011). High herbicide rates will select for major gene resistance (target site resistance) while low herbicide rates are assumed to select for quantitative inherited resistance mechanisms (minor gene resistance or non-target site resistance), a situation that has been described as a "*Catch 22*" by GRESSEL (1995). Enhanced metabolism, as it has been observed in several outcrossing grass weed species, is an example of what is believed to be a quantitative inherited non-target site resistance mechanism that could be promoted by the use of low herbicide rates. There is, however, still some controversy about the role of reduced rates in promoting non-target site resistance to herbicides as none of the studies has directly compared high and low rate selection in the field (NEVE *et al.,* 2014).

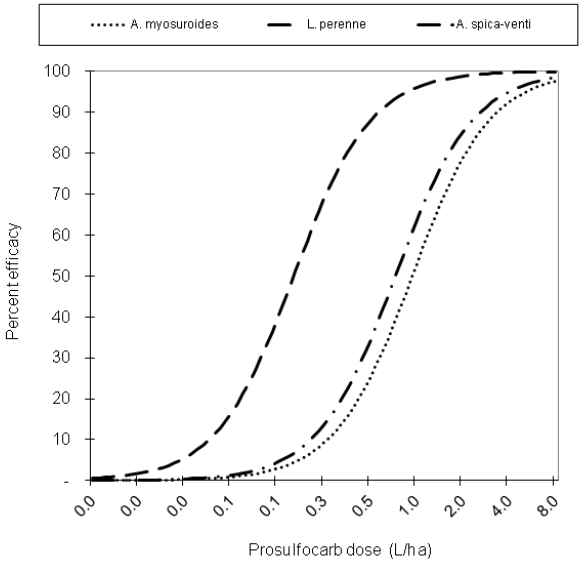

Fig. 2 Dose response curves from CPO-Weed for prosulfocarb on three grass weed species at the 0-2 leaf stage, minimum and maximum temperatures of 8 and 14 ^{0}C and no soil moisture stress.

Abb. 2 *Dosis-Wirkungskurven nach CPO-Weed von Prosulfocarb für 3 Ungrasarten im 0- bis 2-Blatt-Stadium; Minimum- und Maximum-Temperatur 8 bzw. 14 °C und ohne Einfluss der Bodenfeuchte.*

In the on-going discussion reduced herbicide rates are often considered to be synonymous with a reduced or sub-lethal effect. As highlighted in this article this is far from always the case because weed species differ markedly in their susceptibility to herbicides. Grass weed species like *A. myosuroides*, *Apera spica-venti* and *Lolium spp.* are very competitive weed species that require a high level of control to prevent yield losses. If reduced herbicide rates are recommended by CPO-Weed the cause is a high susceptibility to the herbicide, as it is illustrated in Figure 2. The reduced prosulfocarb rates that farmers are recommended to use against *A. spica-venti* are the result of the

high susceptibility of this weed species to prosulfocarb and not the acceptance of a low efficacy level. In contrast, the reduced herbicide rates recommended against many poorly competitive broadleaved weed species are often partly due to an acceptance among Danish farmers of a lower efficacy. Until now only one example of quantitative inherited resistance mechanisms has been reported in broadleaved weed species, thus the risk that reduced rates of herbicides will select for non-target site resistant biotypes of broadleaved weed species seems minor.

Integrated pest management and reduced herbicide rates

In 2011 EU Directive 2009/128/EC came into force. One of the objectives of the directive is to ensure the adoption of IPM by all professional users of pesticides by January 1, 2014, and to support this conversion eight IPM principles have been listed in the directive.

The most important of the eight IPM principles is #1 requiring farmers to prevent the build-up of large pest populations, e.g. by adopting a diverse crop rotation and implementing cultivation techniques that minimize problems with weeds and other crop pests. A diverse weed flora and a low weed density will allow for lower control levels and hence the use of reduced herbicide rates because higher survival rates can be tolerated compared to fields with high weed densities. Preventing the build-up of large weed populations is also one of the main tools to prevent resistance building up. Herbicides do not cause the mutations conferring resistance, their use merely favours the propagation of resistant plants in the population. As resistant plants are present at very low frequencies the chance that a resistant plant can be found altogether in a field depends very much on the weed density. The risk of herbicide resistance is therefore very much a numbers game and if the farmers keep the weed numbers low, as it is the intention with IPM, the risk that reduced herbicide rates will promote resistance will also be lower. As a matter of fact IPM principle #6 states that "*the professional user should keep the use of pesticides and other form of intervention to levels that are necessary, e.g. by reduced doses, reduced application frequency and partial applications, considering that the level of risk in vegetation is acceptable and they do not increase the risk of development of resistance in populations of harmful organisms*", i.e. reduced rates are actually seen as one of the many IPM tools that farmers should adopt, which makes sense because of the lower risk for promoting resistance than in many of the current cropping systems. Further adding to a reduced risk of herbicide resistance in an IPM scenario is that herbicide use should be combined with non-chemical control measures.

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