ABSTRACT

In the present study, the influence of soil properties on pre-emergence herbicide effectiveness was estimated in bioassays. Dose-response experiments were carried out to estimate the relationship between soil organic matter content and herbicide efficacy. Two weed species (Alopecurus myosuroides and Stellaria media) and two herbicides (pendimethalin, chlorotoluron) were included in the experiments. In bioassay trials on soil with varying organic matter content, dose-response curves were estimated for pendimethalin and chlorotoluron. Effective dose ($ED_{50}$) values were calculated. The experiments were conducted in a climate chamber under defined conditions. The results demonstrate that the efficacy of soil-applied herbicides is related to the soil organic matter content within agricultural fields. Therefore precise usage with variable herbicide application rates can be part of a precision farming concept. A reduction in herbicide is possible.

Keywords: Bioassay; chlorotoluron; dose response; herbicide efficacy; pendimethalin; weed.

1. INTRODUCTION

Herbicides are used in weed control worldwide in crop production on a large scale to prevent a reduction in yield. In that regard, soil-applied herbicides are still an important component in weed control concepts. Soil-applied pre-
emergence herbicides are used to control germinating weeds in many crops. They are normally sprayed uniformly on the entire field. In general, the recommended dose rates are based on efficacy and dose justification trials. These recommendations are based on worst-case situations and do not take into account specific field situations like spatial soil (e.g. varying soil organic matter within fields) and weed variability.

Each herbicide has a unique set of chemical characteristics that influences its behaviour. The interaction between herbicide chemistry and soil properties affects the efficacy of herbicide weed control. Research has shown that soil characteristics (e.g. soil organic matter, pH) clearly influence bioavailability, plant uptake and herbicidal efficacy [1,2]. Also, the uneven occurrence of weeds can be correlated with soil characteristics [3].

Depending on their physical/chemical properties soil-applied herbicides are adsorbed more or less by the clay and organic matter (OM) found in soils, meaning that a certain percentage of the herbicide is not available to the plants. Adsorption of herbicides in soil is a key factor for soil bioavailability, plant uptake and efficacy. Herbicide adsorption varies with soil organic matter and other soil characteristics (e.g. clay content, mineral oxides, soil pH, soil water content). The important factor for the adsorption and bioavailability of most herbicides is the soil organic matter content [4-6]. This was investigated and confirmed in field trials [7]. In Germany, the organic matter content in agricultural soils was found to range from 1 to 15%. Clay content and other soil factors were often less correlated. Herbicide adsorption was described dependent on clay content in Arizona soils [8]. But besides soil factors, also environmental factors (e.g. temperature, soil moisture) can influence herbicide activity. It must basically be stated that the efficacy of soil-applied herbicides depends on the application rate and their availability to weeds.

The interactions between soil organic matter and herbicides are often studied in the laboratory using batch-equilibrium experiments in combination with techniques that quantify the chemical and structural characteristics of organic matter and bioassay tests [9]. Greenhouse bioassays are a simple and sensitive tool to detect efficacy and phytotoxicity of herbicides [10-12]. Herbicide adsorption to soil can be described using soil/organic matter (Koc) and soil/soil solution coefficients (Kd). The Koc and Kd values are defined as the ratio between the amount of herbicide adsorbed and the amount in soil solution [13]. The soil organic matter and/or humic matter fraction is highly correlated with the adsorption of herbicides in soils. In literature soil organic matter is considered as the single most important soil constituent influencing herbicide sorption in soils. Pedersen et al. [9] showed the relationship between adsorption and the effective doses of five soil-applied herbicides. Gautier et al. [14] showed that the sorption of 2,4-D by soil was positively correlated with soil organic matter content. The objective of the study was to quantify the variability of soil properties and 2,4-D sorption. These results are supported by further sorption experiments.

Normally, according to label recommendations, herbicides are sprayed with a uniform application rate throughout the entire field. But each field has a natural variability in soil characteristics and weed occurrence [15-17]. Soil parameters are known to vary spatially. Therefore, herbicide application according to soil parameters is conceivable [18]. Nolte et al. [19] used variable rate technologies for soil-applied herbicides.

Depending on field history, fields vary in organic matter content and weed occurrence. This means that a full area application with a uniform application rate is not an appropriate application of herbicides. According to small-scale soil variability, differences in herbicide adsorption and the availability of herbicides to plants can be generally assumed. Blumhorst et al. [20] reported that, in most cases, the optimum rate of herbicide could be determined with a linear regression equation based on organic matter content. Knezevic et al. [21] reported different herbicide application rates depending on soil organic matter content. Soils with high organic matter content and a high adsorptive capacity need a higher herbicide application rate to ensure sufficient effectiveness.

In precision farming, variable rate technologies offer the possibility to spray herbicides according to field heterogeneity [22]. However, soil information is often not available. With global positioning system (GPS) technology and soil sensors [23], soil variability can be mapped precisely. Furthermore, spatially variable herbicide application according to weed distribution or varying soil properties offers the opportunity for herbicide minimisation and the protection of beneficial weeds. This is in
Two statistical analyses were conducted for normal distribution using the Kolmogorov-Smirnov test.
and subsequently tested using one-way ANOVA and the Duncan test for significant differences between treatments (p<0.05). Statistical analyses were performed in Statgraphics Centurion XV. Dose-response curves were conducted by the Excel macro BIOASSAY97 [24]. The effective dose (ED$_{10}$, ED$_{30}$, ED$_{50}$ and ED$_{90}$-values) was conducted using the statistical program R version 3.03.

3. RESULTS AND DISCUSSION

Efficacy of 4 application rates of pendimethalin can be seen in Fig. 2. The efficacy on Stellaria media is shown depending on soil organic matter content. In general, an increasing application rate up to 4 kg ai/ha shows an increasing efficacy against Stellaria media. All organic matter levels show an increasing efficacy with increasing application rates. At level 3.5%, OM efficacy increased from 10% at 0.5 kg ai/ha to 56% at the 4 kg ai/ha application rate. At level 2.5%, OM efficacy increased from 4% at 0.5 kg ai/ha to 74% at the 4 kg ai/ha application rate. At the lowest organic matter content (< 0.1%), all application rates show nearly the same efficacy (nearly 90%). It is characteristic that the efficacy is very low for dose rates of 0.5 and 1 kg ai/ha at OM levels 2.5, 3.0 and 3.5%. At lower OM levels, the efficacy increased significantly. Differences in efficacy between the tested dose rates are greater in the soils' organic matter content (see Fig. 2, for example, 4.3 and 0.43% OM).

Fig. 1. Agricultural field (2013) with different soil sampling points (64, 70, 73) varying in soil organic matter content (OM)

Fig. 2. Herbicidal effects of different concentrations of pendimethalin against Stellaria media in soils with varying organic matter content (n=4). Columns with different letters are significantly different. Vertical bars represent the standard deviation
Fig. 3 shows the efficacy of chlorotoluron against *Alopecurus myosuroides*, demonstrating efficacy in dependence on the soil organic matter content. Soil 70 (OM = 2.2%) already shows good weed control (>80%) with low doses (0.525 and 1.05 kg ai/ha). It results in an efficiency of up to 90%. Higher application rates do not result in greater efficacy. Soil 64 (OM = 3.5%) shows a slower increase in efficacy against *Alopecurus myosuroides* in comparison to soil 70. A maximum efficacy (82%) was reached with an application rate of 2.1 kg/ha. Efficacy was lower than in soil 70. It is obvious that soil organic matter content influences herbicide efficacy.

Fig. 4 shows fitted dose-response curves (21 days after application) of chlorotoluron applied to *Stellaria media*. Differences in curve progression are small. From the efficacy curves (Fig. 2 and 3) ED values were calculated (Table 1, Table 2). The ED$_{10}$, ED$_{30}$, ED$_{50}$ and ED$_{90}$ values show great differences between soil 70 and soil 64 (Table 1). The factor is about 3 to 5. The ED values for *Stellaria media* show only small differences between soil samples 73 and 64. For the farmer this means that he needs a higher herbicide dose rate at location 64 for effective weed control in comparison to location 70.
In this study the effect of soil organic matter on herbicide efficacy was determined. Soil-applied herbicides (pre-emergence or early post-emergence) can be a very important component in weed control. This is particularly applicable for the control of herbicide-resistant weeds. After spraying soil-applied herbicides, bioavailability in the soils depends on the herbicide properties, weather conditions and soil factors such as texture, moisture, pH and organic matter. For the efficacy assessment of soil-applied herbicides, it is important to know the different factors that affect their fate. The behaviour and plant uptake of pre-emergence herbicides is strongly influenced by soil properties. Herbicide adsorption varies with soil organic matter content. Soils with high organic matter content are more adsorptive. These soils may require higher rates. Many investigations have shown soil organic matter content varying between fields or within field [4-6].

The results demonstrate the relationship between soil organic matter and herbicide efficacy. The experiments confirm the results of other investigations demonstrating that soil organic matter is an important factor for herbicide adsorption. Knezevic et al. [22] used dose-response curves to determine the effective application rate that provides 90% weed control. Knezevic et al. [21] used an experimental herbicide KIH-485 as a model substance. The results from Pedersen et al. [9] indicate the possibility of adjusting the herbicide application rate according to soil factors. This can be an important part of integrated weed management, as pointed out by Swanton et al. [25].

The results show that variable rate application could be done in a precision farming concept within fields with varying organic matter content according to Fig. 1. This could be a good approach to reduce herbicide use and that will allow the reduction of costs at the same time. But to describe the relationship between soil organic matter and herbicide efficacy more investigations are necessary.

Under field conditions, there is a complex interaction of several soil factors affecting the bioavailability of herbicides. Some factors have a high temporal variability (e.g. soil moisture) whereas others have low variability (e.g. soil organic matter). Dry soil conditions will lead to low plant uptake even though we have low adsorption due to low organic matter content. This makes it difficult to find appropriate application rates based on soil organic matter. Other soil factors (e.g. soil texture, soil moisture, pH) and weather conditions at the time of application should be considered. The strong relationship between soil organic matter content and herbicide adsorption and effectiveness is only valid if all other factors are optimal. It is only in these conditions that using a herbicide application rate according to the organic matter content can be varied without a loss of efficacy.

However, this is only one step required for the precise usage of herbicides according to soil variability. In further investigations it will be necessary to clarify how to implement the results in agricultural practice and precision farming. Economic [26] and ecological benefits [27] of precision weed control are obvious. In economic analysis the potential of herbicide savings was shown [28,29]. Depending on crop, weed, soil, sowing date, soil cultivation and weather conditions, it is not possible to make any general statements. Therefore, in particular cases savings can range from 0 to 100%. A reduction in herbicide use reducing per se environmental risks. Therefore herbicide application based on soil organic matter can provide an essential contribution to use herbicides more targeted.

### 4. CONCLUSION

In a field varying in organic matter content, the use of herbicides can be reduced if herbicides are sprayed with the right amount in the right place. Herbicides must be sprayed as required

| Table 1. Effective dose of chlorotoluron applied to *Alopecurus myosuroides* – calculated ED values (dose rate) |
|--------------------------|--------------------------|
| Soil sample 70 (2.2% OM) | Soil sample 64 (3.5% OM) |
| ED<sub>10</sub> | 0.02 | 0.06 |
| ED<sub>30</sub> | 0.06 | 0.25 |
| ED<sub>50</sub> | 0.14 | 0.61 |
| ED<sub>80</sub> | 1.26 | 6.21 |

| Table 2. Effective dose of pendimethalin applied to *Stellaria media* – calculated ED values (dose rate) |
|--------------------------|--------------------------|
| Soil sample 73 (1.9% OM) | Soil sample 64 (3.5% OM) |
| ED<sub>10</sub> | 0.48 | 0.56 |
| ED<sub>30</sub> | 0.58 | 0.65 |
| ED<sub>50</sub> | 0.66 | 0.71 |
| ED<sub>80</sub> | 0.89 | 0.91 |
by the situation. Detailed information on soil heterogeneity at the field scale is required. In this case, the potential benefits of site-specific herbicide application are obvious. It leads to reduced exposure of herbicides to the environment, better weed control, reduced crop injury and lower costs. Furthermore, small-scale variation in herbicide application requires specific application techniques with high accuracy in spatial application. The hypothesis that in a field varying widely in organic matter, the use of herbicides can be adjusted to small-scale field differences was confirmed by the results. The results demonstrate that farmers can adjust the dose rate of soil applied herbicides. Economic and ecological benefits can be expected to soil organic matter without efficacy loss.

COMPETING INTERESTS

Author has declared that no competing interests exist.

REFERENCES

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