The influence of organic matter on the efficacy of soil-applied herbicides

Options for the use of low dosages

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Preface

This report is a result of my research conducted at the Agrosystems group of Plant Research International. I have worked with a lot of pleasure here for my MSc thesis. During my thesis, I learned a lot about how research is conducted in a research organization which combines academic research with the requests and problems the market is dealing with. It was very nice to see research being conducted that really led to solutions suitable for implementation in practical situations. This was and is for me an important motive to conduct research. It was nice to be part of the research team, and to see how the organization was built up. Although it was sometimes though to find a good solution to analyze the results, it was nice to see that the final result looks promising. It shows that environmental savings are possible while having the same herbicidal efficiency.

I would like to thank Corné Kempenaar for his day to day advice on the project, and for supervising me very well. I really appreciated that I was also able to see the diversity of the work conducted by Corné. I would like to thank Lammert Bastiaans for his supervision by helping me analyze the results and for safe-guarding the scientific quality of the work. I would like to thank André Uffing for his help in the application of the herbicides. I would like to thank the Unifarm employees for looking after the weed plants during the weekends. Finally, I would like to thank Marleen Riemens and Jacques Withagen for helping me to tackle the statistical analysis.

Summary

In the Netherlands, soil-applied herbicides are often used to conduct weed control in maize. Excessive usage of these herbicides can bring along risks for human health, environment, and risks of resistant weeds. Therefore, it is important to reduce herbicide use. Soil organic matter content influences herbicide performance, but is currently not used to determine herbicide dose recommendation rates in the Netherlands.

Experiments to reveal the quantitative relationship between soil organic matter content and herbicide efficacy were conducted using the herbicides Merlin (isoxaflutole), Frontier Optima (dimethenamid-P), and their mixture. This was done for three weed species (*Stellaria media*, *Senecio vulgaris* and *Digitaria ischaemum*). Dose-response experiments were conducted in a greenhouse, and fresh biomass was determined to indicate herbicide performance. For all herbicides that were tested, the relationship between herbicide efficacy and organic matter content was negative. However, the rate at which organic matter content influenced herbicide efficacy was different for the different herbicides and the different weed species. When *Senecio vulgaris* was controlled, the rate at which organic matter content influenced herbicide efficacy was always highest. Relationship between organic matter content and herbicide efficacy is linearly for all experiments, except for *Digitaria ischaemum*, treated by the mixture of Frontier Optima and Merlin. Furthermore, *Senecio vulgaris* could not be controlled by Frontier Optima at high organic matter contents without exceeding the maximum allowed dose. *Digitaria ischaemum* was controlled very efficiently by Frontier Optima, Merlin, and the mixture of Frontier Optima and Merlin.

The experiments resulted in formulas describing dose advices based on soil organic matter content. This was done by formulation of the dose at which 90% of the weeds are controlled (ED_{90}). This was done for all tested herbicides:

ED_{90} *Merlin = 1.30 X % O.M. + 13.7 (gram* ha^{-1}*)*

ED_{90} *Frontier Optima = 0.105 X % O.M. + 0.08 (l* ha^{-1}*)*

ED_{90} *mixture Merlin and Frontier Optima*

Merlin = 1.08 X % O.M. + 26.56 (gram ha^{-1}*)*

Frontier Optima = 0.011 X % O.M. + 0.27 (l ha^{-1}*)*

Determining herbicide dose advices based on soil organic matter content is however just one step required for practical implementation of a herbicide dose advise system, based on soil organic matter content. Another necessary step for implementation is the availability of maps containing detailed information regarding organic matter content. These best can be developed using on-the-go soil sensors, such as sensors measuring reflectance, electrical conductivity or gamma radiation. The development of these kind of sensors is still in its infancy. More decision rules regarding the effect of (soil) factors on herbicide performance have to be develop to enable wide adaptation by farmers. Furthermore, technical solutions have to be developed to be able to conduct weed control at a high

resolution. This has to be done to bring the right amount of herbicide to the right place. Since high resolution soil maps, and spraying devices to apply herbicides at high resolution are still in development, it might be worth adjusting herbicide rates at field level in fields containing low organic matter content to the average organic matter content. This might already save much herbicides, and is more easy to implement compared to adjusting herbicide rates within field level based on organic matter content .

Finally, an example is showed to get an idea of the potential environmental- and economic savings of tailor-made soil-applied herbicide dose recommendations, based on soil organic matter content. This shows that in a field varying largely in organic matter content use of herbicides can be reduced by 73%. Furthermore, environmental pressure is reduced when adjusting dose advices to organic matter contents. Also considerable savings in herbicide costs can be realized due to the lower herbicide input.

1. Introduction

1.1 General introduction

Due to developments in cultivation technology, mechanization, increased input levels and plant breeding, crop productivity in Europe has improved drastically during the last 45 years. In the Netherlands, for example, average potato yields increased from 28 t ha^{-1} to 42 t ha^{-1}, sugar beet yields increased from 45 t ha^{-1} to 65 t ha^{-1} and wheat yields increased from 3.9 t ha^{-1} to 8.5 t ha^{-1} (FAOSTAT data, 2006). This large increase in productivity is partially the result of the use of a wide range of chemical pesticides to reduce yield losses due to e.g. fungal diseases, insects and weed competition. In the European Union, the total amount of active ingredient from pesticides sold between 1995 and 2001 grew from 1995 until 1998 to a level of $3.6*10^5$ tons. From 1999 on, the amount reduced to $3.3*10^5$ tons of active ingredient in 2001 (Eurostat, 2001). In 2001, about 34% of these pesticides were herbicides ($1.1*10^5$ tons active ingredient). In the Netherlands, in 2005, this fraction was about 27% (on a total of $9.3*10^3$ ton active ingredient for all pesticides).

Pesticides are often not only harmful to the target organism, but might also have negative consequences for the environment and for human health. According to Olson *et al.* (1991), in Minnesota in 1988, pesticides led to 2209 cases of poisoning that were reported in regional poison control centers. Of these cases, 1428 were analyzed and in this group 12% of the cases were identified as poisoning resulting from herbicide contact. Of the 1428 analyzed cases occupational related exposure made up 4 %. However, the nature of 95 % of the analyzed cases was general (not otherwise specified). Another example of negative side effects from the use of herbicides was described by Haynes *et al.* (2000). The herbicide diuron, applied near the shore of Queensland, Australia, had negative effects on different seagrasses. Additionally, it also affected different corals negatively.

Next to the risks for environment and human health, the excessive use of herbicides also brings about risks of resistance. This happened for example after frequent application of the phenyl-urea chlorotoluron for the control of black-grass (*Alopecurus myosuroides* Huds.) in Germany, England and the Netherlands (van Oorschot and van Leeuwen, 1992). Resistance in the Netherlands showed up in a population of black-grass on a place where winter wheat was grown continuously since 1978, and where chlorotoluron had been applied yearly (Smant, 1991). Tranel and Wright (2002) described the case that more and more weed populations appeared to be resistant to ALS-inhibiting herbicides. In 2002, 70 weed species were known to be resistant to this type of herbicides. The resistance mostly was the result of the reliance on ALS-inhibiting herbicides to control weeds. Also the high efficacy of ALS-inhibiting herbicides and the soil residual activity of this type of herbicides led to a very high selection pressure, resulting in the increasing number of resistant weed species against ALS-inhibiting herbicides.

Because of all these negative effects of pesticides, the European Commission (EC commission, 2002) made a thematic strategy on the use of pesticides. This strategy consists of the following five major points:

- To minimize the hazards and risks to health and environment from the use of pesticides;

- To improve the control on the use and distribution of pesticides;
- To reduce the levels of harmful active substances, in particular by replacing the most dangerous by safer (including non-chemical) alternatives;
- To encourage the use of low-input or pesticide-free crop farming;
- To establish a transparent system for reporting and monitoring the progress in achieving the objectives of the strategy, including the development of appropriate indicators for this development.

Furthermore, every herbicide application adds to the costs made by farmers. The possibility to reduce herbicide use without reducing the weed control level results in more cost effective weed management.

Because of the above mentioned environmental, agronomic, political and financial considerations, it is very important to look for methods to reduce the amount of pesticides used in European agriculture.

1.2 Precision usage of herbicides

Herbicide manufacturers label their products with dose recommendations for adequate weed control. Since the agrochemical companies want to prevent being held liable by farmers when control is not satisfactory, they tend to advise dose recommendations based on worst case scenario. Under optimal conditions often a lower dose would satisfy. In some European countries this is widely adopted by farmers, both due to environmental concern and due to the cost pressure that many farmers are facing (Kudsk and Streibig, 2003). To help farmers optimize their herbicide dose a three step procedure should be followed. First preventive measures that reduce the requirement for chemical weed control should be implemented (like crop rotation and cultural practices). After doing this, during the actual growth of the crop, it is important to assess exactly the need to control the weeds. After this, in the third step, the specific herbicide (type) as well as the appropriate dose have to be determined.

According to Swanton *et al.* (2008) integrated weed management (IWM) is an important method that can be used to reduce herbicide usage. IWM is a series of interactions among several weed control components and takes agronomic, social, economic and environmental issues into account. It relies on essential knowledge for its implementation and focuses on crop health. A way to help growers accepting the IWM methodology is supporting them with Decision Support Systems (DSS). These systems should advice farmers about when to perform a herbicide application, what kind of herbicide to use and in what quantity. The DSS therefore should be predictive in stead of descriptive. The systems should be simple in use, although all complexities of IWM should be integrated in it. Communication with, and demonstrations for farmers is very important to take away the present hesitations.

In the Netherlands, the Minimal Lethal Herbicide Dose (MLHD) method was introduced in 1997. This method translated physiological knowledge of photosynthesis inhibiting (PI) herbicides into a minimum dosing method for these herbicides (Kempenaar and Lotz, 2004). This is combined with herbicide efficacy measurements, to be able to know, even before visible by human eye, if a herbicide application will ultimately lead to the result that was wanted.

The MLHD method is a very suitable method to reduce the used dosage of PI herbicides without affecting the efficacy of the herbicidal treatment. To implement precision usage of herbicides in other classes of herbicides, the factors that determine the efficacy of these herbicides have to be revealed. Once these factors have been identified, estimations can be made about what minimal herbicidal dose is required to obtain accurate weed control. For soil-applied herbicides, several soil characteristics are influencing herbicidal efficacy (Weber *et al.*, 1974; Peter and Weber, 1985 and Weber *et al.*, 1987).

1.3 Effect soil characteristics on herbicide performance

A lot of investigations have been done on the effect of soil characteristics on bioactivity and performance of soil-applied herbicides. These investigations show that performance of herbicides is inversely related to the organic matter content of soil (Weber *et al.*, 1974), inversely related to soil clay mineral content (Peter and Weber, 1985) and related to soil pH (Lowder and Weber, 1982). Herbicide performance is also inversely related to humic matter content (Weber *et al.*, 1987). All above proves that soil characteristics influence herbicide performance. Despite this influence, little is done to inform herbicide users on these effects. Recommended soil herbicide rate is often generalized and not specified according to one or more soil characteristics. For instance for the soil herbicide Frontier Optima (*dimethenamid-P*), there is, at least in the Netherlands, no adjustment in dose advice according to soil characteristics. In Australia and California recommended rates for *dimethanamid-P* are specified per soil type, what indicates that *dimethenamid-P* responds differently in different soil types (APVMA, 2007, CDPR, 2007). Because of the known high toxicity of *dimethenamid-P* to water life, it is important to reduce the use of this herbicide when possible. For other soil-applied herbicides used in maize like Merlin (*isoxaflutole*), Stomp (*pendimethalin*) and herbicides based on *terbuthylazine* (Gardoprim, Laddok), there is no specific dose advise based on soil properties.

1.4 Implementation of soil parameters for herbicide rate recommendation

Although research has shown that soil characteristics are clearly influencing herbicide performance, for quite a number of soil herbicides rate recommendations are not specified for different soil characteristics. Currently soil characteristics are usually not taken into account when farmers decide what dose to apply. When using soil characteristics as a guide for rate recommendations, a decision has to be made at what scale this should be done. To determine organic matter content at field level and adjust the herbicide dose accordingly for each field would already be a big change compared to current practice. But soil-applied herbicide use can even be reduced more when within-field variability is taken into account. However, to realize this, cheap and solid methods for determination of the relevant soil characteristics need to be available. Technically, it is possible to vary within-field doses of herbicides. For this a prototype sprayer has been developed at the PPO test-farm in Lelystad, the

Netherlands. This sprayer has a 27 meter wide spraying boom which is divided in seven sections. The dose applied in each section can be varied within parts of a second. With this, the accuracy of the device is about 10 m^2. If this device gets input about desired herbicide doses in the order of 10 m^2, it can spray these doses on the right place with the help of GPS.

To implement soil parameters in herbicide rate recommendations, farmers should have a good insight in the spatial variability of soil characteristics within their field. According to a study done by Lokers and de Jong (2008), there is currently not enough data available on a small scale (order of 10 m^2) about soil parameters, like organic matter, CEC and clay percentage. To make use of the (possible) lower dose rate recommendations in combination with the technical options of very accurate spraying, it is important to look for a way to map the soil characteristics in an economically feasible way. As is the case with a lot of innovation, after being able to implement this, it is still uncertain whether benefits (lower herbicide use) would be worth the investments that have to be made.

1.5 Research aims

The most important aim of this project was to quantify the relation between soil organic matter level and the efficacy of soil-applied herbicides. This was done by experiments in a greenhouse. The other aim of this project was to describe the current status of some of the other necessary steps for implementation of a dose-advise system which is based on organic matter content. Therefore an overview of techniques to determine organic matter content is provided. Furthermore status of techniques for applying herbicides at high resolution is presented. The final aim was to provide an example of the possible benefits of a organic matter content-based herbicide dosage system. The latter aims were reached by conducting a literature review.

2. Materials and methods

2.1 Experimental set-up

In a section of the Unifarm greenhouses in Wageningen (the Netherlands, 52º north latitude), experiments were conducted to determine the effect of soil organic matter content on the performance of soil-applied herbicides. The soil-applied herbicides that were tested were Frontier Optima (*dimethenamid-P*), Merlin (*isoxaflutole*) and a mixture of Frontier Optima and Merlin. The biochemical target of isoxaflutole is 4-hydroxyphenylpyruvate dioxygenase (HPPD). Inhibition of HPPD results in a depletion of plastoquinone. This is a co-factor of phytoene desaturase, which results in a depletion of carotenoids and an absence of chloroplast development in emerging foliar tissues. Therefore susceptible species show a characteristic bleaching. (Pallett *et al.*, 2001). Dimethenamid-P interferes with normal cell development. It inhibits cell division, resulting in ultimate death of the weed. Dimethenamid-p is absorbed by the coleoptiles of grasses when the germinating plant emerges. It is also absorbed by the roots of the weeds. The efficacy of these soil-applied herbicides was tested on three weed species, namely common groundsel (*Senecio vulgaris* L.), common chickweed (*Stellaria media* L.) and smooth finger-grass (*Digitaria ischaemum* (Schreb.) Mühlenb.). Each combination of weed species x herbicide was treated as a separate experiment.

The purpose of the experiments was to quantify the effect of soil organic matter content on herbicide efficacy. For this, the performance of the above-mentioned herbicides was tested on six soil mixtures, containing organic matter contents of 1%, 6%, 11%, 16%, 21% and 26%. Testing was done by applying six herbicide-doses to the weed species on each of the six soil mixtures. Doses that were applied are shown in table 2.1 and 2.2. The set-up of the experiments is shown schematically in figure 2.1. There were four replications within each experiment (herbicide x weed species combination). Within each replication the different herbicide doses and different soils were completely randomized. To obtain more accurate estimates, all experiments were replicated twice in time.

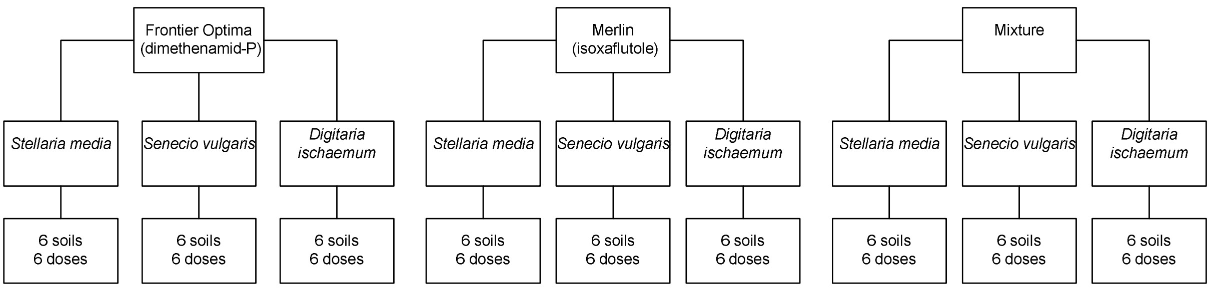

Fig. 2.1 Set-up of experiments conducted to quantify the effect of organic matter on herbicide efficacy. Soil mixtures contained 1%, 6%, 11%, 16%, 21% and 26% organic matter. Herbicide dose contained 6 levels, which are shown in table 2.1 and table 2.2.

Table 2.1 Herbicide doses for first experiments. Doses were similar for all weed species.

Merlin (gha^{-1})	0	5	25	70	100	133
Frontier Optima (lha^{-1})	0	0.05	0.25	0.7	1.0	1.4
Merlin (gha^{-1})+Frontier Optima (lha^{-1})	0 + 0	2.5+0.025	12.5+0.125	35+0.35	50+0.5	66.5+0.7

As mentioned above, experiments were duplicated in time. For the second experiments, the herbicide dose range was adjusted, as presented in table 2.2. Adjustments of applied doses were a result of the generated results of the first experiments, and aimed at obtaining a better distribution of the plant responses to herbicide application.

Table 2.2 Herbicide doses for replication experiments.

Merlin (gha^{-1})	Se[1], St	0	1	2.5	5	25	70
	Di	0	0.5	1	2.5	10	25
Frontier Optima (lha^{-1})	Se, St	0	0.05	0.25	0.7	1.0	1.4
	Di	0	0.01	0.025	0.05	0.125	0.7
Merlin (gha^{-1})+Frontier Optima (lha^{-1})	Se, St	0+0	2.5+0.025	12.5+0.125	35+0.35	50+0.5	66.5+0.7
	Di	0+0	1.25+0.0125	2.5+0.025	12.5+0.125	35+0.35	50+0.5

[1]Se = *Senecio vulgaris*, St= *Stellaria media*, Di= Digitarium ischaemum

The experimental unit was a 0.5 l plastic pot in which weeds were grown. Each replication within an experiment (herbicide x weed species combination) consisted of 6 doses x 6 soils = 36 experimental units. Each experiment consisted of 4 replications, resulting in 4 x 36 = 144 experimental units.

Soils were created by mixing the soil from the applied research station in Valthermond (*province of Drenthe, the Netherlands*) (peaty sandy soil containing 26% of organic matter) with soil from a farmers field in America (*province of Limburg, the Netherlands*) (sandy soil containing 1% of organic matter). Weed seeds were ordered from Herbiseed (*www.herbiseed.com*) and herbicides were obtained from Unifarm, the firm that owns the experimental fields for applied research in Wageningen.

2.2 Procedures

Soil containing a high amount of organic matter was mixed with soil containing a low amount of organic matter in different ratios, to create a variety of soil mixtures, with a range of organic matter contents. The mixing was based on volumetric proportions of the soils. Pots were filled with soil mixtures, and weed seeds were sown in the pots manually. The purpose was to grow 20 weeds in each pot. Taking into account the germinability of the different weed species, the amount of seeds that was sown is shown in table 2.3.

Table 2.3 Amount of seeds necessary to reach the desired amount of weed plants.

	desired # of plants	germinability	# seeds required
Stellaria media	20	75 %	27
Senecio vulgaris	20	93 %	22
Digitaria ischaemum	20	63%	32

During these experiments, germination rates proved to be quite low in certain cases. Therefore, to obtain better results, during the repetition experiment, the purpose was to grow 30 weeds in each pot. The amount of seeds that was sown is shown in table 2.4.

Table 2.4 Amount of seeds necessary to reach the desired amount of weed plants.

	desired # of plants	germinability	# seeds required
Stellaria media	30	75 %	33
Senecio vulgaris	30	93 %	40
Digitaria ischaemum	30	63%	48

Seeds were counted using a seed counter of Franken Machines. After sowing, the seeds were covered with about 2 mm soil. At 1 day after sowing, pots were sprayed with the concerning herbicide, using a spray cabinet available at the Unifarm greenhouse. Doses were applied from low to high, to avoid the risk of pots receiving an overdose of herbicide if there was residue left in the spraying devise. Amount of water applied was equivalent to 400 l ha^{-1}, the normal amount of water used per hectare for these soil herbicides. Herbicides were applied by using Birchmeier nozzles (1.2mm, drilled (0.6mm) top), using a pressure of 3 atmosphere. After spraying, pots were put in the greenhouse. Each pot got an own aluminum water tray to avoid herbicide spreading between different pots via irrigation water. Plants received 16 h light d^{-1} and were kept in dark for 8 hours d^{-1}. Temperature settings were 20ºC during daytime and 16ºC during nighttime. Realized temperature and relative humidity levels are presented in Appendix I. Plants were irrigated regularly, and continued growing for five weeks. Water was applied at the plant roots, using the water tray. After three weeks, the number of plants in every pot was counted. After five weeks, plants were harvested by cutting the above-ground plant parts. From each species the number of plants, and the fresh mass of the above-ground plant parts was determined. Plants that did not look viable anymore were disregarded. If something looked strange, remarks for different pots were noted.

2.3 Statistical analysis

Using the measured above-ground fresh weight the reduction in fresh weight was calculated using

*Reduction in fresh weight (%) = ((fresh weight control – fresh weight treatment) / fresh weight control) * 100 %*

The same was done for the reduction in number of weed plants, using

*Reduction in number of plants (%) = ((number of plants control – number of plants treatment) / number of plants control) * 100 %*

During the execution of the experiments, the conclusion was drawn that number of weed plants did not represent weed pressure very well. Sometimes weed number was reduced with 85 %, but no reduction in plant weight was measured due to the larger plants. Therefore, it was decided to solely base herbicide efficacy on the biomass of the weeds.

The fresh weight reduction as a function of herbicide dose can be described by a logistic model as described by Seefeldt *et al.* (1995):

$$y = c + (d - c) / (1 + e^{b\ \log(x) - \log(e)}) \qquad (1)$$

In this model *e* stands for ED_{50} (this is the dose producing a response half-way between upper limit and lower limit); *b* stands for relative slope around *e*; *c* stands for lower limit and d stands for upper limit. The lower limit was set to 0, since 0% weight reduction occurred in the control plants. The upper limit was set to 100, since complete weight reduction, which occurred if all plants were killed, was the theoretical maximum. For this situation, equation 1 could thus be simplified to:

$$y = 100 / (1 + e^{b\ (\log(x) - \log(e))}) \qquad (2)$$

Data obtained from the experiments were fit to the model. Parameter estimation was done by non-linear regression analysis with R (version 2.8.1, with the add-on package DRC, as described by Ritz and Streibig (2005)). Parameter estimation was done separately for each experiment (herbicide x weed species combination).

The analysis was conducted by using fresh weight reduction as y variable. After conducting a general analysis of variance on the control values of the different blocks within an experiment, it was shown that the different blocks did not have influence on the fresh weight of the control treatment. Therefore, it was decided to use the average weight of the control pots as “fresh weight control” value in the formula to calculate fresh weight reduction. By doing this, a large influence of one measurement on all treatments was prevented.

Model performance was determined by using a general analysis of variance. Obtained parameter values were compared by using the “CompParm” function in R, using a significance level of 5%. Furthermore, p-values of every parameter were determined to have an indication how robust the estimated parameter values were. Estimated dose response curves were plotted using R. The commando structure used in R is presented in Appendix II.

Next to this, the expected ED_{90} values (*dose at which 90% of treated plants will die*) were calculated using R and the DRC add-on package. For each herbicide x weed species combination the ED_{90} values were plotted against organic matter content. To have adequate weed control, all weeds should be suppressed reasonably well. Therefore, the ED_{90} results of the different weed species were combined. The relation between this ED_{90} value and soil organic matter content was determined using linear regression. The slope of these lines provides information on the influence of organic matter content on herbicide efficacy.

3. Results

Soil organic matter content was an important factor in the experiments. This factor contained six levels, obtained by mixing soil containing low organic matter with soil containing high organic matter (in the ratios 5:0, 4:1, 3:2, 2:3, 1:4 and 0:5). Because of this, in the results the unit used to describe organic matter content is “% soil containing high organic matter”. In the following table the absolute organic matter levels are shown for the soil mixtures that were used.

Table 3.1 Expected amounts of organic matter in different soils used for experiments

Label in results	**0**	**20**	**40**	**60**	**80**	**100**
Percentage rich soil (26% organic matter)	0	20	40	60	80	100
Percentage poor soil (1% organic matter)	100	80	60	40	20	0
Expected percentage organic matter	**1%**	**6%**	**11%**	**16%**	**21%**	**26%**

All weed plants were grown for five weeks in the greenhouse before harvest took place. Within this period of time, the number of plants per pot was determined once, by counting the number of plants present in every pot. This was done in the third week after sowing. Five weeks after sowing, the plants were taken to the botanical laboratory, where both number of plants per pot as well as fresh weight per pot were determined. Early analysis of the obtained data showed that, compared to the number of plants, the fresh weight per pot gave a better representation of the visual observed results. In some cases the number of plants was significantly reduced, whereas fresh weight per pot was not reduced due to a higher weight per plant. This total amount of biomass per pot was assumed to represent the efficacy of the herbicide treatment better. Therefore, further analysis was conducted on “fresh weight per pot”. The results are presented according to herbicide.

3.1 Frontier Optima

In the first experiment Frontier Optima was used. The three weed species received doses of 0, 0.05, 0.25, 0.7, 1.0 and 1.4 l ha^{-1}. After five weeks, a higher herbicide dose resulted in a significantly lower plant biomass for all the treated weeds ($p < 0.05$). In the first experiment, all the *Digitaria ischaemum* plants that were treated died, and the results of this species were therefore not taken into account. In the duplication experiment, lower doses were taken for *Digitaria ischaemum* (0, 0.01, 0.025, 0.05, 0.125 and 0.7 l ha^{-1}), to be better able to evaluate the effect of Frontier Optima on *Digitaria ischaemum*. Herbicide doses for *Senecio vulgaris* and *Stellaria media* were the same as in the first experiment.

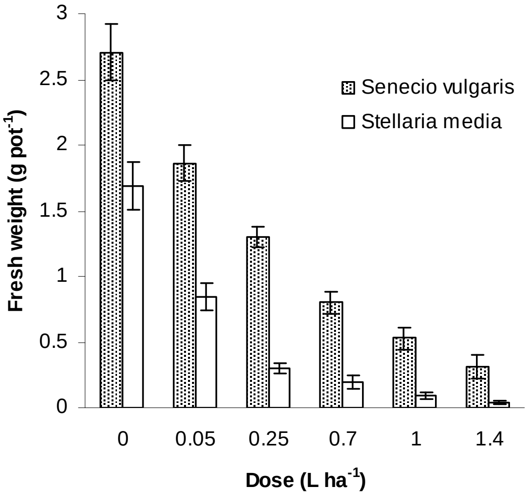

Fig. 3.1 Effect of herbicide dose (Frontier Optima) on fresh weight of *Senecio vulgaris* and *Stellaria media*. Results were obtained during the first experiment. Values are averages of 6 different soil types. Error bars represent SEM. Data of *Digitaria ischaemum* are not presented, since all plants were killed, regardless of dose rate applied.

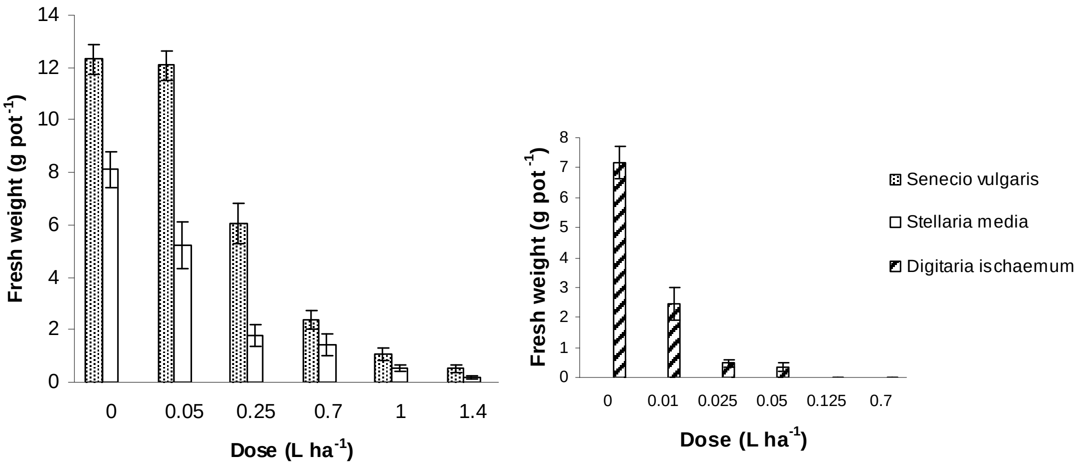

Fig. 3.2 Effect of herbicide dose (Frontier Optima) on fresh weight of *Senecio vulgaris*, *Stellaria media* and *Digitaria ischaemum*. Results were obtained in second replication experiment**.** Values are average values of 6 different soil types. Error bars represent SEM.

As can be seen in the figures presented above, the application of Frontier Optima resulted in both experiments in a significant reduction in plant biomass per pot (p < 0.05). Using the fresh weight reduction rates, regression analysis was conducted to obtain parameter values for the dose-response curves of the different organic matter levels. For this a three parameter logistic function was used in which the upper limit was set at 100%. Generated parameter values for *Stellaria media* and *Senecio vulgaris* fitted the data very well. Parameter values clearly differed from zero (p < 0.001), except for *Stellaria media*, grown at the soil mixture containing 20 % of soil with a high organic matter content. Regression for *Digitaria ischaemum* could not be performed for the individual soil types. Therefore data of different soils were taken together to be able to give a general description of the dose-response curve of *Digitaria ischaemum* for Frontier Optima, independent of the organic matter level.

Table 3.2 Parameter values to describe fresh weight reduction due to herbicide application of Frontier Optima compared to control for different weed species. ED_{90} values were calculated by using the estimated *b* and *e* parameter values.

Treatment	Soil	Slope (*b*)	ED_{50} (*e*) (lha^{-1})	ED_{90} (lha^{-1})
Stellaria media	0	-1.28 ± 0.36*** [a]	0.060 ± 0.013*** [b]	0.332 ± 0.157
	20	-0.69 ± 0.36 [a]	0.009 ± 0.011 [a]	0.218 ± 0.158
	40	-1.27 ± 0.29*** [a]	0.108 ± 0.022*** [bc]	0.606 ± 0.253
	60	-1.19 ± 0.25*** [a]	0.104 ± 0.022*** [bc]	0.666 ± 0.266
	80	-0.82 ± 0.16*** [a]	0.091 ± 0.027*** [bc]	1.325 ± 0.601
	100	-1.10 ± 0.21*** [a]	0.134 ± 0.030*** [c]	0.996 ± 0.363
Senecio vulgaris	0	-1.30 ± 0.22*** [ab]	0.097 ± 0.016*** [a]	0.524 ± 0.160
	20	-1.17 ± 0.17*** [a]	0.132 ± 0.023*** [a]	0.560 ± 0.223
	40	-1.01 ± 0.15*** [a]	0.134 ± 0.024*** [a]	1.167 ± 0.350
	60	-1.58 ± 0.26*** [ab]	0.387 ± 0.046*** [b]	1.557 ± 0.326
	80	-1.99 ± 0.30*** [b]	0.580 ± 0.053*** [bc]	1.753 ± 0.277
	100	-1.17 ± 0.20*** [a]	0.519 ± 0.065*** [bc]	3.393 ± 1.023
Digitaria ischaemum	All	-1.93 ± 0.44	0.007 ± 0.000	0.021 ± 0.004

****p* < 0.001, ***p* < 0.01, **p* < 0.05. Different letters within a parameter within a species indicate significant differences at the 5% level

Graphical expression of the dose-response curves of the three weed species is presented in figures 3.3, 3.4, and 3.5. These figures are based on the parameter values, generated by the three parameter logistic model, as presented in table 3.2. As can be seen in fig. 3.3, the response of *Stellaria media* plants to Frontier Optima, grown at the soil mixture containing 20 % soil with high organic matter content, ,clearly differed from the response on the other soil mixtures. The datapoint at a dose of 0.05 l ha^{-1} influenced the dose-response curve strongly. However, this datapoint was based on measurements in eight different pots, indicating that there was no good reason to question the validity of this datapoint. Performance of the model was tested using a lack-of-fit test. By doing this, the variance of the model is compared to the variance in the data. If variance in the model is significantly larger compared to variance in the data, there is a lack-of fit of the model. For *Stellaria media*, treated with Frontier Optima, the measured data were very well described by the three parameter logistic model (lack-of-fit p = 1.00). In figure 3.3, the response of *Senecio vulgaris* plants, grown in different soil mixtures, to Frontier Optima is presented. This graph indicates that soils containing increased organic matter content required increased herbicide doses to realize sufficient weed control. The three parameter logistic model described the measured data quite well (lack-of-fit p = 0.45).

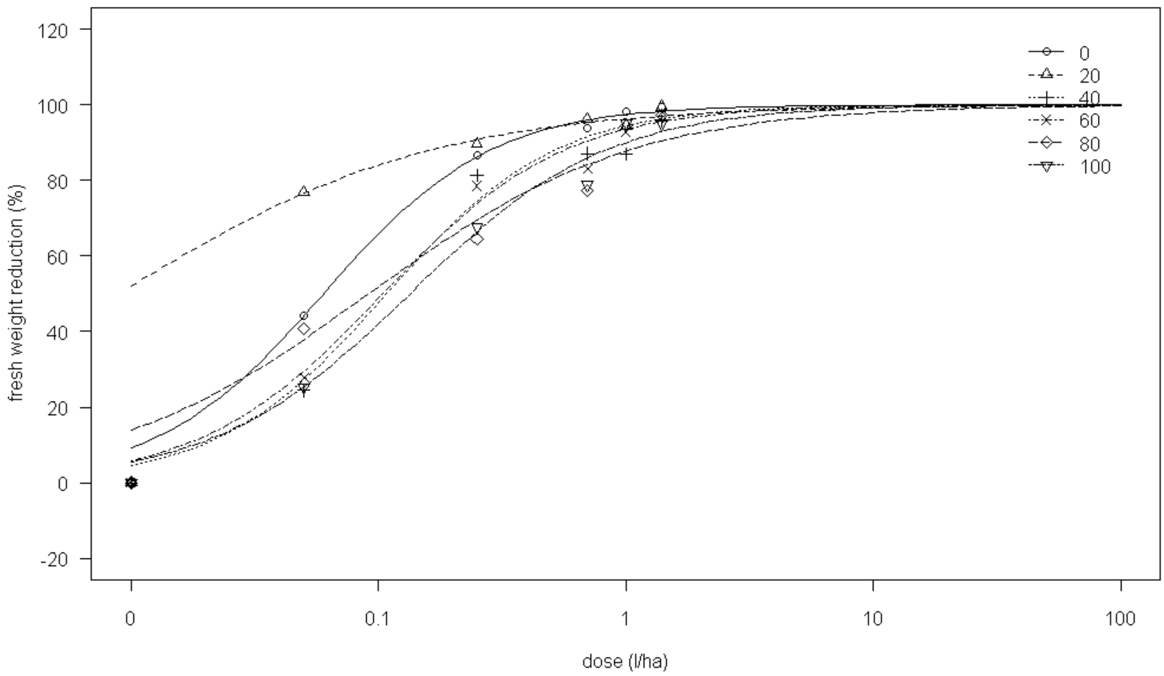

Fig. 3.3 Dose response curves of *Stellaria media* treated with Frontier Optima. Different categories are different percentages of soil containing high organic matter content. Model used: 3 parameter logistic model (p = 1.00).

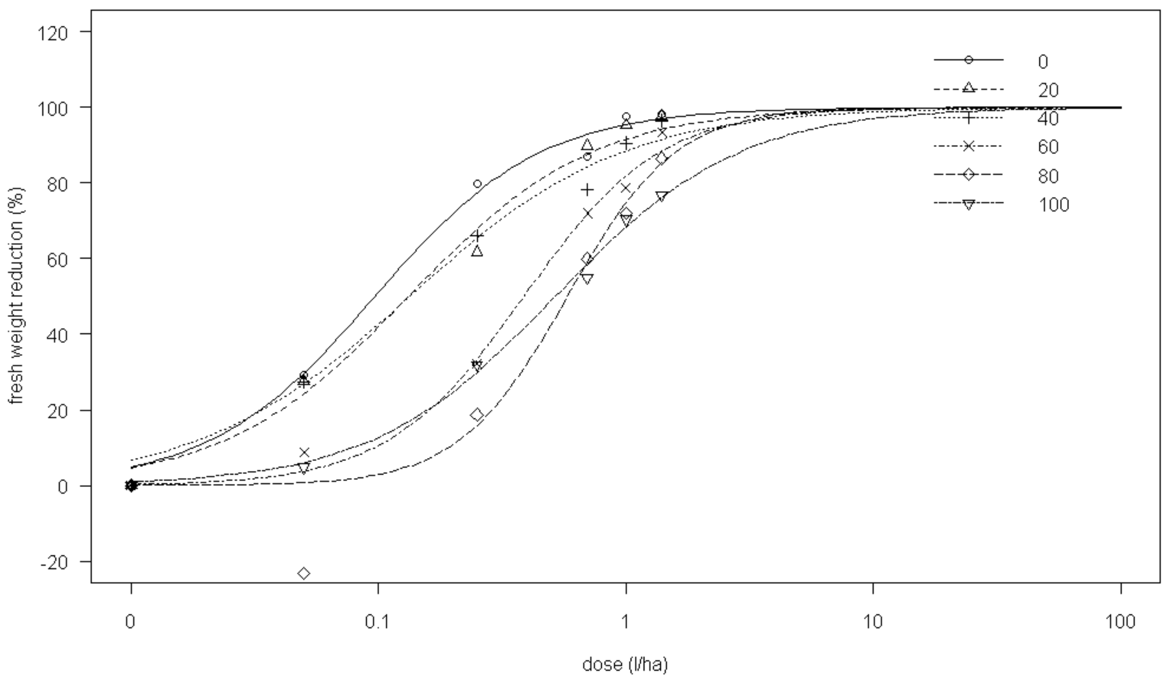

Fig. 3.4 Dose response curves of *Senecio vulgaris* treated with Frontier Optima. Different categories are different percentages of soil containing high organic matter content. Model used: 3 parameter logistic model (p = 0.45).

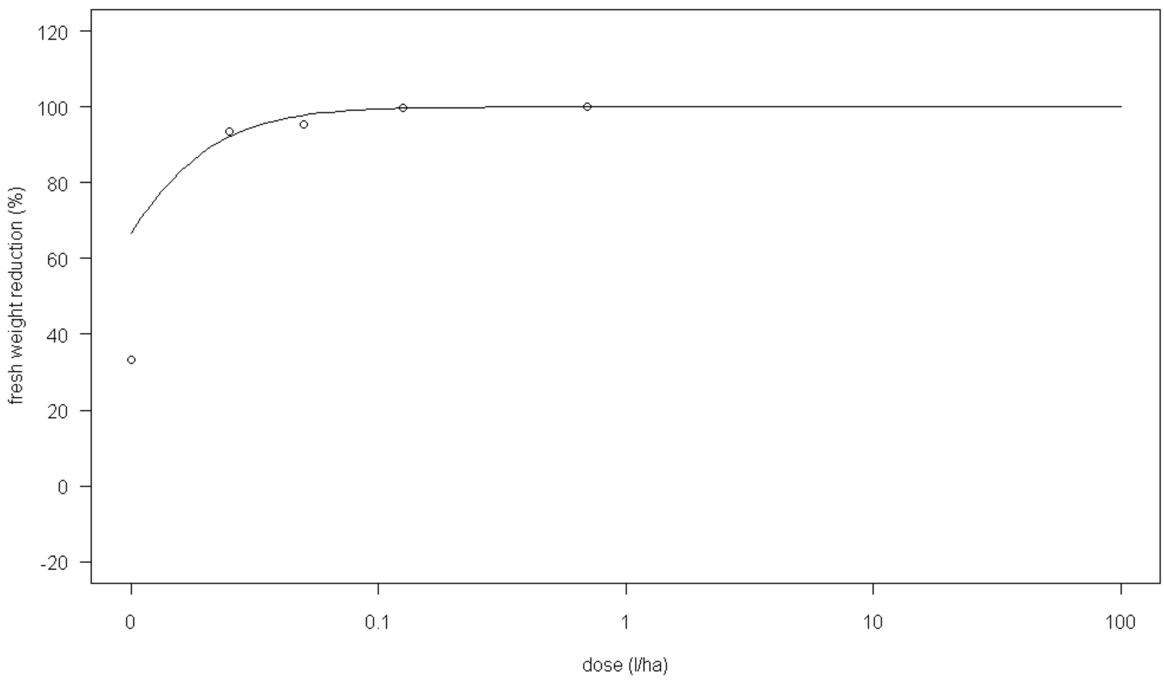

Fig. 3.5 Dose response curves of *Digitaria ischaemum* treated with Frontier Optima. Curve is a result of the average fit of six soils containing different organic matter contents. Separated fits for the different organic matter contents could not be obtained due to a wrong range of herbicide doses used.

As can be seen in fig. 3.5 it was not possible to describe dose response curves for *Digitaria ischaemum* for soils containing different organic matter contents. Therefore an analysis was conducted on the fresh weight reduction values obtained at a dose 0.01 l ha^{-1}, which was the only "descriptive" point for the dose-response curve of *Digitaria ischaemum*, treated with Frontier Optima. This analysis resulted in figure 3.6. This analysis supports the theory that herbicide efficacy is less in soils containing a higher organic matter content ($p < 0.05$).

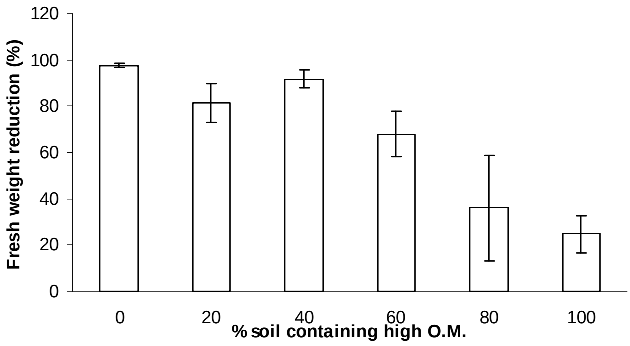

Fig. 3.6 Fresh weight reduction of *Digitaria ischaemum* resulting from Frontier Optima dose of 0.01 lha^{-1} for soils containing different organic matter contents. Error bars represent standard error of mean.

To obtain dose advices for Frontier Optima, the ED_{90} values of the different weeds were analyzed. Linear regression of the ED_{90} values of the different weeds resulted in figure 3.7. R^2 values were 0.75 for *Senecio vulgaris* and 0.86 for *Stellaria media*. As explained before, in *Digitaria ischaemum* no separate ED_{90} values could be estimated for soils containing different amounts of organic matter.

Analysis of the data showed that a quadratic description of the relationship between organic matter percentage and ED_{90} did not result in a better model to describe the data. Therefore, the relationship between organic matter percentage and ED_{90} was described linearly.

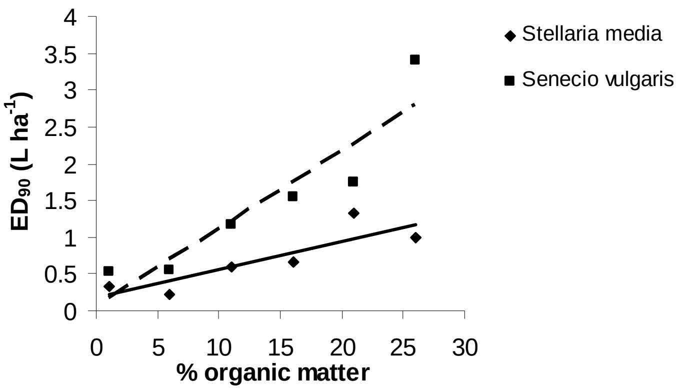

Fig. 3.7 ED_{90} values of different weed species grown under different soil organic matter levels treated with Frontier Optima. *Stellaria media*: ED_{90} = 0.0383 * organic matter percentage + 0.1736. *Senecio vulgaris*: ED_{90} = 0.1047 * organic matter percentage + 0.0795.

From figure 3.7, it can be seen that organic matter content clearly influenced herbicide efficacy for *Stellaria media* and *Senecio vulgaris*. However, the rate in which organic matter influenced the efficacy was different for the two weed species. For *Senecio vulgaris* the amount of herbicide to conduct adequate weed control at soils containing 1% organic matter content was only 6.6% of the amount of herbicide that is required to conduct good weed control at soils containing 26% organic matter content. This ratio was 18% for *Stellaria media*. The absolute quantity of Frontier Optima to realize a sufficient weed control (e.g. 90 % fresh weight reduction) was higher for *Senecio vulgaris*, compared to *Stellaria media* when organic matter contents were higher than 1.4%. The amount of Frontier Optima necessary to realize a sufficient weed control for *Digitaria ischaemum* again is much lower, which was already indicated due to the fact that all weeds were killed when doses were higher than 0.125 l ha^{-1}.

3.2 Merlin

Merlin was used in two tests as herbicide. In both tests three weed species were treated with Merlin. In the first experiment the different weed species received doses of 0, 5, 25, 70, 100 and 133 gha^{-1}. A higher herbicide dose resulted in a significantly lower plant biomass after five weeks for all three treated weed species. In the three highest doses a fresh weight reduction of almost 100% was obtained. Therefore, during the replication experiments, lower doses were used for all three weed species. The doses for *Senecio vulgaris* and *Stellaria media* were 0, 1, 2.5, 10, 25 and 70 gha^{-1}. Doses for *Digitaria ischaemum* were 0, 0.5, 1, 2.5, 10 and 25 gha^{-1}. These doses were slightly lower compared to the doses used for the other weed species because in the first experiment *Digitaria ischaemum* was found to be more sensitive to Merlin then the other two weed species. The following figures give an overview of the effect of herbicide dose on the fresh weight of the different weed species in the two experiments.

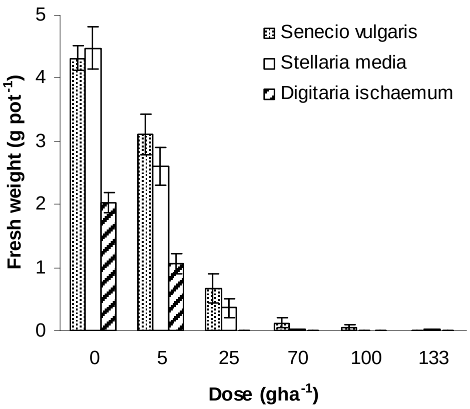

Fig. 3.8 Effect of herbicide dose (Merlin) on fresh weight of *Senecio vulgaris*, *Stellaria media* and *Digitaria ischaemum*. Results were obtained in the first experiment. Values are average values of 6 different soil types.

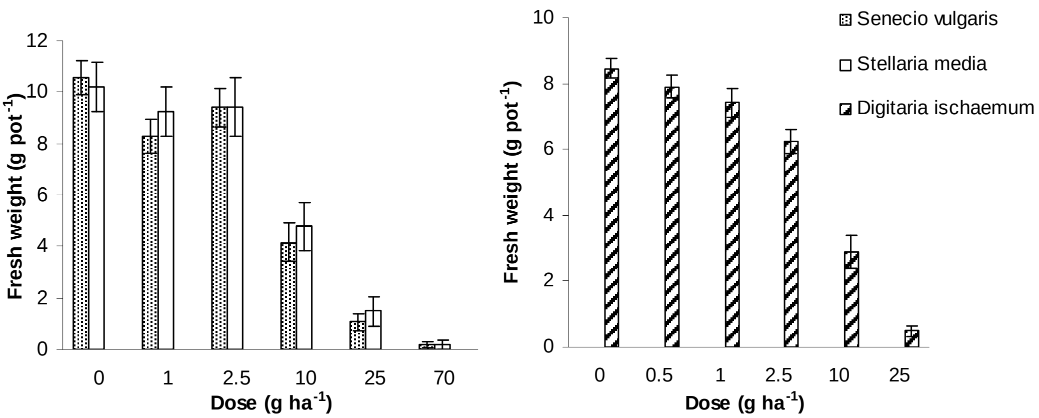

Fig. 3.9 Effect of herbicide dose (Merlin) on fresh weight of *Senecio vulgaris*, *Stellaria media* and *Digitaria ischaemum*. Results were obtained in the second replication experiment. Values are average values of 6 different soil types.

The efficacy of Merlin for soils containing different organic matter contents was compared by calculating the fresh weight reduction due to the different herbicide treatments. This relationship can be described by a three parameter logistic function. Parameter values of the first and second experiment did not differ significantly, as determined by a paired t-test (p = 5%). Therefore, the fresh weight reduction values of both experiments were analyzed together. In table 3.3, generated parameter values for *Senecio vulgaris*, *Stellaria media*, and *Digitaria ischaemum* are presented. The parameter value of the slope of the dose-response curve for *Senecio vulgaris*, grown at soil containing 20 % high organic matter content was not significantly different from zero (p < 0.05), due to the high standard error around this value.

Table 3.3 Fresh weight reduction due to herbicide application of Merlin compared to control for different weed species and average fresh weight reduction over all three weed species.

Treatment	Soil	Slope (b)	ED_{50} (e) (gha^{-1})	ED_{90}
Stellaria media	0	-1.60 ± 0.56** [ab]	4.223 ± 0.831*** [b]	16.7 ± 8.0
	20	-2.00 ± 0.47*** [b]	4.095 ± 0.829*** [b]	12.3 ± 4.8
	40	-0.74 ± 0.19*** [a]	1.789 ± 0.791* [a]	34.2 ± 19.3
	60	-2.38 ± 0.65*** [b]	8.713 ± 1.396*** [c]	22.0 ± 6.7
	80	-1.92 ± 0.53*** [b]	12.815 ± 2.178*** [cd]	40.3 ± 13.6
	100	-2.81 ± 0.96** [b]	16.999 ± 2.563*** [d]	37.2 ± 9.0
Senecio vulgaris	0	-1.02 ± 0.21*** [ab]	1.247 ± 0.316*** [a]	10.8 ± 3.9
	20	-4.04 ± 2.48 [abc]	4.723 ± 0.380*** [b]	8.1 ± 3.0
	40	-1.49 ± 0.32*** [ab]	6.782 ± 0.972*** [c]	29.5 ± 8.3
	60	-4.75 ± 1.27*** [c]	13.975 ± 1.482*** [d]	22.2 ± 4.1
	80	-2.02 ± 0.29*** [b]	13.862 ± 1.587*** [d]	41.2 ± 8.7
	100	-1.75 ± 0.29*** [b]	14.170 ± 1.638*** [d]	49.8 ± 11.7
Digitaria ischaemum	0	-1.06 ± 0.17*** [a]	1.771 ± 0.321*** [a]	14.1 ± 4.4
	20	-2.21 ± 0.60*** [ab]	3.895 ± 0.417*** [b]	10.5 ± 3.2
	40	-1.67 ± 0.30*** [ab]	3.197 ± 0.408*** [b]	11.9 ± 3.0
	60	-1.86 ± 0.33*** [b]	6.773 ± 0.802*** [c]	22.0 ± 4.9
	80	-2.74 ± 0.58*** [b]	11.729 ± 1.154*** [d]	26.2 ± 4.8
	100	-3.60 ± 1.78* [ab]	10.437 ± 0.851*** [d]	19.2 ± 6.2

***p < 0.001, **p < 0.01, *p < 0.05. Different letters within a parameter within a species indicate significant differences at the 5% level.

By using the parameter values provided in table 3.3, dose-response curves were generated for the response of the three weed species on Merlin. These can be seen in figures 3.10, 3.11, and 3.12. In figure 3.10, the dose-response curves of *Stellaria media*, grown on different soil mixtures, and treated with Merlin are shown. As can be seen, dose-response curves of soils containing different organic matter contents differed severely. Model performance of the three parameter logistic model was not very satisfactory (lack-of-fit $p = 7.3 * 10^{-6}$). Figure 3.11 provides the dose-response curves of *Senecio vulgaris*, grown on different soil mixtures, and treated with Merlin. The response of *Senecio vulgaris* on the application of Merlin is clearly dependent on organic matter content of the soil. A higher organic matter content resulted in general results in a higher ED_{90} value. However, the validity of the results can be questioned due to the poor performance of the three parameter logistic model (lack-of-fit $p = 4.52 * 10^{-9}$). In figure 3.12, the response of *Digitaria ischaemum*, grown on different soil mixtures, on

Merlin is shown. A higher organic matter content here also resulted in a higher ED_{90} value. In this case model performance again was quite poor. A lack-of-fit test results in a *p*-value of only 0.0074.

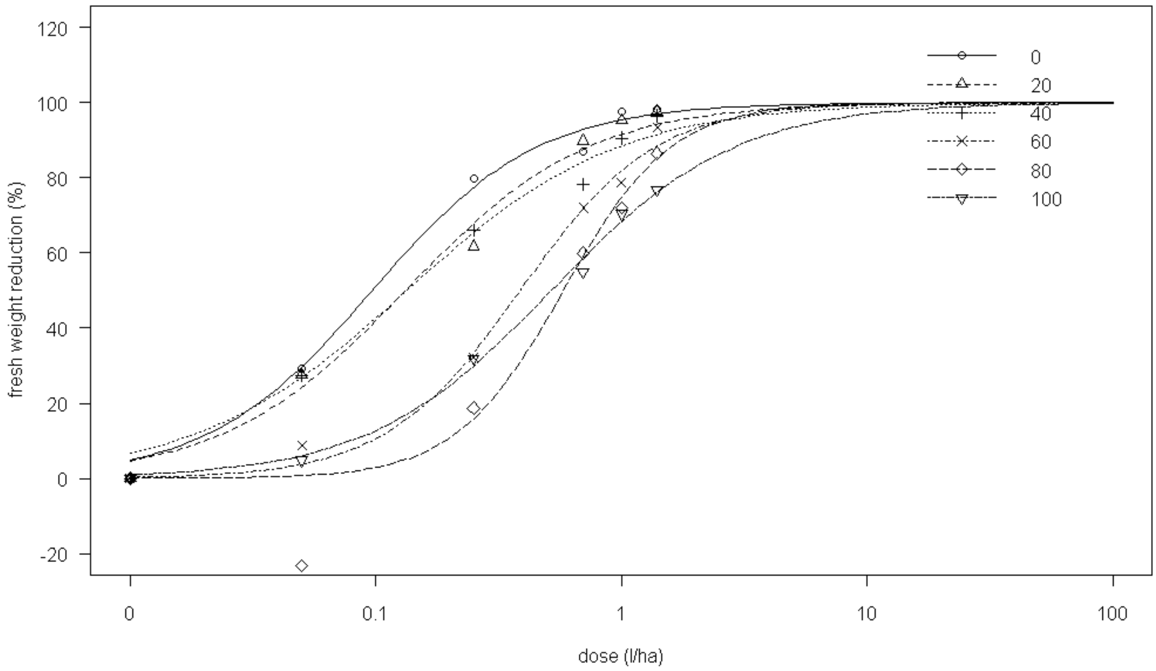

Fig. 3.10 Dose response curves of *Stellaria media* treated with Merlin. Different categories are different percentages of soil containing high organic matter content. Model used: 3 parameter logistic model ($p = 7.3 * 10^{-6}$).

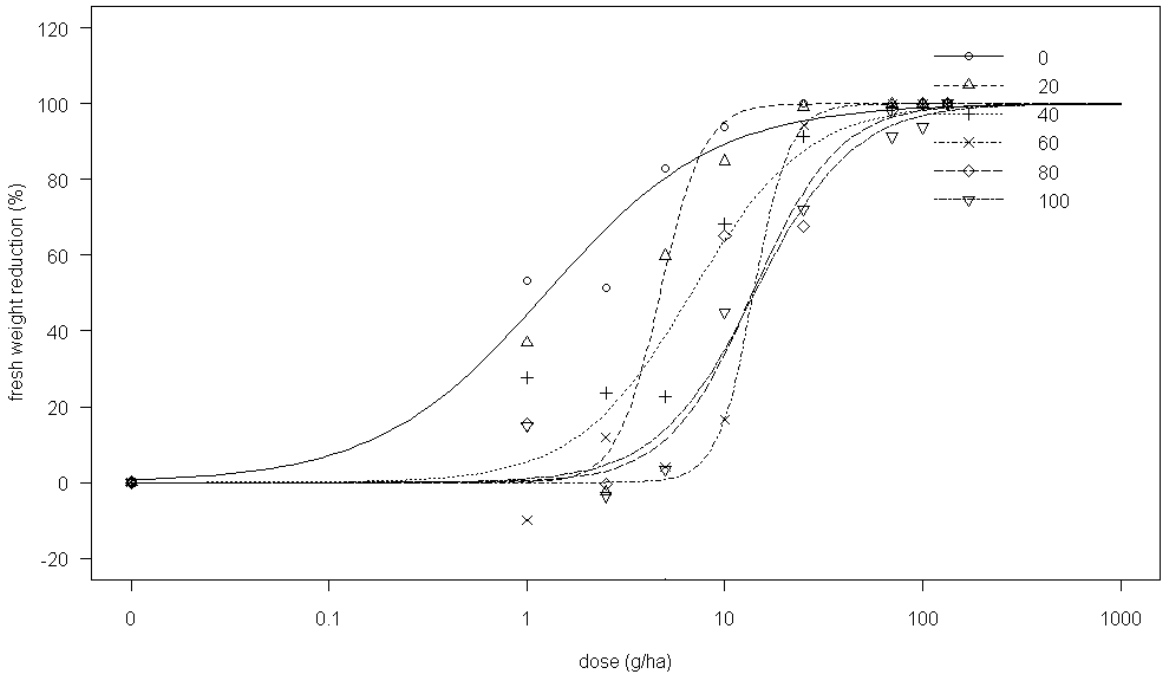

Fig. 3.11 Dose response curves of *Senecio vulgaris* treated with Merlin. Different categories are different percentages of soil containing high organic matter content. Model used: 3 parameter logistic model ($p = 4.5 * 10^{-9}$).

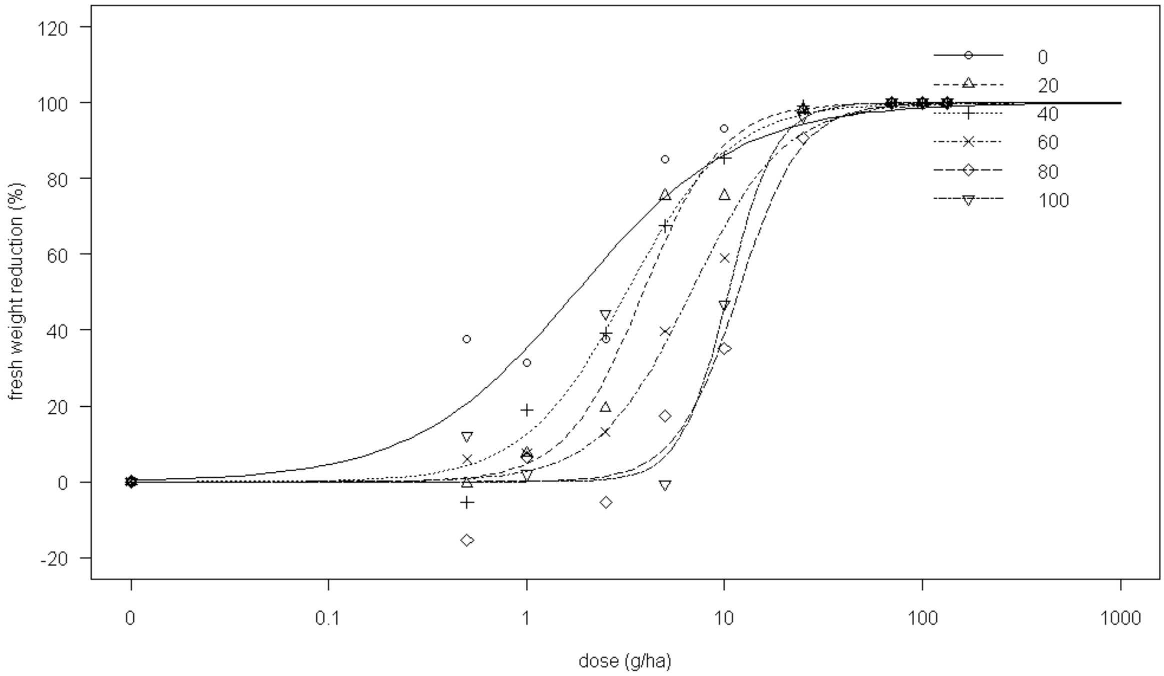

Fig. 3.12 Dose response curves of *Digitaria ischaemum* treated with Merlin. Different categories are different percentages of soil containing high organic matter content. Model used: 3 parameter logistic model (p = 0.0074).

To obtain specific dose advices for Merlin applied on soils containing different organic matter contents, the ED_{90} values of the different weeds were analyzed. Linear regression of the ED_{90} values of the different weeds resulted in figure 3.13. R^2 values were 0.64 for *Stellaria media*, 0.86 for *Senecio vulgaris*, and 0.52 for *Digitaria ischaemum*. Analysis of the data showed that a quadratic description of the relationship between organic matter percentage and ED_{90} did not result in a better model to describe the data, compared to a linear model. Therefore, the relationship between organic matter percentage and ED_{90} is described linearly.

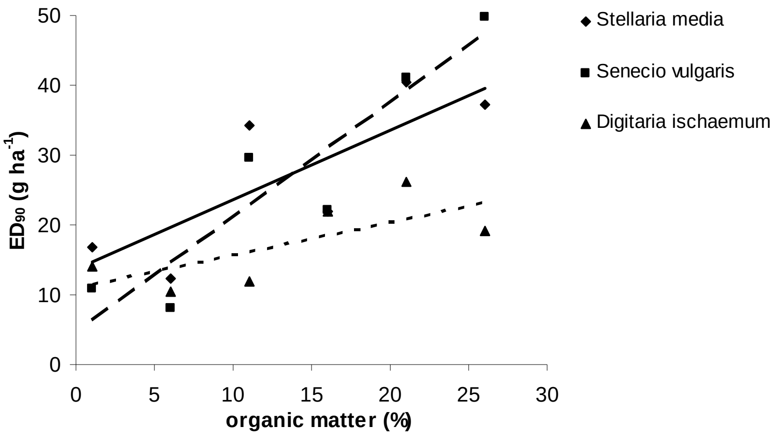

Fig. 3.13 ED_{90} values of different weed species grown under different soil organic matter levels treated with Merlin. *Stellaria media*: ED_{90} = 0.9964 * organic matter percentage + 13.659. *Senecio vulgaris*: ED_{90} = 1.6393 * organic matter percentage + 4.8129. *Digitaria ischaemum*: ED_{90} = 0.4731 * organic matter percentage + 10.916.

From figure 3.13, it can be seen that organic matter content clearly influenced herbicide efficacy for *Stellaria media, Senecio vulgaris*, and *Digitaria ischaemum*. However, the rate in which organic matter influenced the efficacy was different for the three weed species. This rate was highest for *Senecio vulgaris* and lowest for *Digitaria ischaemum*. For *Senecio vulgaris* the amount of herbicide to conduct adequate weed control at soils containing 1% organic matter content was only 13.6% of the amount of herbicide that is required to conduct good weed control at soils containing 26% organic matter content. This ratio was 37% for *Stellaria media*, and 49% for *Digitaria ischaemum*. it can be seen that the absolute quantity of Merlin to realize sufficient weed control (for *Senecio vulgaris* and *Stellaria media* was about the same. At soils containing little organic matter, *Stellaria media* needed a higher herbicide dose, whereas at soils containing high organic matter percentages, *Senecio vulgaris* required a higher herbicide dose for sufficient weed control. The amount of herbicide necessary to control *Digitaria ischaemum* was relatively low compared to the amount necessary to control the other two weed species.

3.3 Mixture Merlin and Frontier Optima

The dose advise of the mixture of Frontier Optima and Merlin is normally based on a 1 : 100 ratio between liter Frontier Optima ha^{-1} and gram Merlin ha^{-1}. All the dose information given in the following graphs is based on the Merlin part of the mixture. If, for example, 50 gram ha^{-1} is given as the dose, 50 gram Merlin ha^{-1} combined with 0.5 l Frontier Optima ha^{-1} is meant by this dose.

The following graphs give an impression regarding the effect of herbicide application on biomass production for the different weed species. Due to the high susceptibility of *Digitaria ischaemum* for the mixture of Frontier Optima and Merlin, the maximum dose for *Digitaria ischaemum* in the second experiment was reduced, and replaced by a lower dose.

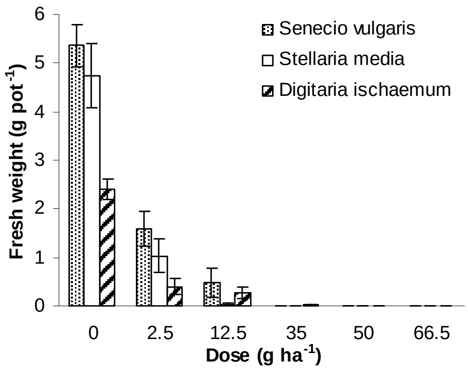

Fig. 3.14 Effect of herbicide dose (mixture Frontier Optima and Merlin) on fresh weight of different weed species. Results are obtained during first experiment. Values are average values of 6 different soil types combined with 4 blocks. Dose unit is the amount of Merlin in gha^{-1}. This value divided by 100 gives the amount of Frontier in lha^{-1} that was added to the mixture.

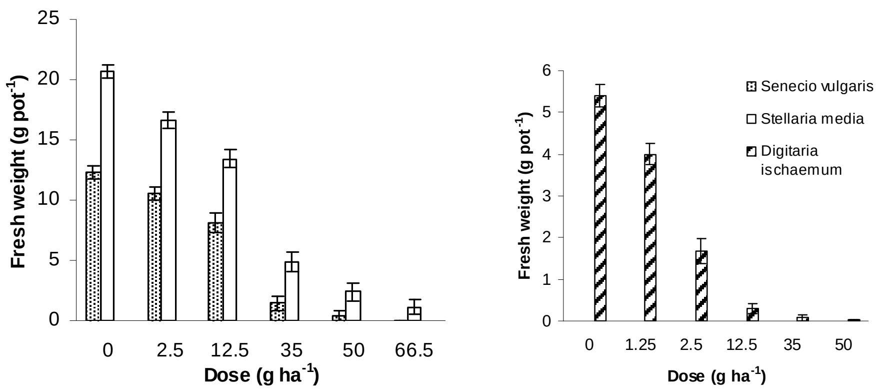

Fig. 3.15 Effect of herbicide dose (mixture Frontier Optima and Merlin) on fresh weight of different weed species. Results were obtained during second replication experiment. Values are average values of 6 different soil types combined with 4 blocks. Dose unit is the amount of Merlin in gha^{-1}. This value divided by 100 gives the amount of Frontier in lha^{-1} that was added to the mixture

The efficacy of the mixture of Frontier Optima and Merlin for soils containing different organic matter contents was compared by calculating the fresh weight reduction due to the different herbicide treatments. This relationship was described by the three parameter logistic function. Parameter values of the first and second experiment did not differ significantly, as determined by a paired t-test (p = 5%). Therefore, the fresh weight reduction values of both experiments were analyzed together. In table 3.4, generated parameter estimates for *Senecio vulgaris*, *Stellaria media*, and *Digitaria ischaemum* are presented. The parameter values of the slope of the dose-response curves for *Digitaria ischaemum*, grown at soils containing 20 % and 40 % high organic matter content were not significantly different from zero ($p < 0.05$), due to the high standard error around these values. Furthermore, the parameter value of the ED_{90} values of the dose-response curves for *Stellaria media*, grown at soils containing 0 % and 60 % high organic matter content also were not significantly different from zero ($p < 0.05$).

Table 3.4 Fresh weight reduction due to herbicide application of Merlin compared to control for different weeds and average fresh weight reduction over all three weed species.

Treatment	Soil	Slope (*b*)	ED_{50} (*e*) (gha^{-1})	ED_{90}
Stellaria media	*0*	*-0.32 ± 0.16** [a]	*0.373 ± 0.681* [a]	*328.7 ± 564.1*
	20	-0.78 ± 0.22*** [ab]	2.034 ± 0.936* [abc]	34.4 ± 20.8
	40	-1.04 ± 0.24*** [b]	3.311 ± 0.961*** [bc]	27.5 ± 12.5
	60	-0.66 ± 0.20** [ab]	1.636 ± 0.961 [ab]	45.7 ± 31.0
	80	-1.04 ± 0.21*** [b]	5.227 ± 1.416*** [cd]	43.1 ± 17.2
	100	-1.23 ± 0.26*** [b]	7.884 ± 1.959*** [d]	46.9 ± 15.3
Senecio vulgaris	0	-0.92 ± 0.30** [a]	1.841 ± 0.768* [a]	19.9 ± 11.7
	20	-1.29 ± 0.34*** [a]	3.177 ± 0.758*** [a]	17.4 ± 8.0
	40	-0.95 ± 0.21*** [a]	3.187 ± 1.022**[a]	32.2 ± 14.5
	60	-0.99 ± 0.20*** [a]	4.181 ± 1.242***[a]	38.3 ± 15.3
	80	-0.87 ± 0.18*** [a]	5.566 ± 1.745** [ab]	68.6 ± 29.4
	100	-1.81 ± 0.69** [a]	11.886 ± 2.912*** [b]	40.1 ± 12.6
Digitaria ischaemum	0	-1.01 ± 0.30*** [a]	1.000 ± 0.259*** [a]	8.9 ± 4.4
	20	-3.20 ± 1.81 [a]	1.012 ± 0.163*** [a]	2.0 ± 0.5
	40	-1.58 ± 0.92 [a]	0.694 ± 0.320* [a]	2.8 ± 1.2
	60	-2.52 ± 0.96** [a]	1.095 ± 0.139*** [a]	2.6 ± 0.7
	80	-2.15 ± 0.81** [a]	1.064 ± 0.163*** [a]	3.0 ± 0.9
	100	-1.66 ± 0.37*** [a]	2.601 ± 0.322*** [b]	9.8 ± 3.5

****p* < 0.001, ***p* < 0.01, **p* < 0.05. Different letters within a parameter within a species indicate significant differences at the 5% level.

By using the parameter values provided in table 3.4, dose-response curves were generated for the response of the three weed species on the mixture of Frontier Optima and Merlin. These can be seen in figures 3.16, 3.17, and 3.18. In figure 3.16, the dose-response curves of *Stellaria media*, grown on different soil mixtures, and treated with the mixture of Frontier Optima and Merlin are shown. As can be seen, dose-response curves of soils containing different organic matter contents differed severely. The dose-response curve for soils containing 0 % of soil with high organic matter content was very different compared to the dose-response curves of the other soils. Model performance of the three parameter logistic model was good (lack-of-fit $p = 0.98$). Figure 3.17 provides the dose-response curves of *Senecio vulgaris*, grown on different soil mixtures, and treated with the mixture of Frontier Optima and Merlin. The response of *Senecio vulgaris* on the application of the mixture of Frontier Optima and Merlin was dependent on organic matter content of the soil. A higher organic matter content generally resulted in a higher ED_{90} value. The three parameter logistic model represented the measured data reasonable well (lack-of-fit p = 0.23). In figure 3.18, the response of *Digitaria ischaemum*, grown on different soil mixtures, on the mixture of Frontier Optima and Merlin is shown. Soils containing the highest and lowest percentage of organic matter had the highest ED_{90} value. Soils containing less extreme organic matter levels had the lowest ED_{90} values. Model performance was very well. A lack-of-fit test resulted in a p-value of 1.00.

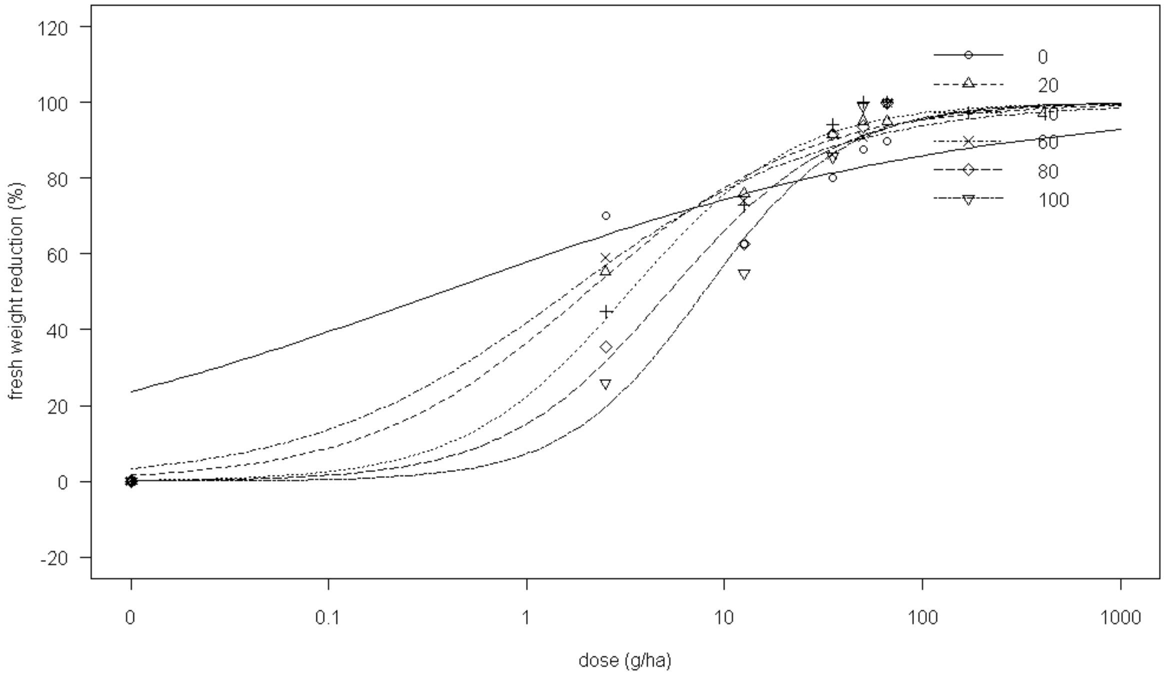

Fig. 3.16 Dose response curves of *Stellaria media* treated with the mixture of Merlin and Frontier Optima. Different categories are different percentages of soil containing high organic matter content. Model used: 3 parameter logistic model (p = 0.98).

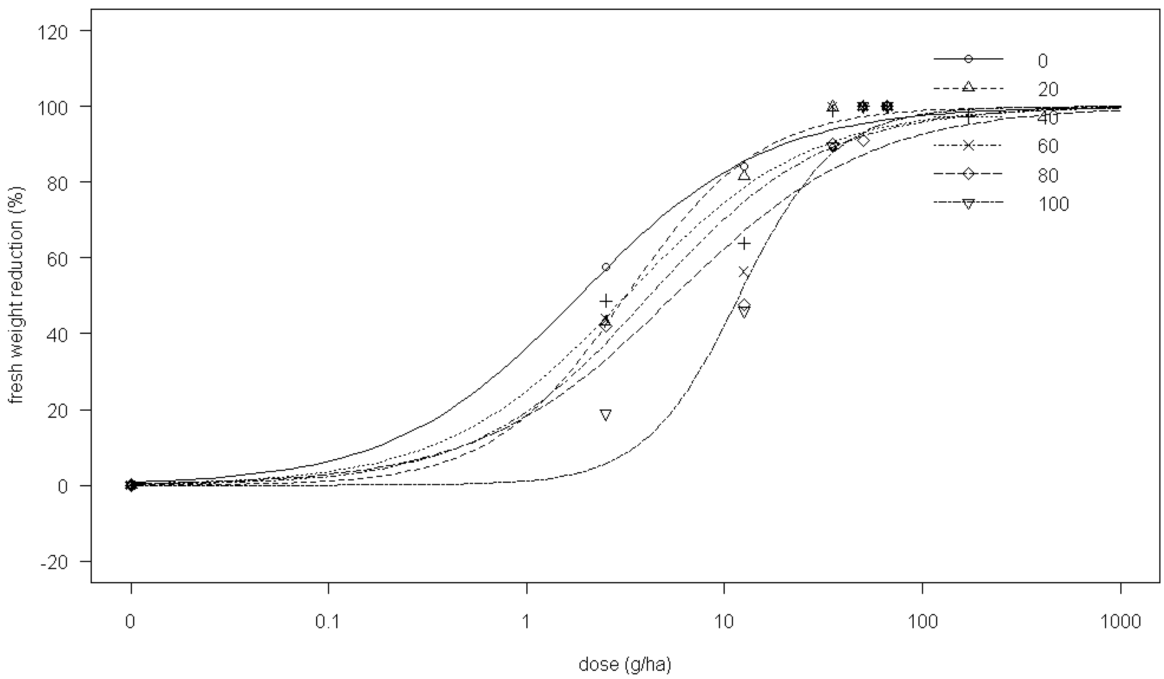

Fig. 3.17 Dose response curves of *Senecio vulgaris* treated with the mixture of Merlin and Frontier Optima. Different categories are different percentages of soil containing high organic matter content. Model used: 3 parameter logistic model (p = 0.23).

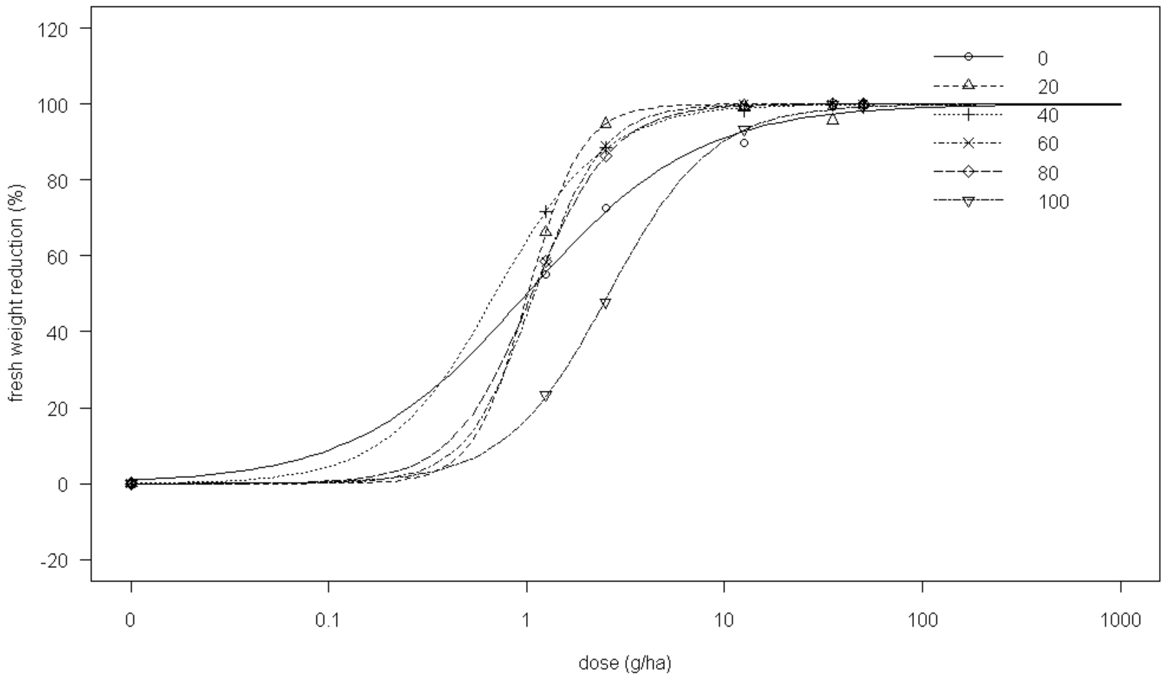

Fig. 3.18 Dose response curves of *Digitaria ischaemum* treated with the mixture of Merlin and Frontier Optima. Different categories are different percentages of soil containing high organic matter content. Model used: 3 parameter logistic model (p = 1.00).

To obtain specific dose advices for the mixture of Frontier Optima and Merlin applied on soils containing different organic matter contents, the ED_{90} values of the different weeds were analyzed. Regression of the ED_{90} values of the different weeds resulted in figure 3.13. R^2 values were 0.59 for *Stellaria media*, 0.57 for *Senecio vulgaris*, and 0.02 for *Digitaria ischaemum*. Analysis of the data proved that a quadratic description of the relationship between organic matter percentage and ED_{90} resulted in a better model to describe the data for *Digitaria ischaemum*. However, for *Stellaria media* and *Senecio vulgaris,* a linear relationship gave a better description of the relation between organic matter percentage and ED_{90}.

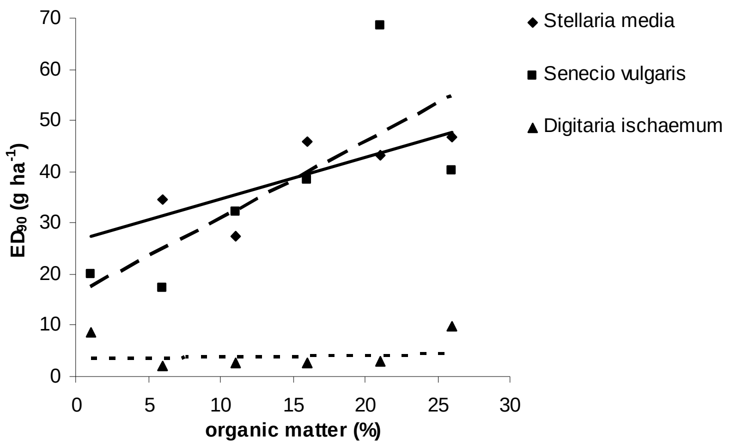

Fig. 3.19 ED_{90} values of different weed species grown under different soil organic matter levels treated with the mixture of Frontier Optima Merlin. *Stellaria media*: ED_{90} = 0.8106 * organic matter percentage + 26.56. *Senecio vulgaris*: ED_{90} = 1.4897 * organic matter percentage + 15.966. *Digitaria ischaemum*: ED_{90} = 9.4 – 1.232 * organic matter percentage + 0.0472 * organic matter percentage * organic matter percentage.

From figure 3.19, it can be seen that for *Stellaria media* and *Senecio vulgaris*, herbicide efficacy is clearly dependent on organic matter content. As seen in weeds treated with solely Frontier Optima and solely Merlin, also for the mixture of Frontier Optima and Merlin it can be seen that the rate in which organic matter influenced the efficacy highest for *Senecio vulgaris*. For *Senecio vulgaris* the amount of herbicide to conduct adequate weed control at soils containing 1% organic matter content was only 32% of the amount of herbicide that is required to conduct good weed control at soils containing 26% organic matter content. This ratio was 57% for *Stellaria media*. The absolute quantity of Merlin to realize sufficient weed control (for *Senecio vulgaris* and *Stellaria media* is about the same on average. At soils containing little organic matter, *Stellaria media* needed a higher herbicide dose, whereas at soils containing high organic matter percentages, *Senecio vulgaris* required a higher herbicide dose for sufficient weed control. The amount of herbicide necessary to control *Digitaria ischaemum* was very low compared to the amount necessary to control the other two weed species.

4. Discussion

4.1 Interpretation of the results

There was a clear negative effect of soil organic matter content on the efficacy of Frontier Optima. Both with *Senecio vulgaris* and *Stellaria media* a higher organic matter level resulted in a higher ED_{90} value. For both species the relation between ED90 and soil organic matter content was best described with a linear equation. However, the rate at which the efficacy of Frontier Optima responded to the organic matter content was much higher for *Senecio vulgaris* compared to *Stellaria media*. Due to this high response rate of the efficacy of Frontier Optima against *Senecio vulgaris*, maximum allowed dose was exceeded for soils containing over 13% organic matter. Therefore, the use of Frontier Optima is not supported to control *Senecio vulgaris* if soils contain large organic matter contents. Furthermore, the experiments showed that Frontier Optima was very effective against *Digitaria ischaemum*, and for that reason, the selected dose range did not allow a good estimation of the ED_{90} value for this weed species. This is remarkable, since *Digitaria ischaemum* is mentioned as a problem weed, especially at poor soils.

For Merlin, effects of organic matter on ED_{90} values were also very clear. A higher organic matter content resulted in a higher ED_{90} value (and thus a lower herbicide efficacy). However, the three parameter logistic model that was used to describe the effect of organic matter on performance of Merlin proved to badly fit the data due to lack-of-fit. This could be seen back in the parameter estimation, where several parameter values to describe the responses of weed species on herbicide dose were not significantly different from zero. The relationship between soil organic matter content and ED_{90} value was positive in all three weed species that were tested. This relationship was best described linear in all three weed species. However, rate at which organic matter content influenced ED_{90} value was, like for Frontier Optima, highest for *Senecio vulgaris* again. However, when applying Merlin, maximum allowed dose was not exceeded at high organic matter contents. Due to the difference in rates at which organic matter content influenced ED_{90} value, the experiments showed that *Stellaria media* was hardest to control at soils containing low organic matter contents, whereas *Senecio vulgaris* was hardest to control at soils containing high organic matter contents.

The parameter values to describe the response of *Stellaria media* on a treatment of the mixture of Frontier Optima and Merlin could not be estimated at soil containing 1% organic matter content. The variance of these parameters proved to be unacceptable large (larger than value of parameter estimate). Therefore, this situation was not used in the further analysis. Furthermore, some other parameter values to describe the responses of weed species on herbicide dose were not significantly different from zero. The effect of soil organic matter content on ED_{90} value was best described linearly in *Stellaria media* and *Senecio vulgaris.* Again, like for the treatment by Merlin, and the treatment by Frontier Optima, rate at which organic matter content influenced ED_{90} was highest for *Senecio vulgaris*. Another similarity with the experiments with Merlin was the fact that when controlling weeds by using the mixture of Frontier Optima and Merlin, *Stellaria media* was hardest to control at soils containing low organic matter contents, whereas *Senecio vulgaris* was hardest to control at soils containing high organic matter contents. In *Digitaria ischaemum* the effect of soil organic matter content on ED_{90} value was, differently from *Senecio vulgaris* and *Stellaria media*, best described quadratic. However, the calculated ED_{90} value in *Digitaria ischaemum* was exceptionally low, indicating that these values might be wrong.

The results of the current experiments clearly confirm that the behavior of herbicides in soil is related to organic matter content. It is confirmed that a higher organic matter content results in a lower herbicide efficacy for Frontier Optima, Merlin, and the mixture of these two. The mechanism behind the relation between herbicide performance and organic matter content is probably soil sorption. Sorption is based on factors such as the amount and quality of soil organic carbon, texture, pH, and soil moisture (Wauchope *et al.*, 2002). Research conducted by Mitra *et al.* (1999) showed that soil organic matter, together with soil pH, is highly correlated with sorption of isoxaflutole, the active ingredient of Merlin. Higher sorption leads to lower risk of crop injury and to lower risks of contamination of ground water. The correlation between sorption and risk of crop injury supports the idea that the sorption of herbicides has a negative influence on the efficacy of herbicide applications. Mitra *et al.* (1999) tested sorption of isoxaflutole for four soils, ranging from 1.8% organic matter to 3.6% organic matter. Furthermore, sorption was tested on a soil containing 57% organic matter. They found a linear relationship between the sorption of these soils and their organic matter content. However, according to Xing and Pignatello (1997) sorption in soil organic matter is not linearly related with organic matter level. This so called “dual-mode model of sorption” can also be applied to *isoxaflutole* sorption (Xing, 2001). Responses of herbicide efficacy to soil organic matter in this research was non-linear in one experiment (for *Digitaria ischaemum,* treated with the mixture of Frontier Optima and Merlin). In all the other experiments, however, the relationship between soil organic matter content and ED_{90} value was better described linearly.

Research conducted in Belgium by Rouchaud *et al.* (1998) showed that isoxaflutole sorption is highly dependent on soil organic matter and on organic manure application prior to the growing season. Higher organic matter content and recent organic manure applications lead to a higher sorption of organic matter, and thus to a longer soil half-live time of isoxaflutole. Unfortunately, the research did not provide detailed information about the efficacy of the herbicide in the different soil types, although the statement is made that higher herbicide sorption leads to a higher local herbicide concentration, resulting in a higher herbicidal efficacy. This statement is not supported at all by the results of the experiments conducted for this research.

Not much information regarding the influence of organic matter content on herbicide efficacy of Frontier Optima (*dimethenamid*-P) was found. However, according to Hartzler (2002) the K_{oc} value of dimethenamid was 155. This value shows the ratio between soil bound herbicide, and herbicide dissolved in water. The K_{oc} of isoxaflutole was not found. When looking at the validity of the hypothesis that a higher soil organic matter content results in a lower herbicide efficacy, it might be wise to look whether this relation exists in other soil applied herbicides. Gonese and Weber (1998) conducted research on the effect of organic matter on the performance of soil applied herbicides such as pendimethalin, chlorimuron and imazaquin. They concluded that herbicide performance was correlated to organic matter level of the soil. For chlorimuron and imazaquin, dose to realize 100 % weed control was linearly related to organic matter level (p < *0.01*). This also held for pendimethalin (p < 0.05). In another report, Weber *et al.* (1987) described the relationship between soil organic matter content and performance of soil applied herbicides such as alachlor, butralin, metolachlor, metribuzin and trifluralin. Results were based on field experiments for soils containing organic matter contents between 0.7 % and 15.5 %. A linear and curvilinear description of the relationship between effective herbicide rate and organic matter level resulted in about the same herbicide dose advices. Unfortunately, no statistical information regarding the reliability of the given formulas was provided.

The quantitative effect of soil organic matter content on the performance of the different herbicides was different for the three weed species that were tested. However, for all weed species a lower organic matter level led to a lower ED_{90} value. But the rate at which organic matter level influenced herbicide performance was highest for *Senecio vulgaris*, regardless of the herbicide that was used. An explanation for this was not found, but results indicate that *Senecio vulgaris* might influence soil sorption negatively at low organic matter contents, or positively at high organic matter contents. However, it is shown that the herbicidal doses can be reduced at soils containing low amounts of organic matter, without affecting the efficacy of an herbicidal treatment for all weed species that were tested. This saves costs for the farmer and is also beneficial for the environment.

For every herbicide type and weed species, the ED_{90} values were expressed against percentage organic matter. Since each herbicide was tested on three weed species, per herbicide three dose-response curves were obtained, as can be seen in figures 3.7, 3.13, and 3.19. In practical situations several different weed species will be present in the fields where weed control needs to be conducted. Weed control has to result in a satisfying reduction of all weed species that are present. For herbicide dose recommendation rates, it is assumed in this research that the applied herbicide dose should at least result in 90% weed control in all weed species that are present. In the experiments where Merlin and the mixture of Merlin and Frontier Optima were applied, the slope and intercept of the relationship between organic matter content and ED_{90} value of *Stellaria media* and *Senecio vulgaris* differed a lot. This resulted in lower dose advices for *Senecio vulgaris* compared to *Stellaria media* at low organic matter levels, and higher dose advices for *Senecio vulgaris* compared to *Stellaria media* at high organic matter levels. The final dose advice formulas therefore are based partly on the curves of both weed species, resulting in adequate weed control for both weed species. When using Frontier Optima, optimal treatment of *Senecio vulgaris* always required more herbicide compared to optimal control of *Stellaria media* and *Digitaria ischaemum* if organic matter contents are over 1.4%. Therefore, for Frontier Optima, the dose advice formula relating organic matter content to herbicide dose recommendation is solely based on data obtained with *Senecio vulgaris*. The calculated dose advices to realize adequate weed control for the tested herbicides are presented here:

Dose Merlin = 1.30 X % O.M. + 13.7 (gram ha^{-1}*)*

Dose Frontier Optima = 0.105 X % O.M. + 0.08 (l ha^{-1}*)*

Dose mixture Merlin and Frontier Optima

Merlin = 1.08 X % O.M. + 26.56 (gram ha^{-1})

Frontier Optima = 0.011 X % O.M. + 0.27 (l ha^{-1})

Using these formulas results, as mentioned before, in an exceeding of the maximum allowed dose of Frontier Optima at higher organic matter contents. However, when applying Merlin in rates mentioned in the formula will result in a lower rate compared to the advised, and maximum rate. It can be questioned whether it is realistic that the dose advised by the formula presented above is always at least 50% lower compared to the maximum dose.

In conclusion, it can be concluded from the experiments that organic matter content is related to soil applied herbicide efficacy. A higher soil organic matter content results in a higher herbicide efficacy. This is supported by earlier research (Mitra *et al.*, 1999; Xing, 2001). In our research, this relationship was best described linearly. Currently there is no agreement whether it really is a linear relationship, or whether a non-linear approach would be better (Mitra *et al.*, 1999; Xing and Pignatello, 1997). For Merlin, Frontier Optima, and the mixture between Merlin and Frontier Optima, formulas describing the effect of organic matter level on herbicide dose to realize adequate weed control were obtained.

4.2 Evaluation experimental setup

A though aspect in these experiments was the fact that throughout the experiments the germination rate was quite variable. It would have been ideal if the germination rate of the three wed species would have been more stable. In that case, the different experiments could be compared more easily. Since soil herbicides are applied before weed emergence and are likely to affect the emergence rate, it is also impossible to correct for these differences in hindsight. Therefore, it is impossible to adjust the obtained herbicidal results for variation in emergence rate. A relatively high variability in results is thus unavoidable and can only be counteracted by increasing the number of replicates.

Experiments were conducted in greenhouses in Wageningen in the period between May 2008 and August 2008. This experimental setting guaranteed adequate climate control, which is rather important to compare obtained data with data of other (replication) experiments. Another result of this experimental setting is, however, that it is hard to make statements about absolute herbicide recommendation rates. On one hand, herbicide efficacy is promoted due to the fact that the soil was kept quite wet during the entire experiment. Next to this, water was taken up from the aluminum trays under the pots, resulting in a possible higher herbicide uptake rate, since no herbicide could drain away. On the other hand, plant growth is promoted strongly due to the rather high temperature and the lack of water shortage. Under field conditions these circumstances will not always be met, what might result in different absolute responses of the weeds to the herbicides. However, the relative differences between the performance of an herbicide on a weed species, and the organic matter level of the soil will also be present under field conditions. There is no reason to assume different relative responses under field conditions compared to greenhouse conditions.

Plant biomass was used for calculating herbicide efficacy. However, due to the absence of a crop in these experiments, weed plants that escaped from the herbicide treatment were able to grow with unlimited resources, thus obtaining a large biomass. Most likely, this situation would not occur in field circumstances. In these situations, using plant biomass for explaining herbicide performance might result in an underestimation of the performance realized in a true field situation.

Furthermore, for conducting these experiments, soils of two different locations were mixed in different ratios to generate different organic matter levels. Doing this will probably imply that other physical characteristics of the soils will also dependent on the mixing ration of the two soils. The pH for instance, ranged from 4.8 in the soil having the highest organic matter content to 6.1 in the soil having the lowest organic matter content. Furthermore, the cation exchange capacity (CEC) ranged from 54 mmol kg^{-1} for the soil containing the lowest organic matter content to 282 mmol kg^{-1} for the soil containing the highest organic matter content. Due to the experimental setting used in the current experiments, it is therefore impossible to exclusively allocate differences in performance of the different herbicides to organic matter content. The presence of these confounding factors is however difficult to avoid.

Despite the improvements in experimental set-up that are possible, clear formulas describing the relationship between soil organic matter content and herbicide efficacy were obtained for Frontier Optima, Merlin, and the mixture of Frontier Optima and Merlin. Formulas describing this relationship are necessary to realize a tailor made herbicide dose advice based on organic matter level. However, more steps are necessary to realize this. This will be described in the following chapter, where the perspective of this research is described.

5. Perspective

During this research project, the effect of soil organic matter content on the efficacy of a number of soil-applied herbicides was determined. Determining herbicide dose advices based on soil organic matter content is however just one step required for practical implementation. In this chapter the current status of some of the other necessary steps for implementation are discussed. Furthermore, an example is taken to get an idea of the potential environmental- and economic savings of tailor-made soil-applied herbicide dose recommendations.

5.1 Framework for research implementation

Determining soil organic matter content

For the realization of a tailor made herbicide dose advice based on soil organic matter level, it is important to have knowledge of the spatial variability of organic matter in the soil. Currently, however, obtaining representative soil samples regarding soil organic matter content is a critical issue (Adamchuk *et al.*, 2004). Such samples should be collected with adequate spatial density at the proper depth and during the appropriate time. According to Hummel *et al.* (2001), differences in soil parameters such as organic matter content might occur on a finer spatial resolution than can be documented with manual or laboratory methods, due to the costs of sampling and analysis procedures. Therefore there is a need for the development of sensors that characterize within-field variability more accurately at acceptable costs and effort (Hummel *et al.*, 2001; Patzold *et al.* 2008).

Currently soil organic matter content is mostly determined by the analyses of soil samples in a laboratory. Most often this is determined at field level. However, in fields with high variability in organic matter amount, a lot of soil samples need to be taken to make an accurate map of the organic matter level at different locations within the field. This comes along with high sampling costs. A solution for this problem might be the development of on-the-go sensors.

Several new on-the-go sensors have been developed to describe soil properties (Adamchuk *et al.*, 2004). Organic matter, among other soil properties, is reporter to be targeted by using electrical and electromagnetic sensors. These sensors can measure electrical resistivity (ER) or electrical conductivity (EC). Due to the rapid response, low costs and high durability, electrical and electromagnetic sensors are most attainable techniques for on-the-go soil mapping (Adamchuk *et al.*, 2004). However, Sudduth *et al*. (2001) showed that factors such as soil moisture, temperature, and operation speed and height had an effect on the outcome of the measurements.

Another class of sensors that can be used to determine organic matter level is the group of optical and radiometric sensors. Using these methods provides a non-destructive and rapid technique to determine soil properties. Level of reflectance, absorption or transmittance of energy is affected by different soil properties such as moisture, organic matter, particle size, iron oxides, mineral composition, and other attributes (Baumgardner *et al.*, 1985; cited by Adamchuk *et al.,* 2004). Near infrared (NIR) soil spectral response is highly suitable to predict soil factors such as organic matter. However, soil should be homogenous to obtain valid data regarding organic matter, since reflectance is only based on the topsoil layer.

A final method to sense organic matter levels on-the-go is by measuring gamma radiation (van Egmond *et al.*, 2008; Loonstra and van Egmond, 2009). This sensor measures the radiation of naturally occurring radioactive elements such as potassium (^{40}K) and uranium (^{238}U). 90 % of the measured radiation originates from the top 0.3 m of soil. Different soil- and sediment types are showing unique concentrations of such elements. From this, several soil characteristics such as organic matter level can be derived. According to van Egmond *et al.* (2008), R^2 between estimated values based on organic matter measurements, and measured (sampled) soil property values are between 0.7 and 0.95. The Dutch company "the Soil Company" offers services to map soil properties using the gamma radiation sensor. In the Netherlands, already a lot of gamma radiation measurements have been conducted. Therefore, the quantitative relationship between gamma radiation and soil organic matter content is known to be valid for a wide range of soil types. Due to this, only very few calibration samples are required (e.g. for soil texture, only one calibration sample per 10 hectare of land. (Loonstra, 2008). Wong and Harper (1999) reported a strong relationship between organic carbon content and measurements of gamma radiation (R^2 = 0.89). However, according to them it is questionable whether gamma ray spectrometry provides good surrogates of other soil properties such as organic matter. Local calibration remains important.

A method to realize a more accurate prediction of soil organic matter content is by combining several on-the-go sensors (Mahmood *et al.*, 2009). According to them the combined use of fundamentally different sensors (e.g. gamma ray, electro magnetic and reflectance) will possibly provide more reliable measurements compared to the use of a single sensor.

In conclusion, it can be mentioned that determination of organic matter level by sampling is not yet suitable in fields which vary largely in organic matter content. The development of on-the-go sensors, which can measure organic matter content at high resolution, is still in its infancy. Often the theoretical support of these methods is not yet complete.

Decision rules

During the experiments described in this report, only the effects of two herbicides have been tested on three weed species. To develop decision rules for farmers in a good way, data for more different soil-applied herbicides should be obtained. Also, the amount of weed species that is tested should increase, to give a good overview of reductions in herbicide use that can be reached without influencing the efficacy of the treatment. To gain an as much as possible reduction in herbicide use it is important to test the soil-applied herbicides that are most commonly used in the Netherlands. It is important to conduct field trials to generate decision rules applicable by farmers. Furthermore, it might be interesting to not only take organic matter into account, but also soil properties as soil type and pH. Taking these factors into account might give a better representation of herbicide efficacy, since these factors also have an influence on soil sorption, like organic matter (Mitra *et al.*, 1999; Wauchope *et al.*, 2002).

Precise application methods

Using the techniques described above might result in high resolution estimations of organic matter content in the field. However, the preciseness of a herbicide application is dependent on the accuracy of the spraying equipment. If one knows precise details regarding organic matter level, and one can apply a precise amount of herbicide at a very small scale this can result in a large reduction in herbicide use. Spraying devices currently are often over 27 m wide. A simple way to adjust herbicide rate is by slightly adjusting driving speed. However, prototype devices are being developed which can realize a higher accuracy compared to spraying devices that are currently used in practice. Kempenaar *et al.* (2010) reported about SensiSpray, a prototype spraying device that can adjust the applied pesticide dose per section of the spraying boom. Applying variable herbicide doses is possible by using the Lechner Varioselect nozzle system. Using such a device for weed control would result in a spraying accuracy of 10 m^2. Investments in such a system would be high, especially if it is only used for weed control in maize cultivation. However, according to Stokkermans (2008) weed control at 80 % of the maize that is grown on Dutch farms, is conducted by contractors. Compared to farmers, contractors spray more hectares with their sprayer, which leads to lower costs per hectare. Furthermore, if the system can also be used in other crops, for example to spray against *Phytophtera infestans* in potatoes, demanding multiple fungicide applications per growing season, investments would be paid off more rapidly.

Within field variability

Reductions in soil-applied herbicide input are clearly possible when basing herbicide dose on soil organic matter content. Especially in fields varying largely in organic matter content, applying soil-applied herbicides has to be done according to a worst-case scenario. One can not take a risk of applying a too low herbicide level, since the efficacy of the herbicide is too low at soils containing high organic matter contents. Therefore, the usage of methodologies for determining soil organic matter content, and the accompanying decision rules and application methods as described above, will be most beneficial for these fields. However, in fields varying largely in organic matter content, using a herbicide dose advice based on soil organic matter content is not easy yet. High resolution determination of organic matter content is hard, and techniques for very precise application of herbicides are no common practice yet, as described above. Therefore, currently one might consider first to only adjust herbicide dose on average organic matter content, in fields where variability is small. As indicated by the formulas described in chapter 4.1, this might already reduce herbicide use largely in fields containing low organic matter contents. Since weed control is mostly conducted by contractors (Stokkermans, 2008), it is important that information regarding organic matter content is provided by the farmer.

5.2 Practical example

In figure 4.1 a map containing the organic matter levels of a field in the province of Drenthe, the Netherlands is presented. The presented map is part of a field in which soil organic matter was determined using gamma ray detectors (van Egmond *et al.*, 2008). The map is divided in 1122 grids of

16 m^2, corresponding to a total area of about 1.80 ha. For this example, it is assumed that the provided information regarding organic matter level is reliable. Organic matter level in this field is highly variable and ranges from about 2.5 to 17.5 % organic matter. Using a device such as SensiSpray (Kempenaar *et al.*, 2010) would make it possible to apply different doses of herbicide in each grid of the field.

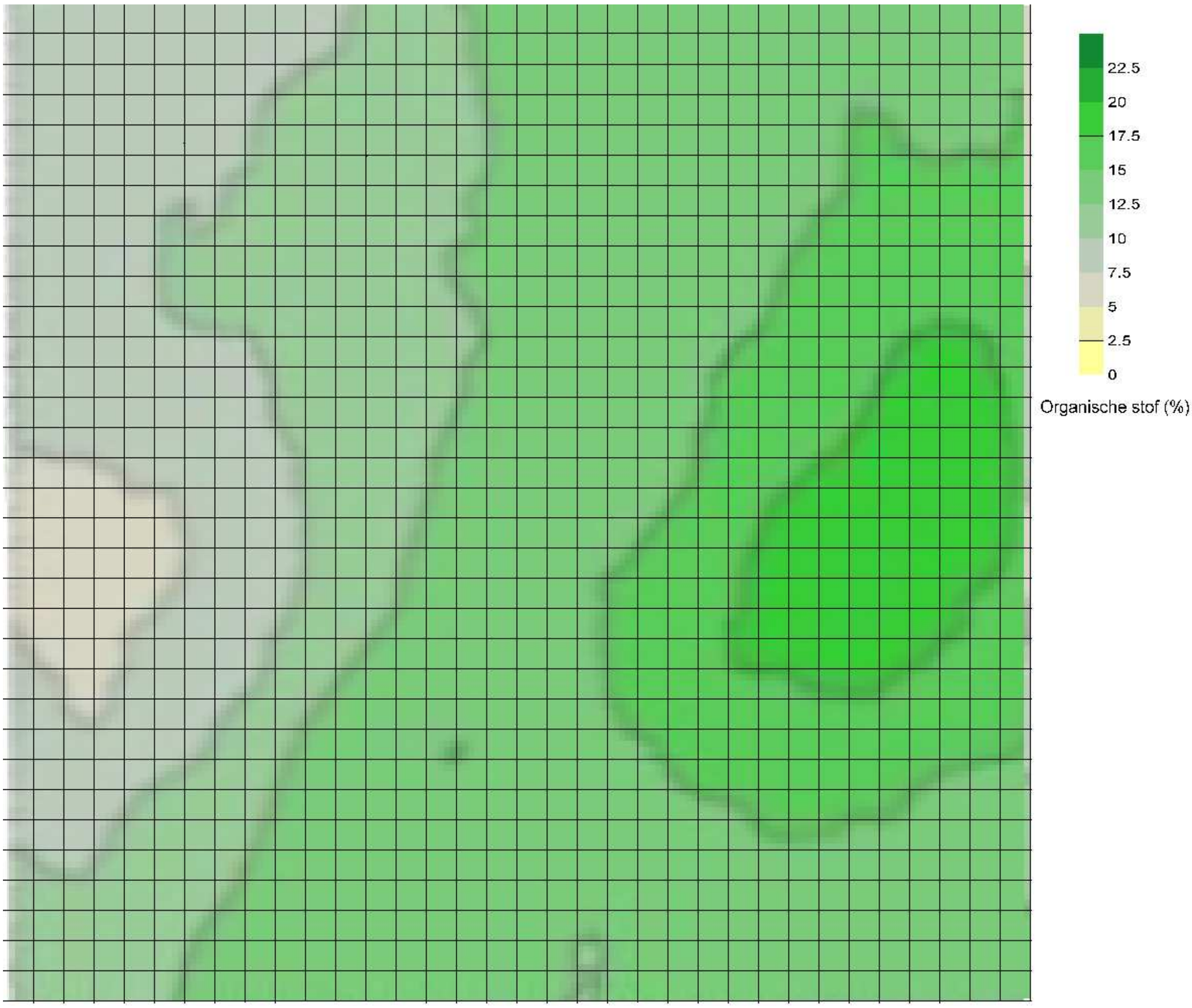

Fig. 5.1 Soil organic matter contents in a 1.8 ha field in the province of Drenthe. Grid size is 4 m x 4 m. Data are obtained and adjusted from the Soil Company, Groningen, the Netherlands.

The majority of the soil of the field presented in figure 5.1 contains between 10 to 12.5 % organic matter (42.1 % of the area). When weed control is conducted on this field, most likely a strategy is chosen in which adequate weed control for the whole field is guaranteed. The recommended dose advices for the herbicides that were tested during this research are 1.4 l Frontier Optima ha^{-1} and 100 g Merlin ha^{-1} (DLV, 2008). The advice for the mixture is 0.7 l Frontier Optima and 70 g Merlin (Certis, 2007). However, when the applied dose is based on soil organic matter content, the dose advise can be adjusted. The map presented in figure 5.1 is shown again in figure 5.2, but in the latter one, each grid received the colour belonging to the majority of the surface of the grid. In this way, it becomes clear what dose would be applied in a low dosage system.

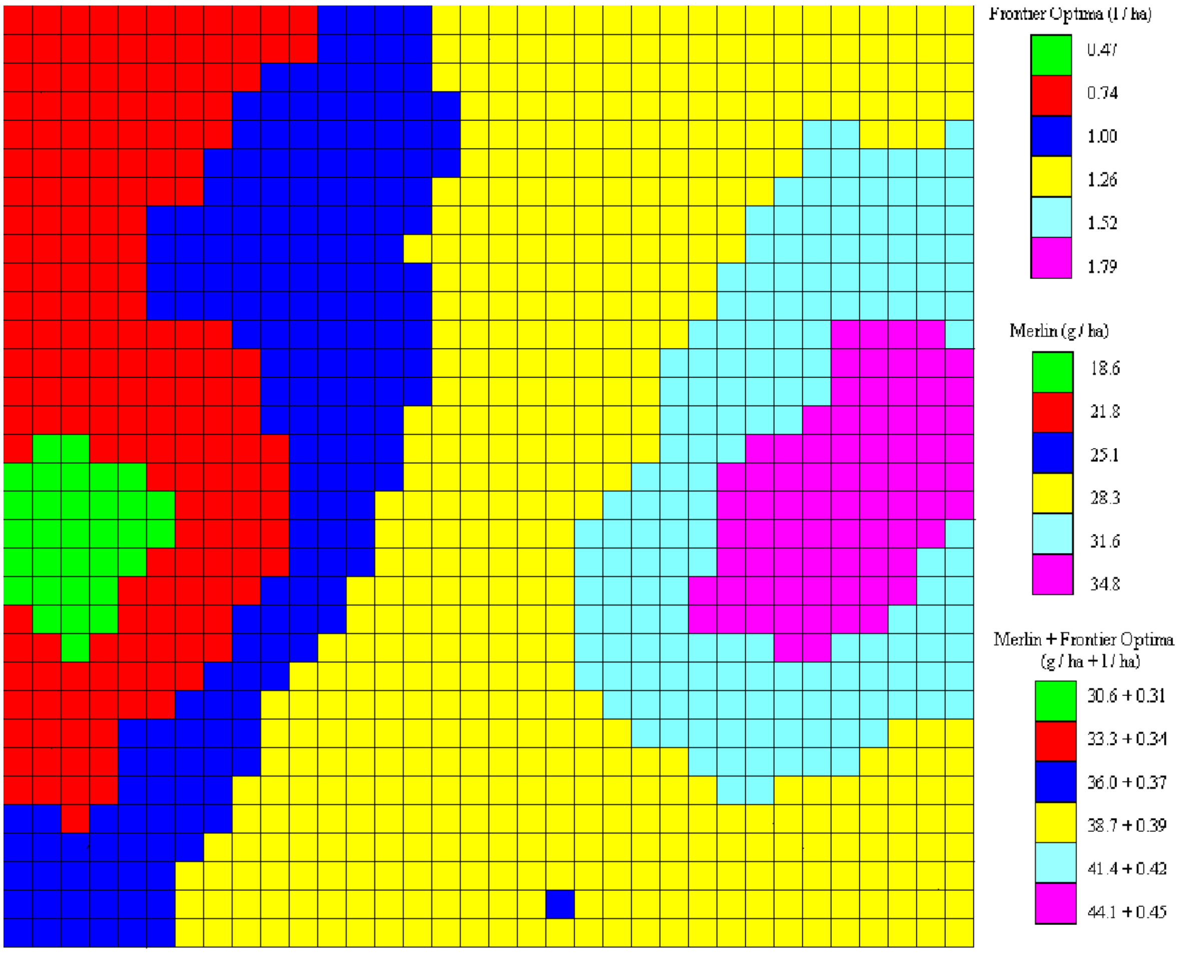

Fig. 5.2 Herbicide dose advices for a 1.8 ha field in the province of Drenthe, the Netherlands. Grid size is 4 m x 4 m. Dose advices are calculated using the formulas presented in paragraph 4.1.

Using the map presented in figure 5.2, one can calculate how frequent each soil organic matter content is present. With this information, a calculation can be made to determine the soil-herbicide input of the different soil-applied herbicides in this field. This has been done in table 5.1. An overview has been provided of doses used at both a conventional system, in which herbicide dose is based on the recommended dose advices of DLV (2008), and a system in which herbicide dose is based on organic matter content, using the formulas presented in chapter 4.1.

Table 5.1 Analysis of environmental load and herbicide costs of Merlin, Frontier Optima, and the mixture of Merlin and Frontier when applied at conventional recommended doses and at doses based on soil organic matter content. For this the field presented in fig. 5.1 and fig. 5.2 is taken as example. Different colours indicate risk of damage to environment (red = high risk, orange = moderate risk, and green = low risk)

Herbicide	Organic matter content	Area	Using recommended doses: Dose (gha-1, lha-1)	amount (g , l)	MBP[1] waterlife	MBP soil life	MBP soil water	Costs[2] (€)	Using doses that are adjusted for organic matter content: Dose (gha-1, lha-1)	Amount (g , l)	MBP waterlife	MBP soil life	MBP soil water	Costs (€)	Savings
Merlin	2.5 – 5.0%	0.05	100	5	3	0	65	2.25	18.6	0.9	0	0	13	0.41	82%
	5.0 – 7.5%	0.30	100	30	3	0	1	13.50	21.8	6.5	1	0	0	2.93	78%
	7.5 – 10.0%	0.30	100	30	3	0	0	13.50	25.1	7.5	1	0	0	3.38	75%
	10.0 – 12.5%	0.76	100	76	3	0	0	34.20	28.3	21.5	1	0	0	9.68	72%
	12.5 – 15.0%	0.27	100	27	3	0	0	12.15	31.6	8.5	1	0	0	3.83	69%
	15.0 – 17.5%	0.13	100	13	3	0	0	5.85	34.8	4.5	1	0	0	2.03	65%
	Total	**1.81**		**181**				**81.45**		**49.6**				**22.24**	**73%**
Frontier Optima	2.5 – 5.0%	0.05	1.4	0.07	238	10	0	1.44	0.47	0.02	80	3	0	0.41	71%
	5.0 – 7.5%	0.30	1.4	0.42	238	10	0	8.61	0.74	0.22	126	5	0	4.51	48%
	7.5 – 10.0%	0.30	1.4	0.42	238	10	0	8.61	1.00	0.30	170	7	0	6.15	29%
	10.0 – 12.5%	0.76	1.4	1.06	238	10	0	21.73	1.26	0.96	214	9	0	19.68	9%
	12.5 – 15.0%	0.27	1.4	0.38	238	10	0	7.79	1.52	0.41	258	11	0	8.41	-8%
	15.0 – 17.5%	0.13	1.4	0.18	238	10	0	3.69	1.79	0.23	304	13	0	4.72	-28%
	Total	**1.81**		**2.53**				**51.87**		**2.14**				**43.87**	**15%**
Mixture	2.5 – 5.0%	0.05	70	3.5	121	5	46	2.29	30.6	1.5	54	2	4	0.98	57%
	5.0 – 7.5%	0.30	70	21	121	5	1	13.76	33.3	10.0	58	2	0	6.55	52%
	7.5 – 10.0%	0.30	70	21	121	5	0	13.76	36.0	10.8	62	3	0	7.07	49%
	10.0 – 12.5%	0.76	70	53	121	5	0	34.72	38.7	29.4	67	3	0	19.26	45%
	12.5 – 15.0%	0.27	70	19	121	5	0	12.45	41.4	11.2	71	3	0	7.34	41%
	15.0 – 17.5%	0.13	70	9	121	5	0	5.90	44.1	5.7	76	3	0	3.73	37%
	Total	**1.81**		**127**				**83.19**		**68.6**				**44.93**	**46%**

[1] MBP means milieu belasting punten = environmental load points. These are based on 1 ha containing the given organic matter content

[2] Costs are costs of herbicide, based on adviced prices of 2007, excl. VAT. Frontier Optima = €20.50 / liter, Merlin = €450,00 / kg

As can be seen in table 5.1 herbicide saving is dependent on organic matter level. When organic matter levels are low, savings until 82% are possible when using Merlin. Furthermore, it is clear that savings are very herbicide specific. When looking at the overall savings, Merlin use can be reduced by 73%, whereas use of Frontier Optima can only be reduced by 15%. However, it should be mentioned that the organic matter content based herbicide dose advice of Frontier Optima exceeds the highest legal allowed dose of Frontier Optima, and therefore will not be applied in practice.

Merlin, Frontier Optima and their combination have an effect on the environment. Frontier Optima contains 64% dimethenamid-P, having a density of 1.13 kg l^{-1}. If 1 liter of Frontier Optima is applied, this results in 1.13 kg Frontier Optima, resulting in 0.72 gram dimethenamid-P. This means that when the advised dose is applied, 0.720 * 1.4 l = 1.01 kg dimethenamid-P is applied on one hectare. Dimethenamid-P can have a negative influence on waterlife and soil life. Merlin contains 75 % isoxaflutole. The recommended dose for Merlin is 0.100 kg ha^{-1}. This results in a recommended dose of 0.075 kilogram isoxaflutole per hectare. Isoxaflutole can have a negative impact on soil water quality, especially in soils containing low organic matter content, having a large risk of leaching. By using the “milieumeetlat” (*“environmental indicator*”) of CLM (Centrum voor Landbouw en Milieu) (*Centre for Agriculture and Environment*), the influence of the different herbicides on the environment can be compared. This has been done in table 5.1. As can be seen, the application of Frontier Optima (solely or in a mixture) results in a high risk for waterlife. However, if herbicide rates would be based on organic matter content, the risk for waterlife will be reduced. This is the case at all organic matter contents for the mixture of Frontier Optima and Merlin. At soils containing very low amounts of organic matter, risk of waterlife will also be reduced when Frontier Optima is applied. Furthermore, applying Merlin at soils containing very low organic matter contents (not presented in table 5.1) results in a moderate risk for soil water quality. This risk would be reduced to low if dose of Merlin was based on soil organic matter content.

Applying herbicides brings along costs for the farmers, which are analyzed here. In this analysis only the purchase costs of the herbicide have been taken into account. Costs for spraying are assumed to be equal for all options. Mixing Frontier Optima and Merlin does not cause any extra costs, since they can be combined in one tank mixture without problems. Therefore they can both be applied within one spraying application. Costs of using Merlin, Frontier Optima, and the mixture of Merlin and Frontier Optima are presented in table 5.1. The costs are based on the herbicide prices of 2007 (DLV, 2008). It can be seen that when applying the advised herbicide rates the costs for applying Frontier Optima are lower compared to applying Merlin or the mixture of Merlin and Frontier Optima. However, when basing herbicide rate on organic matter content, the use of Merlin is most attractive, due to the large reduction in herbicide use of Merlin. From that point of view, basing herbicide usage on organic matter content will be beneficial twice. If farmers chose using Merlin to control weeds in maize, it is both the cheapest and the most environmental friendly option.

6. Conclusions

- For *Senecio vulgaris*, *Stellaria media*, and *Digitaria* ischaemum, organic matter content is linearly related to herbicide efficacy of Frontier Optima (*dimethenamid-P*). A higher organic matter content results in a lower herbicide efficacy.
- *Senecio vulgaris* is harder to control using Frontier Optima compared to *Stellaria media* and *Digitaria ischaemum*, regardless of soil organic matter content.
- For *Senecio vulgaris*, *Stellaria media*, and *Digitaria* ischaemum, organic matter content is linearly related to herbicide efficacy of Merlin (*isoxaflutole*). A higher organic matter content results in a lower herbicide efficacy.
- When comparing control of *Stellaria media* and *Senecio vulgaris* using Merlin, or using the mixture of Frontier Optima and Merlin, it is harder to control *Stellaria media* at soils containing low organic matter content compared to soils containing high organic matter content, whereas it is harder to control *Senecio vulgaris* at soils containing high organic matter contents, compared to soils containing low organic matter contents..
- For *Senecio vulgaris* and *Stellaria media*, organic matter content is linearly related to herbicide efficacy of the mixture of Frontier Optima and Merlin. A higher organic matter content results in a lower herbicide efficacy. This relationship is quadratic for *Digitaria ischaemum*.
- *Digitaria ischaemum* is controlled highly efficient by Frontier Optima and Merlin in pot experiments. This is contradictory the situation in practice, where it is a hard to control this weed species, especially at soils containing low organic matter content.
- Rate at which the efficacy of all tested herbicides responds to soil organic matter content is always highest when controlling *Senecio vulgaris*.
- Frontier Optima should not be used for controlling *Senecio vulgaris* if organic matter contents are over 12%.
- When applying recommended soil-herbicide dose rates, Frontier Optima is the cheapest solution.
- When adjusting herbicide dose rates based on organic matter content, Merlin is economically most beneficial.
- Herbicide usage of Merlin can be reduced by 73% when adjusting herbicide rate to organic matter content, compared to using recommended dose rates. This is only 15% for Frontier Optima.
- Adjusting herbicide dose rates based on organic matter content is more beneficial for waterlife compared to applying recommended doses for Frontier Optima.
- The development of on-the-go sensors for measuring organic matter content are still in its infancy.
- More research regarding the determination of organic matter content, techniques for high resolution herbicide application, and decision rules is needed to implement herbicide dose strategies based on organic matter level.
- Adjusting herbicide dose on average organic matter content, in fields containing low organic matter content would already save much herbicides.

Literature

Adamchuk, V.I., Hummel, J.W., Morgan, M.T. and Upadhyaya, S.K. (2004): On-the-go soil sensors for precision agriculture. *Computers and Electronics in Agriculture* **44**: 71 – 91.

Australian Pesticides and Veterinary Medicines Authority (2007): Evaluation of the active Dimethenamid-P in the product Frontier-P herbicide. *Australian Pesticides and Veterinary Medicines Authority,* Canberra.

California Department of Pesticide Regulation (2007): Dimethenamid-P. *Public report* **2007-2**.

Certis (2007): Merlin in maïs na zaaien. *Certis Actueel*, 20 april 2007

DLV (2008): Gewasbescherming in de akkerbouw en veehouderij.

EC Commission (2002): Towards a thematic strategy on the sustainable use of pesticides (*COM(2002) 349 final*).

Egmond, F.M. van, Loonstra, E.H. and Limburg, J. (2008): Gamma-ray sensor for topsoil mapping: the Mole. *Global workshop on high resolution digital soil sensing & mapping, Sydney, Australia.*

Eurostat: website ec.europa.eu/eurostat. Agricultural tables, subcategory agriculture and environment

FAOSTAT: website faostat.fao.org. Category production (ProdSTAT), subcategory crops.

Gonese, J.U. and Weber, J.B. (1998): Herbicide rate recommendations: soil parameter equations vs registered rate recommendations. *Weed Technology* **12**: 235 – 242.

Haynes, D., Ralph, P., Pranges, J. and Dinnison, B. (2000): The impact of the herbicide diuron on photosynthesis in three species of tropical seagrass. *Marine Pollution Bulletin* (**41**): 288 – 293.

Herzler, B. (2002): Absorption of soil-applied herbicides. *Iowa Stat University*. http://www.weeds.iastate.edu/mgmt/2002/soilabsorption.htm, checked on 22-04-2010.

Hummel, J.W., Sudduth, K.A. and Hollinger, S.E. (2001): Soil moisture and organic matter prediction of surface and subsurface soils using an NIR soil sensor. *Computers and Electronics in Agriculture* **32**: 149 – 165.

Kempenaar, C. and Lotz, L.A.P. (2004): Reduction of herbicide use and emission by new weed control methods and strategies. *Water Science and Technology* **49**(3): 135 – 138.

Kempenaar, C., Oosterhuis, H., Lans, A. van der, Schans, D. van de, Stilma, E., Hendriks, V., Verwijs, B., Wijk, K. van, and Zande, J. van de (2010): Ontwikkeling van het prototype van SensiSpray in de gewassen aardappel en tulp. *Plant Research International, Wageningen, nota* **667**.

Kudsk, P. and Streibig, J.C. (2003): Herbicides – a two edged sword. *Weed Research* **43**: 90 – 102.

Lokers, R.M. and de Jong, A. (2008): Bodemdata voor precisielandbouw. *Report, Alterra, Wageningen.*

Loonstra, E.H. (2008): A Mole collecting fingerprints. *IAMFE Denmark 2008*, Aarhus.

Loonstra, E.H. and Egmond, F.M. van (2009): On-the-go measurement of soil gamma radiation. In: *Henten, E.J. van, Goense, D. and Lokhorst, C. (eds): Precision agriculture '09*. Wageningen, Wageningen Academic Publishers.

Lowder, S.W. and Weber, J.B. (1982): Atrazine efficacy and longevity as affected by tillage, liming and fertilizer type. *Weed science* **30**: 273 – 280.

Mahmood, H.S., Hoogmoed, W.B. and Henten, E.J. van (2009): Combined sensor system for mapping soil properties. In: *Henten, E.J. van, Goense, D. and Lokhorst C. (eds): Precision agriculture '09.* Wageningen, Wageningen Academic Publishers.

Mitra, S. Bhowmik, P.C. and Xing, B. (1999): Sorption of isoxaflutole by five different soils varying in physical and chemical properties. *Pesticide Science* **55**: 935 – 942.

Olson, D.K., Sax, L., Gunderson, P. and Sioris, L.(1991): Pesticide poisoning surveillance through regional poison control centers. *American Journal of Public Health* **81** (6): 750 – 753.

Oorschot, J.L.P. van and Leeuwen, P.H. van (1992): Use of fluorescence induction to diagnose resistance of *Alopecurus myosuroides* Huds. (black-grass) to cholorotoluron. *Weed Research* **32**: 473 – 482.

Pallett, K.E., Cramp, S.M., Little, J.P., Veerasekaran, P., Crudace, A.J. and Slater, A.E. (2001): Isoxaflutole: the background to its discovery and the basis of its herbicidal properties. *Pest Management Science* **57**: 133 – 142.

Patzold, S., Mertens, F.M., Bornemann, L., Koleczek, B., Franke, J., Feilhauer, H. and Welp, G. (2008): Soil heterogeneity at the field scale: a challenge for precision crop protection. *Precision Agriculture* **9**: 367 – 390.

Peter, J.B. and Weber, J.B. (1985): Adsorption, mobility, and efficacy of metribuzin as influenced by soil properties. *Weed Science* **33**(6): 868 – 873.

Ritz, C. and Streibig, J.C. (2005): Bioassay analysis using R. *Journal of statistical software* **12** (5): 1 – 22.

Rouchaud, J., Neus, O., Callens, D. and Bulcke, R. (1998): Isoxaflutole herbicide soil persistence and mobility in summer corn and winter wheat crops. *Bulletin of Environmental Contamination and Toxicology* **60**: 577 – 684.

Seefeldt, S.S, Jensen, J.E. and Fuerst, E.P. (1995): Log-logistic analysis of herbicide dose-response relationships. *Weed technology* **9**: 218 – 227.

Smant, G. (1991): Eerste vaststelling van resistentie bij duist tegen chloortoluron in Nederland. *Gewasbescherming* **22**: 62 – 64.

Stokkermans, P. (2008): Telen met toekomst voor behoud rendabel maisteelt. *Nieuwe Oogst* 17 mei 2008: 8.

Sudduth, K.A., Drummond, S.T. and Kitchen, N.R. (2001): Accuracy issues in electromagnetic induction sensing of soil electrical conductivity for precision agriculture. *Computers and Electronics in Agriculture* **31**: 239 – 264.

Swanton, C. J., Mahoney, K.J., Chandler, K. and Gulden, R.H. (2008): Integrated weed management: knowledge-based weed management systems. *Weed Science* **56**: 168 – 172.

Tranel, P.J. and Wright, T.R. (2002): Resistance of weeds to ALS-inhibiting herbicides: what have we learned? *Weed Science* **50**: 700 – 712.

Wauchope, R.D., Yeh, S., Linders, J.B.H.J., Kloskowski, R., Tanaka, K., Rubin, B., Katayama, A., Kördel, W. Gerstl, Z., Lane, M. and Unsworth, J.B. (2002): Pesticide soil sorption parameters: Theory, measurement, uses, limitations and reliability. *Pest Management Science* **58**: 419 – 445.

Weber, J.B., Weed, S.B. and Waldrep, T.W. (1974): Effect of soil constituents on herbicide activity in modified soil field plots. *Weed Science* **22**(5): 454 – 459.

Weber, J.B., Tucker, M.R. and Isaac, R.A. (1987): Making herbicide rate recommendations based on soil tests. *Weed Technology* **1**: 41 – 45.

Wong, M.T.F. and Harper, R.J. (1999): Use of on-ground gamma-ray spectrometry to measure plant-available potassium and other topsoil attributes. *Australian Journal of Soil Research* **37**: 267 – 277.

Xing, B.S. and Pignatello, J.J. (1997): Dual-mode sorption of low-polarity compounds in glassy poly(vinyl chloride) and soil organic matter. *Environmental Science & Technology* **31**: 792 – 799.

Xing, B.S. (2001): Sorption of anthropogenic organic compounds by soil organic matter: a mechanistic consideration. *Canadian Journal of Soil Science* **81**: 317 – 323.

Appendices

Appendix I: Climatic data

Realized temperatures and realized relative humidity in greenhouse compartment 6.13. Data are averages per month, from May 1, 2008 until August 15, 2008.

		Temperature (ºC)	Relative humidity (%)
May	night	16.9	76.9
	day	20.9	74.6
June	night	18.1	78.1
	day	22.2	71.9
July	night	19.5	79.5
	day	23.5	71.3
August	night	19.5	78.4
	day	23.0	70.7

Appendix II: Commando structure "R"

This is an example of the command structure, used to determine the parameter values of a three parameter logistic dose-response model. Example is based on the experiments in which *Stellaria media* is treated by Frontier Optima.

```
*******R files DRC's experimenten Frontier tot Muur*********
library(drc)
frontier.muur<-read.csv ("F:/AV/R/Frontier_tot_muur_contr_blok_samen.csv", header=TRUE, sep=",", dec=".")
frontier.muur

******* 4 parameter logistic model*******
model.frontier.muur.l4<-drm(Bestrijding~Dose,Soil, data=frontier.muur)
anova(model.frontier.muur.l4)
summary(model.frontier.muur.l4)


******Collapse parameter d (higher limit)*******
model.frontier.muur.l3<-drm(Bestrijding~Dose,Soil, data=frontier.muur, fct=l3(fixed=c(NA,100,NA)))
modelFit(model.frontier.muur.l3)
summary(model.frontier.muur.l3)

*******Plot dose-response model******
plot(model.frontier.muur.l3,xlab="Dose",ylab="Fresh weight reduction (%)",ylim=c(0,120), xlim=c(0,100),col = TRUE)

******ED-90 values*******
ED(model.frontier.muur.l3, c(90), interval = "delta")

******Compare parameters*******
compParm(model.frontier.muur.l3,"b","-")
compParm(model.frontier.muur.l3,"e","-")
```

Appendix III: Pictures experiments

Frontier Optima

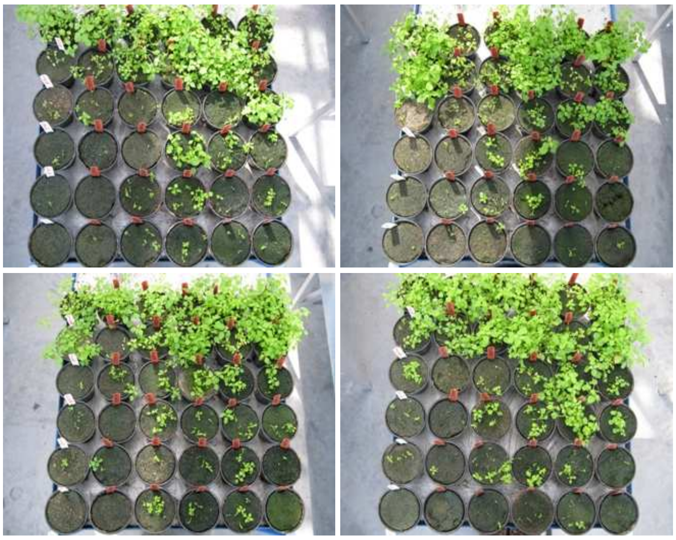

Fig. III.1 Pictures of *Stellaria media* treated with Frontier Optima. Organic matter level increases from left to right, herbicide dose increases from top to bottom. Pictures are four different blocks, obtained during the second replication experiment.

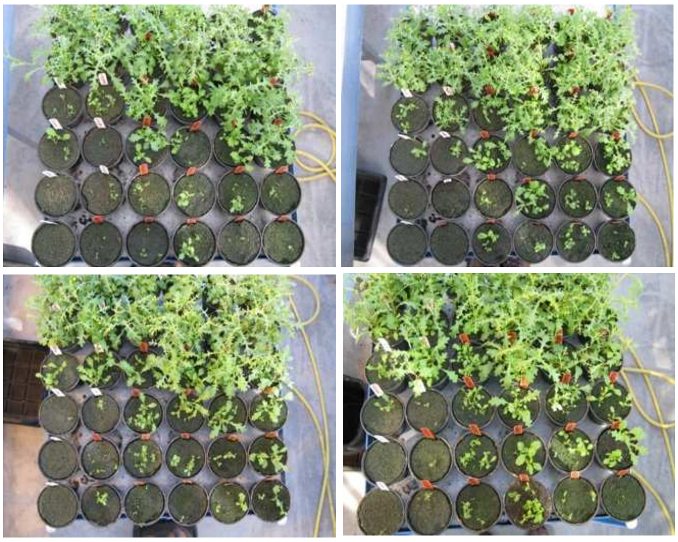

Fig. III.2 Pictures of *Senecio vulgaris* treated with Frontier Optima. Organic matter level increases from left to right, herbicide dose increases from top to bottom. Pictures are four different blocks, obtained during the second replication experiment.

Fig. III.3 Pictures of *Digitaria ischaemum* treated with Frontier Optima. Organic matter level increases from left to right. Pictures are four different blocks, obtained during the second replication experiment. Since treatment was highly efficient, only plants of one dose (0.01 l ha^{-1}) are shown.

Merlin

Fig. III.4 Pictures of *Stellaria media* treated with Merlin. Organic matter level increases from left to right, herbicide dose increases from top to bottom. Pictures are four different blocks, obtained during the second replication experiment.

Fig. III.5 Pictures of *Senecio vulgaris* treated with Merlin. Organic matter level increases from left to right, herbicide dose increases from top to bottom. Pictures are four different blocks, obtained during the second replication experiment.

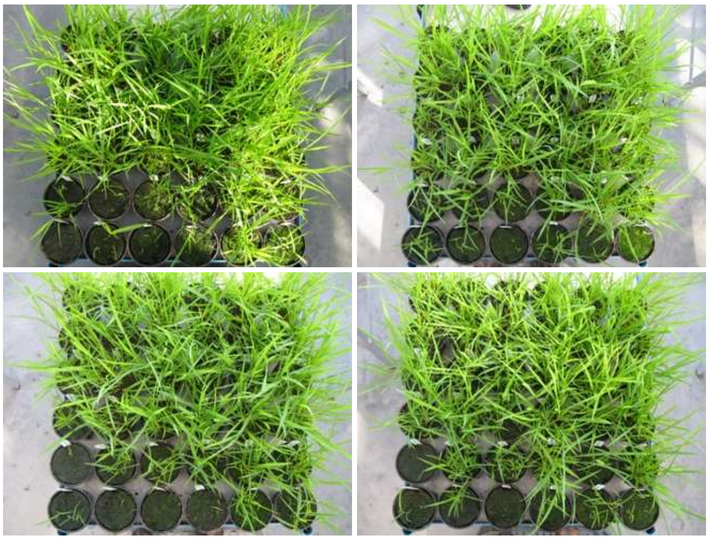

Fig. III.6 Pictures of *Digitaria ischaemum* treated with Merlin. Organic matter level increases from left to right, herbicide dose increases from top to bottom. Pictures are four different blocks, obtained during the second replication experiment.

Mixture Frontier Optima and Merlin

Fig. III.7 Pictures of *Stellaria media* treated with the mixture of Frontier Optima and Merlin. Organic matter level increases from left to right, herbicide dose increases from top to bottom. Pictures are four different blocks, obtained during the second replication experiment.

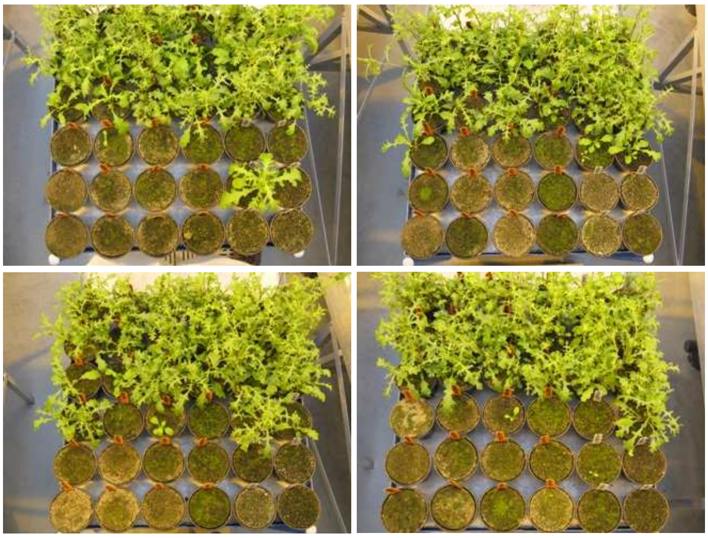

Fig. III.8 Pictures of *Senecio vulgaris* treated with the mixture of Frontier Optima and Merlin. Organic matter level increases from left to right, herbicide dose increases from top to bottom. Pictures are four different blocks, obtained during the second replication experiment.

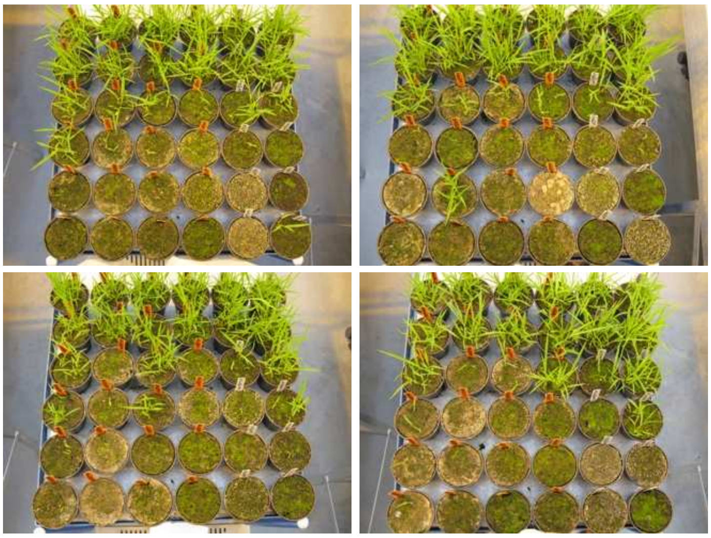

Fig. III.9 Pictures of *Digitaria ischaemum* treated with the mixture of Frontier Optima and Merlin. Organic matter level increases from left to right, herbicide dose increases from top to bottom. Pictures are four different blocks, obtained during the second replication experiment.