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Integrated weed management (IWM) case study – report on field studies, literature review, general conclusions and recommendations and future IWM research

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Summary

Integrated weed management (IWM) is a broad term covering many methods that can be combined and applied in various ways in the crop to constitute an IWM approach. In principle, an IWM strategy can be applied in any crop, and this case study decided to limit the study due to the available resources and equipment for experimentation. It was decided to focus on IWM in silage maize (*Zea mays* L.) but the results are also valid for grain maize. Silage maize is a widespread row crop in Europe for fodder production. It has a low competitive ability against weeds until it reaches canopy closure, and consequently there is a high demand for weed control in its initial growth phases. Many non-chemical weed control methods are applicable in maize and the crop is a suitable crop for studying IWM strategies based on combinations of non-chemical and chemical weed control methods. The group in this case study consisted of 6 scientists from 6 different countries. The group met 3 times during the 18 month duration of the study with the aim to plan field experiments with combinations of preventive, cultural, physical and chemical weed control methods to make up an IWM strategy. In addition to the field study, previous experiences from IWM in maize in the Netherlands and results from other studies, in which maize was an element in whole cropping systems, were also analysed and included in the work. The aim of the field study was to compare two integrated weed management (IWM) strategies to the (a) standard chemical treatment in maize: an (b) intermediate IWM strategy and an (c) advanced IWM strategy. To achieve strategies (b) and (c), we integrated knowledge from mechanical weeding strategies developed for organic maize cropping with chemical methods, with (c) being the one with lowest herbicide use. The strategies were evaluated in 2007 at 3 sites: 1) Pisa (Italy), 2) Dijon (France) and 3) Flakkebjerg (Denmark). The methods included in the strategies varied among sites according to available equipment, experiences and agronomic relevance. Reductions in chemical input were achieved through the use of pre-emergence cultivation, increased crop stands, reduced herbicide dosages, inter-row hoeing equipped with tools for intra-row weed control and band-spraying. Compared with strategy (a), strategy (b) changed the amount of active ingredients by 0% at Pisa, -39% at Dijon and +149% at Flakkebjerg, with no changes in the number of treatments at all sites. For strategy (c), the amount of active ingredients were changed by -65% at Pisa, -95% at Dijon, and -91% at Flakkebjerg, and the number of treatments by 0% at Pisa, -67% at Dijon and -50% at Flakkebjerg. The higher amount of active ingredients at Flakkebjerg for strategy (b) came about when we changed to another compound considered being environmentally friendlier according to calculated *Ipest* indexes. Strategy (b) at Pisa did not deviate from (a) because the first herbicide application, which was similar for (a) and (b), gave sufficient overall weed control. Strategy (b) resulted in the same weeding effectiveness and provided yields similar to standard chemical control (strategy (a)) at all sites. Weed control effects following strategy (c) was similar to (a) at Dijon but slightly lower at Pisa and Flakkebjerg with effects in the range of 85-90% compared to effects above 95% for strategy (a). Cob yield was slightly lower after strategy (c) compared to (a) at Pisa with total maize yield being the same. At Dijon the opposite was true with total maize yield being lower following strategy (c). In conclusion, the field studies and literature review undertaken in the case study have revealed a potential for markedly reducing both herbicide input and environmental impact from herbicides in European maize cropping. The inclusion of preventive, cultural and mechanical methods reduces the necessity for herbicide application. However, the amount of weeds surviving weed control is coincidently more likely to increase when reliance on herbicides is being reduced. This necessitates including IWM in a wider context that goes beyond the single crop. The case study suggests cover cropping and diversified crop rotations as relevant options to counteract negative outcomes of IWM from a single year. Finally, this report suggests a number of recommendations which are considered useful for implementation in maize in the near future.

Introduction

The case study on integrated weed management (IWM) was initiated in spring 2007 with the aim to explore and identify relevant IWM strategies for major European crops. IWM strategies based on combinations of non-chemical and chemical weed control methods are sparsely reported in the scientific literature and practical experiences are limited. In fact, IWM can be applied in many crops and may consist of various solutions even for the same crop.

The IWM case study group consisted of *Maurizio Sattin* CNR (Italy), *Rommie van der Weide* PRI (the Netherlands), *Arnd Verschwele* JKI (Germany), *Paolo Barberi* SSSUP (Italy), *Nicolas Munier-Jolain* INRA (France) and sub-activity leader *Bo Melander* AU (Denmark). It was decided to focus on the implementation of IWM in one major European crop and to evaluate the effects of relevant IWM strategies at three European sites in 2007. Silage maize (*Zea mays* L.) was chosen, and pertinent chemical and non-chemical methods were identified and combined for field studies. Maize is a widespread cereal crop in Europe, in which several physical and cultural methods are applicable. It is an important break crop in crop rotations in northern Europe as the growing of crops with different cropping cycles will obstruct unilateral weed proliferation. In contrast, it is mostly the main crop in southern Europe and other crops should be considered as break crops. The group estimated that substantial reductions in herbicide input were to be achieved in maize through IWM.

The group met for the first time in March 2007 to decide on which crop to focus for field evaluation, to identify relevant weed control methods and their combinations for IWM and to plan the experimentation and the continuation of the case study as such. Then the group met again in late May 2007 in Pisa (IT) to inspect the Italian experiment and to discuss the further progress in the case study. Finally, the group gathered in Dijon (FR) in April 2008 to discuss the results of the 2007 field experiments and to plan the final reporting of the activities.

This report contains a summary of the experiments, the results achieved, a summary of other relevant IWM strategies for maize not studied experimentally in ENDURE, IWM in a wider cropping system context and final conclusions and recommendations.

Field studies

It was decided to conduct three IWM strategies in maize: 1) Standard chemical weed control, 2) Intermediate IWM and 3) Advanced IWM. The strategies were evaluated in the growing season 2007 at 3 sites: a) SSSUP (Pisa, Italy (IT)), b) INRA (Dijon, France (FR)) and c) AU (Flakkebjerg, Denmark (DK)). The methods included in the strategies varied among sites according to available equipment, practical knowledge and agronomic relevance.

Pisa (IT)

Basic treatments

The experiment was established on a sandy loam to sandy clay soil. Primary tillage consisted in harrowing and chisel ploughing (at 50 cm depth), carried out on 26 April 2007, followed by harrowing and ploughing (at 25 cm depth) on the following day. Seedbed preparation was done by a pass of rotary harrow. Maize (cv. PR31K18) sowing was performed with a Gaspardo seeder at 75 cm inter-row spacing. Maize was sown at a density of 127,000 seeds ha^{-2}. The soil was rolled immediately after sowing.

Fertilisation consisted in (1) pre-sowing manure application according to the standard practice; (2) mineral fertilisation at sowing, with 600 kg ha^{-1} of 8-24-24 and 200 kg ha^{-1} of urea. Therefore, the total N rate applied was 140 kg ha^{-1}. No insecticides or fungicides were applied.

Standard weed control
- 30 April 2007: pre-emergence application (4 L ha^{-1}) of Lumax (3.39% mesotrione, 28.23% S-metolachlor, 27.00% terbuthylazine) in 250 L ha^{-1} of water.
- 5 June 2007: standard hoeing (hoe with goose-foot shares).

Intermediate IWM (IIWM)
- 30 April 2007: pre-emergence application (4 L ha^{-1}) of Lumax (3.39% mesotrione, 28.23% S-metolachlor, 27.00% terbuthylazine) in 250 L ha^{-1} of water.
- 5 June 2007: precision hoeing (hoe manually steered).

Advanced IWM (AIWM)
- 1 June 2007: post-emergence application (1.5 L ha^{-1}) of Callisto (9.1% mesotrione) in 250 L ha^{-1} water.
- 5 June 2007: precision hoeing (hoe manually steered).

Doses of a.i. applied:
- Standard and IIWM: 135.6 g ha^{-1} mesotrione, 1129.2 g ha^{-1} S-metolachlor, 1080 g ha^{-1} terbuthylazine.
- AIWM: 136.5 g ha^{-1} mesotrione.

Principal weed flora
Veronica persica, Solanum nigrum, Datura stramonium, Chenopodium album.

Results

Table 1 shows weed biomass at canopy closure, differentiated between inter- and intra-row biomass. Both inter- and intra-row weed biomass were significantly higher in AIWM than in the standard or IIWC systems. However, all systems attained a per cent weed control higher than 93%.

Table 1. Dry weed biomass assessed between the maize rows (inter-row) and in the rows (intra-row) at maize canopy closure (with standard errors of the means shown in parentheses). Weed control effects are calculated as % of untreated.

Weed control	**Dry weed biomass (g m^{-2})**		**Effects relative to untreated (%)**	
	Inter-row	Intra-row	Inter-row	Intra-row
Untreated	65.98 (10.62)	25.98 (8.36)	-	-
Standard	^{a}0.16 (0.08)	^{a}0.11 (0.08)	99.76%	99.58%
IIWM	^{a}0.28 (0.16)	^{a}0 (0)	99.58%	100.00%
AIWM	^{b}4.45 (1.43)	^{b}7.78 (1.86)	93.26%	70.05%

Values with the same letter are not significantly different at the 5% probability level.

There were no significant differences among treatments in maize stand density, cob number and total dry matter (d.m.) yield (Table 2). In contrast, cob dry matter yield was approx. 36% lower in AIWM than in the standard or IIWM systems.

Table 2. Maize yield harvested in early August 2007 in each weed control strategy (standard errors of the means are shown in parentheses).

Weed control	Crop stand (plants ha^{-1})	Cob number (no ha^{-1})	Total dry matter yield (t ha^{-1})	Cob d.m. yield (t ha^{-1})
Untreated	81,666 (10,215)	115,000 (11,526)	10.84 (1.82)	3.71 (1.02)
Standard	^{a}75,000 (3,175)	^{a}121,666 (5,288)	^{a}16.33 (0.90)	^{a}7.25 (0.74)
IIWM	^{a}85,833 (5,013)	^{a}126,666 (9,490)	^{a}16.82 (0.75)	^{a}7.02 (0.51)
AIWM	^{a}77,500 (3,035)	^{a}119,999 (2,372)	^{a}15.21 (0.31)	^{b}5.25 (0.53)

Values with the same letter are not significantly different at the 5% level.

Discussion

The AIWM system differed from the standard and IIWM ones mainly in the absence of pre-emergence herbicide spraying: this had a significant effect on both intra- and inter-row weed biomass and on cob yield. Cob d.m. yield showed a significant negative correlation with total inter-row weed biomass (r=0.73 P<0.01). Higher variability in intra-row weed biomass turned out to have a non-significant correlation with cob yield. In fact, results from block 3 of the experiment were often different compared to the other blocks (lower cob yield and weed control). This corresponds to our field observations regarding the success of soil tillage: in block 3 soil structure was more heterogeneous due to large clod formation.

Although pre-emergence herbicide application (standard and IIWM) was more effective than post-emergence application (AIWM), weeds did not undergo uncontrollable proliferation. Considering that, besides a higher cob yield, the actual cost of herbicide treatments was lower in the standard and IIWM systems than in the AIWM one (Table 3), from an agronomic viewpoint the latter seems less preferable. However, this has to be weighted upon the higher environmental risk of the standard and IIWM systems, as pointed out by the values of the *Ipest* index (Table 3).

Table 3. Total herbicide input, number of herbicide treatments and calculations of the *Ipest* index.

Weed control	Total herbicide input	Herbicide treatments	Cost (euro ha^{-1})	*Ipest* index*
Standard	2344.8 g ha^{-1}	1	69.89	0.70
IIWM	2344.8 g ha^{-1}	1	69.89	0.70
AIWM	136.5 g ha^{-1}	1	87.45	0.02

* According to Girardin *et al.,* (1999).

Conclusions

Combination between chemical and mechanical methods, as pointed out by the results of standard and IIWM systems, can allow a reduction of herbicide input (e.g. by not applying post-emergence treatments) while preserving crop yield. In a Mediterranean environment, however, the timing of herbicide application in spring-summer crops is more critical than the number of treatments. As such, pre-emergence application still looks like the best technical solution to minimise weed competition. Shifting to post-emergence application would result in significant yield loss and reduced silage quality, due to the relatively minor contribution of cobs to total yield. However, in the Pisa trial post-emergence

hoeing brilliantly substituted post-emergence spraying, thereby reducing the total amount of herbicides applied in the crop. In perspective, a further improvement of herbicide application in silage maize could be to choose active ingredients (a.i.) with potentially lower environmental impact among the array of herbicides available for pre-emergence treatments. Lastly, it must be remembered that a more comprehensive evaluation of the pros and cons of the three weed control systems could only be done in a system (crop rotation) perspective.

Dijon (FR)

Basic treatments

The experiment was conducted at the INRA experimental farm in Dijon-Epoisses, France (47° 20' N, 5° 2' E), on a clayey soil. The previous crop was soya bean. 52 kg ha^{-1} P, 41 kg ha^{-1} K and 23 kg ha^{-1} Mg was applied just after the harvesting of the soya bean. The soil tillage before the beginning of the experiment was shallow cultivation once in March 2007. Maize, variety DK315, was sown on 7 May 2007 at 75 cm row spacing.

Table 4. Weed management options in the 3 strategies (Dijon experiment).

Strategy	Date	Standard	IIWM	AIWM
Stale seed bed	12-04		x	x
Stale seed bed	3-05		x	x
Sowing density	7-05	88.000	105.000	105.000
Sowing depth	7-05	5.5	5.5	7.5
N fertilisation	7-05	Broadcast 140 u	Banded 114 u	Banded 114 u
Acetochlore + dichlormide	7-05	x		
Pre-emergence glyphosate	10-05	x	x	
Post-emergence weed harrow	23-05			x
Bromoxynil	04-06		x	
Clopyralid	18-06	x	x	
Banded post-emergence herbicide bromoxynil + clopyralid	19-06			x
Hoeing	19-06			x

The experiment tested 3 weed management strategies, namely (A) a standard chemical weed control corresponding to the standard maize crop management in the area, (B) an Intermediate IWM (IIWM) and (C) an advanced IWM (AIWM). The crop management of the three strategies differed as shown in Table 4. In the IIWM and AIWM strategies, the stale seed bed technique was implemented with two shallow soil cultivations on 12 April and 5 May, the seeding density was increased to increase crop competitive ability, and N fertilisation was applied on the crop row at sowing to promote crop growth. This allowed also to reduce the amount of N applied. Weed control was adapted: in the standard system, weed control was primarily based on acetochlore + dichlormid applied at sowing, while both IIWM and AIWM did not include such soil-applied pre-emergence herbicides usually used in maize. In these two IWM systems, the control of annual weeds was based on one single application of bromoxynil, but in AIWM this treatment was localised on the crop rows, thereby reducing the treated area and the overall amount of active ingredient applied on the field (1/4 of the field area treated). Only AIWM included mechanical weeding in the crop: an early post-emergence weed harrow, and a late inter-row hoeing that complemented the on-rows herbicide application. In all 3 systems, the herbicide programme was modified because of the

unexpected presence of the perennial weed *Circium arvense*. An early glyphosate application was done on the standard system and IIWM and a late clopyralid application was performed on all the three systems (band application on the crop rows only in the AIWM). No insecticides or fungicides were applied. The experimental design did not include any unweeded plots.

The main weed species that emerged in the field were *Cirsium arvense, Amarantus retroflexus, Polygonum persicaria, Polygonum aviculare, Senecio vulgaris* and *Sonchus asper.*

Results

The strategies used in both IWM systems succeeded in reducing the amount of herbicides (a.i.) applied as compared to the standard system (Table 5). The amount was reduced by about 40% in IIWM and by 96% in AIWM. However, the number of herbicide applications and the Treatment Frequency Index (TFI) was not improved in the IIWM, where the pre-emergence soil-applied herbicide was replaced by a post-emergence herbicide. Only the AIWM system reduced the number of treatments and the TFI, but those indicators showed a strong reduction of the reliance on herbicides for this system (-66% and -81%, respectively). The substitution of herbicides made it possible to improve the *Ipest* index by 42% in the IIWM. This indicator of environmental impact associated with the herbicides was strongly improved in the AIWM (-83%). The band spraying contributed strongly to the reduction of the TFI in AIWM by reducing four fold the amount of herbicide applied. The improvement of the *Ipest* index was related to (i) the saving of the glyphosate application, (ii) the substitution of the herbicide targeting the annual weeds and (iii) the band spraying reducing the amount of active ingredient of all the herbicide used.

Table 5. Total herbicide input (a.i.), number of herbicide treatments and calculations of the *Ipest* index and the Treatment Frequency Index (TFI) (Dijon experiment).

	Total herbicide input	Herbicide treatments	*Ipest* index*	TFI (treatment frequency index) #
Standard	4618 g ha^{-1}	3	1.05	2.86
IIWM	2847 g ha^{-1}	3	0.61	2.86
AIWM	183 g ha^{-1}	1	0.18	0.53

* According to Girardin *et al.* (1999).

\# Doses for TFI=1 in maize : acetochlore + dichlormide : 2000 + 333.5 g ha^{-1} ; glyphosate: 2520 g ha^{-1} bromoxynil : 562.5 g ha^{-1} ; clopyralid : 125 g ha^{-1}.

The weed density and the weed biomass observed after canopy closure (11 July 2007) was low in all the systems. This might have been related with a low potential weed emergence in the experimental field and/or with a satisfying weed control in all the systems. No significant difference was observed between the systems (Table 6), indicating that the weed control was as satisfying in the two IWM systems as in the standard system, although the herbicide used to control annual weeds (bromoxynil) was supposed to have a lower efficacy and a lower spectrum than the soil applied herbicide used in the standard system (acetochlore + dichlormide).

Table 6. Weed density and dry weed biomasses assessed on July 11 between the maize rows (inter-row) and in the rows (intra-row) with standard errors of the means shown in parentheses (Dijon experiment).

System	Weed density (pl m^{-2})		Dry weed biomass (g m^{-2})	
	Inter-row	Intra-row	Inter-row	Intra-row
Standard	ᵃ2.5 (4.5)	ᵃ5.6 (4.6)	ᵃ3.4 (6.1)	ᵃ12.0 (13.5)
IIWM	ᵃ5.3 (4.5)	ᵃ4.8 (3.4)	ᵃ1.4 (1.7)	ᵃ2.7 (2.5)
AIWM	ᵃ5.5 (2.8)	ᵃ3.0 (1.8)	ᵃ6.5 (9.0)	ᵃ1.9 (1.4)

Values with the same letters are not significantly different at the 5% level.

The sowing density was higher in the two IWM systems, and the final maize density was thus significantly higher in the IIWM (Table 7). The post-emergence weed harrowing did not affect significantly the crop density in the AIWM. However, this harrowing covered the crop plants with soil during a few days and therefore reduced the early maize growth, resulting in a significantly lower total crop shoot biomass at the end of the growth cycle, as compared to the IIWM. The cob yield, although slightly lower, was not significantly affected. All the yield components in IIWM were similar to the standard reference.

Table 7. Maize yield harvested on 9 October, 2007 for each weed control strategy with standard errors of the means shown in parentheses (Dijon experiment).

System	Crop stand (plants ha^{-1})	Cob number (no. ha^{-1})	Total dry matter yield (t ha^{-1})	Dry cob yield (t ha^{-1})
Standard	[a]89,167 (15,940)	[a]99,167 (16,843)	[ab]24.7 (3.8)	[a]15.1 (2.3)
IIWM	[b]104,167 (15,563)	[a]109,167 (16,307)	[a]25.2 (2.4)	[a]15.6 (1.4)
AWM	[ab]99,667 (11,894)	[a]103,333 (14,194)	[b]22.9 (3.4)	[a]14.4 (2.2)

Values with the same letters are not significantly different at the 5% level.

The IWM strategies were both more time consuming than the standard system (Table 8), and the difference was stronger for AIWM (+220%). The most time consuming operations were the shallow tillages for the stale seed bed, the hoeing and the banded herbicide application. The machinery costs were also higher in the IWM systems, but the costs of chemicals (herbicides and nitrogen fertiliser) were lower, so that the total costs were similar in the IIWM as compared to the reference, and lower in the AIWM.

Conclusions

The experiment in Dijon (France) demonstrated a trade-off between the reliance on herbicide in maize crop management, the maize yield and the time consumption. The IIWM strategy did not affect either the yield or the crop management costs, however did not improve the treatment frequency Index (TFI). Only the *Ipest* index indicated a decrease of the potential risks for the environment related to the transfer of herbicide residues. The reliance on herbicides was really decreased only with the AIWM strategy, without increasing the production costs, but the early weed harrowing induced a decrease in the maize biomass production. All the strategies controlled the weeds satisfactorily in this experiment that was characterised by a relatively low weed infestation potential.

Table 8. Time consumption and costs for applying the three weed control strategies in maize (Dijon experiment).

Strategy	Treatment	Time consumption (h ha^{-1})	Application cost (€ ha^{-1}), contractor-based#	Application cost (€ ha^{-1}), farm-based§	Cost chemicals (€ ha^{-1})	Total costs
Standard	Broadcast N fertilisation	0.17	7	8	75	-
	1st herbicide	0.15	8	7	42	
	2nd herbicide	0.15	8	7	38	-
	3rd herbicide	0.15	8	7	65	
Total		0.62	31	29	220	251* 249**
IIWM	Stale seed bed (1st)	0.28	21	10		
	Stale seed bed (2nd)	0.28	21	10		-
	Banded N fertilisation	0 (combined with sowing)	0	0	61	-
	1st herbicide (24 m wide sprayer)	0.15	8	7	38	-
	2nd herbicide	0.15	8	7	42	
	3rd herbicide	0.15	8	7	65	
Total		1.01	66	41	206	272* 247**
AIWM	Stale seed bed (1st)	0.28	21	10	-	-
	Stale seed bed (2nd)	0.28	21	10		
	Banded N fertilisation	0 (combined with sowing)	0	0	61	-
	Weed harrow (12 m wide)	0.1	7	6		-
	Banded herbicide	0.67	50¶	24	26	
	Hoeing	0.67	38	24		
Total		2	137	74	87	224* 161**

According to the French price table for Agricultural Mutual Aid
¶ the cost for banded herbicide application was roughly estimated, as no data were found for this operation in contractors catalogues
§ According to an unpublished farm economic performance analysis based on a database of an extension service
* Contractor-based
** Farm-based.

Flakkebjerg (DK)

Basic treatments

The experiment was established on a sandy loam. Primary tillage prior to maize sowing was ploughing at approx. 20 cm depth in the autumn 2006 and then followed by rotary cultivation in spring 2007. Maize, variety *Banguy*, treated with a pesticide to avoid birds from feeding on the seeds, was sown on 7 May 2007 at 75 cm row spacing and 5 cm depth. Sowing density was 14 seeds per m row, which established at a plant density of 7.1 plants per m row corresponding to 94,667 plants ha^{-1}. Fertilisation consisted of 1) pre-sowing mineral fertilisation (150 kg ha^{-1} N; 32 kg ha^{-1} P; 161 kg ha^{-1} K), 2) at sowing, mineral fertiliser banded 5 cm beneath and 5 cm to the side of the maize seeds (25 kg ha^{-1} N; 12.5 kg ha^{-1} P; (including boron and sulphur)). In total, 175 kg ha^{-1} N, 44.5 kg ha^{-1} P and 161 kg ha^{-1} K were applied. No insecticides or fungicides were applied.

<u>Standard chemical weed control</u>
Post-emergence split-application of *MaisTer* (Foramsulforun + Iodosulforun):
1. 100 g ha^{-1} on 31 May
2. 50 g ha^{-1} on 11 June

<u>Intermediate IWM (IIWM)</u>
1. Stale seedbed, seedbed cultivation on 19 April
2. Pre-emergence *glyphosate*, dose 360 g ha^{-1}, on 20 May
3. One banded post-emergence *MaisTer* (Foramsulforun + Iodosulforun) application on 11 June, dose 50 g ha^{-1} corresponding to 13 g ha^{-1} applied
4. One inter-row hoeing on 12 June

<u>Advanced IWM (AIWM)</u>
1. Stale seedbed, seedbed cultivation on 19 April
2. One pre-emergence harrowing on 20 May
3. One banded post-emergence *MaisTer* (Foramsulforun + Iodosulforun) application on 11 June, dose 50 g ha^{-1} corresponding to 13 g ha^{-1} applied
4. One inter-row hoeing on 12 June

<u>Principal weed flora</u>
Galium aparine, Chenopodium album, Sinapis arvensis, *Sonchus spp., Veronica spp., Polygonum convolvulus, Poa annua*

Results

Table 9 shows the input of herbicides and the number of herbicide treatments including calculations of the two environmental indexes: the *Ipest* index and the Danish Treatment Frequency Index TFI. The IIWM strategy gave the highest herbicide input in terms of amount but both indexes were markedly reduced as compared to standard weed control. The AIWM strategy was lowest in all parameters, although the *Ipest* index was only slightly lower than for IIWM. The *Ipest* index mainly takes the environmental and toxicological features of the herbicides into account, while the TFI gives a better picture of the actual dose reduction. The Danish TFI target value for herbicide use in maize is 1.0, and AIWM reduced TFI by 91%.

Table 9. Total herbicide input, number of herbicide treatments and calculations of the *Ipest* index and the Danish treatment frequency index (TFI).

Weed control	**Total herbicide input**	**Herbicide treatments**	***Ipest* index***	**TFI (treatment frequency index)**	
				Dose for TFI = 1.0 in maize	Actual TFI
Standard	150 g ha^{-1}	2	0.40	MaisTer: 150 g ha^{-1}	1.0
IIWM	373 g ha^{-1}	2	0.28	Glyphosate: 1260 g ha^{-1} MaisTer: 150 g ha^{-1}	0.37[#]
AIWM	13 g ha^{-1}	1	0.19	MaisTer: 150 g ha^{-1}	0.09[§]

* According to Girardin *et al.,* (1999)
[#] Calculated as 0.37 = [(360/1260) + (13/150)]
[§] Calculated as 0.09 = (13/150)

Both IWM strategies reduced weed biomass almost to the same extent as the standard treatment with the AIWM strategy leaving most weed biomass behind (Table 10). However, residual weed biomasses of 50-70 g m^{-2} are not assumed to cause uncontrollable weed proliferation. Based on this assumption, all three strategies have controlled the weed population satisfactorily. Crop yield was not affected negatively by the IWM strategies and apparently the mechanical treatments have not reduced crop stand noteworthily (Table 11).

The IWM strategies were both more than twice as time consuming as the standard treatment, while the costs were only moderately higher (5-20%) than the standard treatment (Table 12).

Conclusions

It is possible to reduce herbicide input substantially in silage maize without risking crop yield or abandoning weed biomass of serious concern for uncontrollable weed proliferation. However, integrated weed management based on a combination of non-chemical and chemical methods are more time consuming and slightly more costly.

Table 10. Dry weed biomasses assessed between the maize rows (inter-row) and in the rows (intra-row) at maize canopy closure (with standard errors of the means shown in parentheses). Weed control effects are calculated relative to untreated.

Weed control	**Dry weed biomass (g m^{-2})**		**Effects relative to untreated (%)**	
	Inter-row	Intra-row	Inter-row	Intra-row
Untreated	^{a}414 (62.4)	^{a}1294 (361.5)	-	-
Standard	^{b}14 (2.8)	^{b}10 (4.8)	97	99
IIWM	^{bc}27 (10.7)	^{bc}36 (15.4)	93	97
AIWM	^{c}56 (27.4)	^{c}69 (32.2)	86	95

Values with the same letters are not significantly different at the 5% level.

Table 11. Maize yield harvested in early October 2007 shown for each weed control strategy with standard errors of the means shown in parentheses.

Weed control	**Crop stand (plants ha^{-1})**	**Cob number (no. ha^{-1})**	**Total dry matter yield (t ha^{-1})**	**Dry cob yield (t ha^{-1})**
Untreated	^{a}90,000 (3,600)	^{a}124,166 (14,167)	^{a}13.1 (2.31)	^{a}7.1 (1.20)
Standard	^{a}90,417 (2,222)	^{b}149,583 (4,199)	^{b}18.2 (0.65)	^{b}9.5 (0.39)
IIWM	^{a}97,500 (3,713)	^{b}150,000 (6,455)	^{b}17.2 (0.54)	^{b}9.2 (0.26)
AWM	^{a}87,917 (2,176)	^{ab}141,667 (8,591)	^{b}17.0 (0.31)	^{b}9.2 (0.31)

Values with the same letters are not significantly different at the 5% level.

Table 12. Time consumption and costs for applying the three integrated weed control strategies in silage maize. The calculations are based on common Danish conditions.

Strategy	Treatment	Time consump-tion (h ha^{-1})	Application cost (€ ha^{-1}), contractor-based#	Application cost (€ ha^{-1}), farm-based§	Cost chemicals (€ ha^{-1})	Total costs
Standard	1st application (*MaisTer*), 12 m wide sprayer	0.31	18.8	16.8	41.6	-
	2nd application (*MaisTer*), 12 m wide sprayer	0.31	18.8	16.8	20.8	-
Total		0.62	-	33.6	62.4	96.0*
			37.6	-	62.4	100.0**
IIWM	1st application (glyphosate), 12 m wide sprayer	0.31	18.8	16.8	5.1	-
	2nd application, banded *MaisTer*	0.60	45.6	40.2	5.4	-
	One hoeing (6 m wide)	0.57	45.6	40.2	-	-
Total		1.48	-	97.2	10.5	107.7*
			110	-	10.5	120.5**
AIWM	Pre-emergence harrowing, 12 m wide	0.21	17.4	15.4	-	-
	1st application, banded *MaisTer*	0.60	45.6	40.2	5.4	-
	One hoeing (6 m wide)	0.57	45.6	40.2	-	-
Total		1.38	-	95.8	5.4	101.2*
			108.6	-	5.4	114.0**

According to the Danish Machine Pool Association
§ According to the Danish publication: "Håndbog til Driftsplanlægning"
* Contractor-based
** Farm-based.

Other IWM strategies for maize

Research, practice and policy related to weed control in forage maize in the Netherlands

Herbicide use

The use of herbicides in forage maize has clearly been influenced by research-led innovations, the input of various actors and government policy (see below: Spraying techniques and mechanical control and policy inventions for more information). The following figure shows the number of kilograms of active ingredients used per hectare in forage maize (data obtained from A. ten Heggeler of Syngenta).

As maize is the largest field-grown crop in the Netherlands, various herbicides commonly used on maize crops have been found at unacceptably high levels in ground- and surface water. This has led to numerous discussions on the use of atrazine (banned in 2000), bentazon, terbuthylazine (used since 2000 instead of atrazine), metolachlor and dimethenamid (all mentioned in water board reports).

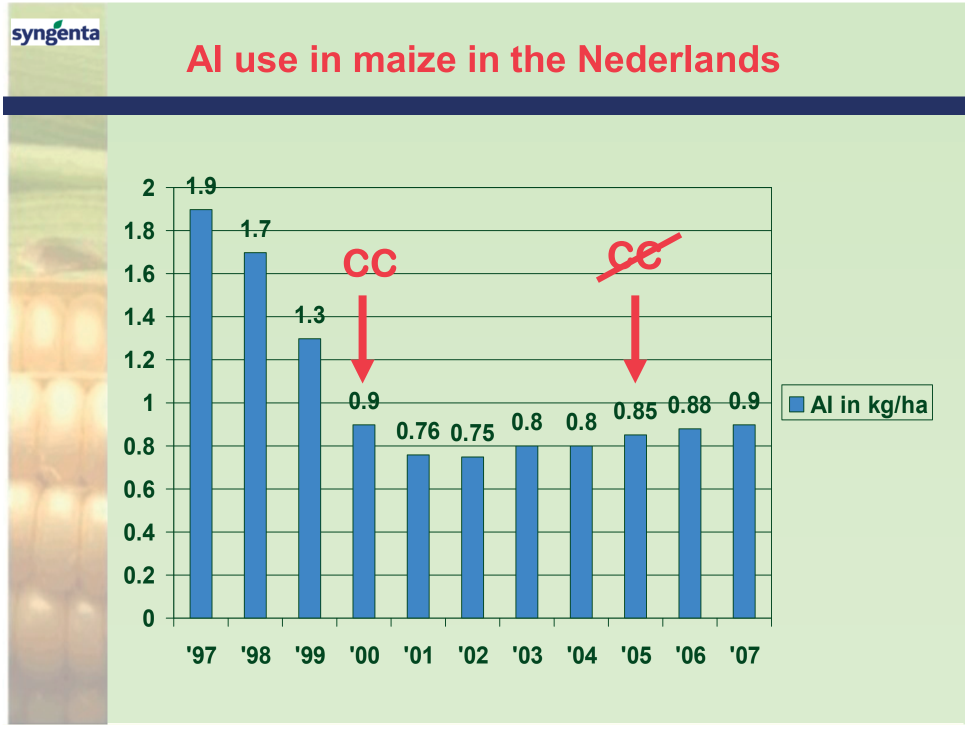

Figure 1. Use of active ingredients (AI) in kg/ha in the Netherlands during the last 10 years.

About 20 million euros was spent in the Netherlands in 2005 on herbicides for forage maize (data vet, Syngenta).

Weed pressure

Weed pressure in maize is high (often tens to hundreds of weeds per square metre), both on sandy and clay soils. The lowest density is found in maize fields in a crop rotation plan on clay soil, and the highest is often found on sandy soils of Dutch cattle farmers. Unsuccessful weed control can cause high yield losses of up to tens of percentage points, particularly on drought-sensitive soils. Some herbicide mixes also inhibit maize growth, which can cause yield losses of a few percentage points.

Over the years, new weeds have appeared and become problematic in maize fields, which has necessitated continual adjustment of the herbicide mix and the weed control strategy. The first new weeds to appear in the Netherlands were grass species that spread rapidly (*Echinochloa crus-galli*, *Digitaria ischaemum* and *Setaria viridis*). *Digitaria ischaemum* has become increasingly problematic and dense in some places, and its eradication now requires a new approach, which is more difficult to implement for labourers working with one sprayer that is also used for beet fields. In more recent years increasing problems have been reported with *Geranium spp.* and *Erodium cicutarium*, and problems are also growing with perennial weeds, such as *Convolvulus arvensis* and *Elymus repens*. This development can be dealt with in part by using the existing herbicide mix, even if this entails a higher use of some chemicals, such as terbutylazin. New manure regulations could have negative consequences with respect to root weeds (fewer control options in the stubble and spraying of the sward at an inappropriate time).

Causes

The changes have been caused primarily by no effect of the frequently used herbicides for some weed species combined with the rapid spread of weed varieties between plots,

possibly via manure. Barnyard grass has now spread throughout the Netherlands and the other grasses are following suit.

The reduction in pre-emergence harrowing in 2005 led to more problems with *Erodium cicutarium*. New manure regulations have made it difficult to control perennial weeds in the maize stubble (a new crop must be planted) and have made it impossible to combat *Elymus repens* in pastures at the optimal time. This makes it more difficult to rotate the crops, which in itself can normally help to control weeds.

Technical development

Varieties

The new maize varieties tend to show better early development. This affects the speed at which the field closes up and may thus also affect the amount of soil herbicide needed to limit the number of late germinators. However, not enough is known about this.

The varieties also differ with respect to their reaction to various herbicides. Some herbicides can damage certain varieties.

Industrial hygiene measures

Within the contracted labour sector, more attention is being paid to limiting transfer from one field to another, among other ways by spraying wheels and applying air pressure to clean machinery. This has not yet resulted in a measurable decrease in the spread of weeds. It may be too soon to measure the impact, or the first spreading with manure could have a greater effect.

Spraying techniques and mechanical control and policy inventions directing practice

As a follow-up to research conducted in the early 1990s into the possibilities of mechanical control of weeds, the Applied Plant Research (PPO) organisation of Wageningen University (WUR) began looking for combinations of mechanical control and adjusted dosing in silage maize.

In response to policy pressures and with financial support from the Ministry of Agriculture, PPO worked together with the agricultural consulting firm DLV in 1996 to carry out experiments and guide contract workers and growers' associations in implementing these methods. This work was taken over in 1998 by LTO (the Dutch Federation of Agriculture and Horticulture) and Cumela (an organisation of agricultural entrepreneurs and contract workers) with scores of demonstrations and introductions, which helped spread the PPO and DLV message about the economic possibilities for integrated control. This large-scale initiative was a good start; however, according to an estimate by DLV (Krebbers) it led to results of no more than 20% of the farmers using integrated strategies. The decrease by 2000 in the amount of active ingredients used was caused in part by this initiative, but also by the industry's product innovations (sulphonylurea and triketone).

In 2000 the ministry introduced cross compliance (CC in Figure 1), which offered a subsidy for integrated weed control in maize. Farmers received a subsidy for their maize crop if they combined chemical and mechanical control measures and used less than one kilogram of active ingredients per hectare. The rush on harrows that year created a temporary supply problem, but the practice was nevertheless immediately applied to 90% of the total area cultivated with maize. In addition to the changes brought about by this new financial incentive and new regulations, the herbicide industry also began to cooperate for the first time rather than resist. Whereas PPO had previously been threatened with litigation if it refused to

change the title of a publication, researchers were now being invited to give lectures at various manufacturing and trading companies. Mechanical control measures were even included in these companies' advertising campaigns (see Figure 2).

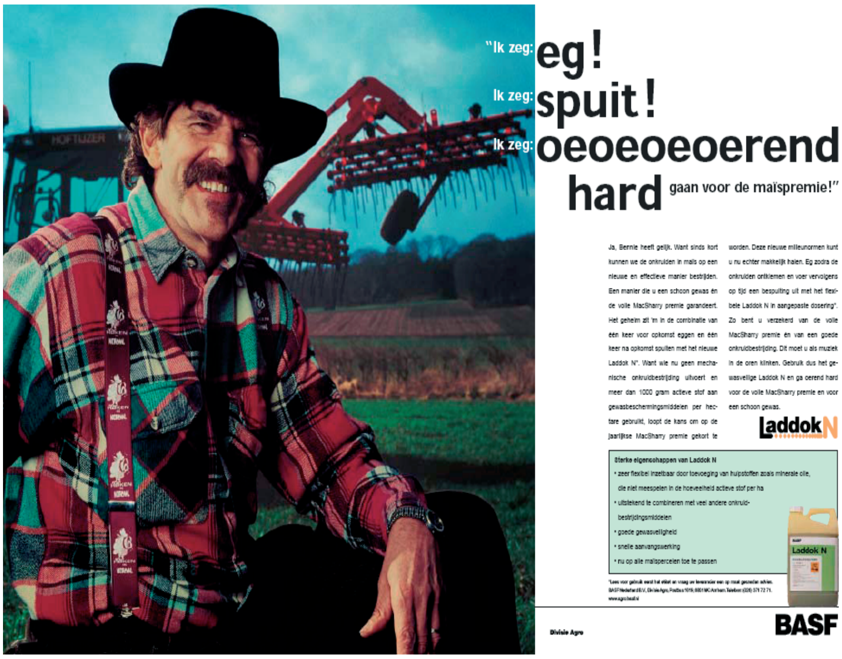

Figure 2. Advertising campaign in farmers weekly in which a Dutch popsinger promotes combination of harrowing and spraying.

Only the middlemen in the herbicide industry were not enthused, and they warned, among other things, that the new measures would allow the weeds to take over. However, the farmers' experiences during the cross compliance were reasonable to good on about 90% of the maize area, and there was thus considerable support for the regulation.

As part of the government's deregulation efforts, the cross compliance requirements to harrow and use less than one kilogram of active ingredients were dropped in 2005. A crop health study conducted in 2006 looked at changes that had taken place in the use of chemicals and harrowing since cross compliance was discontinued. The study consisted of a survey conducted among members of the recently established association in project Farming with a future in the south-eastern part of the Netherlands (ZON), followed by a survey conducted in cooperation with Cumela among contract workers in all regions of the country. The data given below were derived from the ZON group and the national survey of 47 contract workers (who together spray about 10% of the maize area and who are each responsible for an average of 425 hectares).

All of the 47 contract workers surveyed had applied mechanical weed control during the cross compliance. After it was rescinded, about 65% of the contract workers stopped this practice completely. Almost 10% of the workers still harrowed one quarter of the area, and another 10% engaged in mechanical weed control on one to three quarters of the plots. About 15% of the workers still harrowed extensively, meaning that more than three quarters of their area was being worked with a harrow or in a few cases a hoe. The importance of harrowing before emergence is recognised by the members of the "Farming with a future" contract workers' association, but some say that they cannot or are not willing to convince their customers of this. After harrowing, the field is flatter and the clods are smaller. The weeds that emerge after harrowing are usually smaller and less varied in size. Therefore less intensive spraying is needed. The maize crop thus suffers less damage from the chemical control. Demonstrations based on research conducted in cooperation with actors and contract workers can help convince clients.

Demonstrations, research and knowledge transfer are also useful in preserving the effectiveness of, and support for the use of, drift-reducing nozzles. Some people still believe that spraying with drift-reducing nozzles is less effective, which necessitates more spraying and ultimately results in an equal amount of pollution. This is an inaccurate assumption since 90% drift reduction, even when applying a 50% higher dosage, still results in an 85% decrease in drift. Drift-reducing nozzles are very common because they are required when many of the chemicals that are important for maize are sprayed along waterways. Farmers report that compliance with this regulation is monitored.

Chemicals

Although fewer contract workers harrow, the increase in the amount of active ingredients used has been relatively limited. According to a survey conducted during the cross compliance, the average amount of active ingredients used at that time was 0.75 kg per hectare; in 2005 it had only increased to 0.88 kg per hectare. There are, however, large variations among regions and contract workers. The lowest recorded value was 0.1 kg of active ingredients, and the highest was 1.8 kg. The choice of chemicals changed considerably, which definitely affected the volume of active ingredients used. The use of *Frontier optima* (dimethenamid-P) and *Dual* (S-metolachlor), which have higher contents of active ingredients, increased in 2005: the percentage of combinations that contained them increased from 50% to 78%. The dosage of *Frontier* was also increased. This increase in active ingredients was compensated to some extent by the increase from 3% to 17% of combinations that included *MaisTer* (florasulfuron/iodosulfuron), a relatively new product with a very low level of active ingredients. Because many farmers switched to these products, other products were used less often. Those containing *TBA* (terbuthylazine), such as *Lido*, *LaddokN*, *Milagro* and *Samson*, were used less in 2005 by the farms surveyed than they had been in previous years.

The slight increase in active ingredients after discontinuation of the cross compliance did not necessarily lead to a greater environmental impact. On average it appears that the change in products decreased the impact on groundwater. In contract, emissions into the air increased slightly. The number of chemicals in the combinations that exceeded the norm for marine and soil life stayed the same. Improvements are expected thanks to drift-reducing nozzles, which are required when spraying agents such as *Frontier*, *MaisTer* and the new agent *Emblem* (ioxynil) along water-carrying ditches.

Decision support systems (DSS)

At the moment few suitable DSS are available for maize. However, a weather fax is released regularly by Opticrop with information on suggested and discouraged spraying times; and Opticrop's MLHD site (a WUR initiative) provides information on critical dosages of a number of chemical combinations. These decision-support systems are not widely applied, possibly because the contract workers have to spray a large area in a short time, and it is difficult when planning such work to take the various types of weeds and weather conditions into account. They prefer to spray as many fields as possible with just one chemical mixture. However, some contractors are innovative and ask payment for the total weed control strategy. They can save money by saving on herbicide costs and certainly have interest in the possibilities for critical dosing, objective information and planning systems to be developed for critical use of herbicides.

Costs of crop protection

Despite changes in weed control, the average amount of money spent on herbicides remained about the same in 2004 and 2005: € 100 per hectare. The variation between regions and contract workers was large both during and after the cross compliance. Because contract workers harrowed less after cross compliance, the total costs for weed control decreased by an average of 10 euros per hectare. Some of the contract workers and maize farmers who continued to harrow believed that the costs involved would be compensated by the reduced use of chemicals.

Economic competition with respect to weed control in maize is high. The suggested retail prices of some herbicides used in maize, as reported in the DLV crop protection guide, have decreased in recent years (apparently in order to increase the products' market shares). The price contract workers ask for spraying is also under pressure. The normal rate for spraying used to be about 30 euros per hectare, but this appears to be shifting down to 25 euros and even rates as low as 17.50 euros for larger plots are not unheard of. Discounts are often given for larger bulk orders of chemicals. If this discount is not passed on to the clients, it can be a good source of income for the workers, but the possibility of receiving such a discount also puts pressure on them to be less critical in dosing the chemicals.

Land use

The area under maize in the Netherlands is normally somewhere around 250,000 hectare. This number declined slightly in 2006 as a result of the nitrate directive derogation, but it is expected to go up again as the demand for biogas increases.

Possibilities for improvement by 2010

Perspectives

How can we achieve the environmental objectives established for 2010, that is, a 95% reduction in environmental impact compared to 1998 levels?
-measures
-effectiveness, feasibility, costs
-by putting whom/what into action?

Compared to 1998 levels, we have already achieved a 50% reduction. Extra efforts will have to be made, however, to ensure that the situation does not deteriorate and to achieve the objective of 95%. Experience with maize has shown that measures such as those in the cross compliance can be very effective. In addition to creating obligations, it also raised awareness and even stimulated competition among the affected farmers. What is needed, apparently, is more of such incentives.

For example, contract workers could sell weed control more as an entire package, and competitive pricing of packages could be stimulated. This would make it profitable for the contract workers to be more critical in dosing chemicals. Contract workers have the advantage that they are usually better equipped and are in a better position to make investments (in good sprayers, for example) than livestock farmers; they are also monitored more closely, enjoy the trust of their clients (they make decisions for their clients) and gather a lot of knowledge.

It would be good to initiate discussions with contract workers and other actors about how to increase the sale of packages and the critical use of chemicals. It is important to facilitate discussions and brainstorming about these possibilities and the wishes of the contract workers. Support should be provided to the first "Farming with a future" contract work group established in 2006 and the research of the Ministery-paid crop health programme that the group helped direct. This work could also be expended in consultation with Cumela. The

contract workers in this group would like to receive support in communicating with their clients, in gaining insight (also from each other) into the possibilities of selling weed control as a package, in planning and using tools, in gathering knowledge about how to critically and economically apply integrated measures and to stay abreast of developments in the middle-term related to extra precision and chemical possibilities.

Studies and an inventory should be made of other possibilities of encouraging more critical use of herbicides by rewarding contract workers (e.g. the possibility of relieving livestock farmers of the administrative burden could be used as a marketing tool by contract workers, and also allow them to profit from the gains made through critical use of chemicals).

Finally, attention should also be paid to possible point emissions and economically responsible ways in which to prevent them.

Cover crops sustaining IWM in maize

Implications of the use of cover crop in cropping systems

Cover crop use is considered as a management solution enhancing the sustainability of the cropping systems. Cover crops are legumes, cereals or any mixture of these or other plants grown to protect the soil against erosion, enhance soil physical and chemical properties including soil fertility, and to decrease adverse effects of weeds, insects and pathogens on the main crop. They can be inter-seeded with the main crop and form a living mulch, or they can be grown to fill the gaps in time and/or in space where main crops are not present. If used to fill the gap in time, at the moment of main crop sowing, the cover crop can be managed in two different ways. They can be used as a so-called living mulch, which means that they remain wholly or partly alive during the main crop's growing season, or they can be killed, mechanically or in combination with non-selective herbicides like glyphosate, forming a dead mulch, providing soil and crop protection during the main crop's growing season, with a decreasing effect as the growing season advances due to mulch decomposition. If ploughing or disking practices are applied, the cover crop gets incorporated into the soil prior to cash crop planting, providing a green manure. The principal purpose of the cover crop and the planned mulching technique applied at the end of its growth period determine the appropriate growth characteristics. For example, in temperate zones, cover crops aimed to enhance soil fertility should better be sought in the array of N-fixing leguminous crops such as *Vicia villosa* Roth. and various clover (*Trifolium* spp.) types (Lal *et al.*, 1991). In a living mulch system, the cover crop should not be competitive with the main crop for light, moisture and nutrients and should therefore form a low but dense sward. If the cover crop is to be used as a dead mulch, it can have a tall growth habit, and it would be advantageous if it provides as much biomass as possible, in order to enhance weed suppression and to prolong its persistence on the soil surface as long as possible after its destruction.

At northern latitudes, cover crops are mostly grown in the cold season (Lal *et al.*, 1991), except when they are used as a living mulch in the summer crops. In the Mediterranean climate regions both summer and winter species can be grown. However, winter species are preferred over summer species for two main reasons (Campiglia, 1999): in mild and rainy winters cover crop growth is stimulated, thus enhancing N accumulation and reducing soil erosion while the favourable spring climate enhances a quick decomposition in case of green manures, releasing mineral N from the organic source to the crop's advantage whereas the cultivation of summer cover crops can result in a negative soil water balance by increased evapotranspiration and at the same time they often are more difficult to insert in the crop rotation. Campiglia *et al.* (2000) have shown how, in a Mediterranean climate, the introduction of an autumn-sown subterranean clover, which acted as living mulch in winter wheat, as a cover crop in the following winter by self-reseeding, filling the otherwise long

fallow period from wheat harvest in July until sunflower sowing in spring of the next year and as a green manure in sunflower, can result in an almost continuous soil cover all year round, reducing the risk of soil erosion and enhancing soil fertility.

The role of cover crops and their residues in weed management

Cover crops can exert a direct weed suppression effect either as pure crop or as a living mulch underneath the main crop, whereas their residues act as a surface mulch or green manure (Figure 3). The cover crops and living mulches exert a weed suppression capacity mainly through resource competition and depending on the cover type, through volatilisation or leaching of allelochemicals from aerial parts of the plant or through release of allelochemicals from root exudates (Chou, 1999) (Mechanism 1 in Figure 3). The mulch layer left on the soil surface or the residue incorporated in the soil after cover crop destruction result in changed soil physical conditions (Teasdale & Mohler, 1993) (Mechanism 2 in Figure 3). The impact of the surface mulch on the physical conditions of the soil surface layer is dependent on mulch type, quantity and structure (Teasdale & Mohler, 2000). Surface mulches decrease diurnal temperature fluctuation, reduce soil evaporation thus resulting in a higher soil humidity and decrease radiation intensity. Besides a physical effect, also the surface mulch can result in leaching of allelochemicals or release of these substances through mulch decomposition. Both factors influence weed seed germination and seedling early growth. However, the relative contribution of alteration of the physical environment and phytotoxicity to cover crop residue – weed interactions still has to be clarified. The implementation of cover crops in the inter-crop periods of the crop rotation can result in seedbank depletion through suppression of weed growth in the inter-crop period. Eventually this may result in a reduction of weed seed germination in successive crops grown in the same time of year as the cover crop (Mechanism 3 in Figure 3).

Biochemical interactions among plants have been described for natural as well as agricultural ecosystems (Inderjit & Dakshini, 1996; Ohno *et al.*, 2000; Souto *et al.*, 2000). However, despite the many laboratory studies that have proved the existence of germination and growth regulating effects of compounds with allelopathic capacity released by living and dead plant tissues (Barnes & Putnam, 1986; 1987; Aliotta *et al.*, 1996; Reigosa *et al.*, 1999), Blum *et al*. (1999) concluded that no exhaustive techniques are available to demonstrate allelopathy in natural systems. However, the combination of field and laboratory studies can give good indications regarding the mechanisms responsible for weed suppression effect over crops, as shown by a long-term study carried out at CIRAA in San Piero a Grado, Pisa, Italy, in a maize-winter wheat biannual rotation including two tillage systems [conventional (CS) and low-input (LIS)], 4 N fertilisation (0, 100, 200 and 300 kg N ha^{-1}) levels and 4 winter cover types (rye, *Trifolium incarnatum*, *Trifolium subterranea*n and crop stubble). A PhD project carried out at SSSUP in the period 2000-2003 showed that in the maize crop following the cover crops, weed density was lower in the rye plots than in the crop residue plots and although both clover covers had produced a very low biomass, weed density at the maize fourth-leaf stage in the crimson clover plots was lower than in the subterranean clover plots and did not significantly differ from weed density in the rye plots (Moonen, 2004). Since the clover and crop residue plots produced a high weed biomass, which increased with increasing N fertilisation level, these plots had a reasonable mulch layer covering the soil at maize sowing, which persisted until at least 7 weeks after sowing in the N100, N200 and N300 plots, and had disappeared 4 weeks after maize sowing in the unfertilised plots. This suggested that the weed control effect of rye was not only due to physical inhibition. Chemical analysis of the rye and crop residue mulch, originating from plots with different N fertilisation levels to the main crop, showed that there were no differences in the total phenolic acid concentration, as well as in total N and organic carbon content (Moonen & Bàrberi, 2006). The differences for these parameters observed in the soil were related to the biomass production, where soil concentrations increased with increasing biomass. Germination tests with equal amounts of mulch showed no different responses of the tested

weed species and maize to the different mulch types and germination and early growth response to the mulches was species-specific. In a germination experiment with fresh mulch, similar to the field situation, both a physical and chemical weed suppression effect of the mulches were determined already at the lowest mulch density (equivalent to 333 g m^{-2}), which was slightly lower than the average field mulch density produced in the crop residue plots in LIS and half the amount produced in the rye plots. Given that the crop residue mulch in the field exerted a much lower weed suppression than the rye mulch, there must have been other factors acting in the rye cover plots. Since species composition was not different between the rye and crop residue plots in LIS, the difference in weed suppression capacity cannot be attributed to a differential species response. Therefore it can be suggested that rye roots were responsible for release of phytotoxic substances, during the cover crop phase as well as from root decomposition during the maize phase.

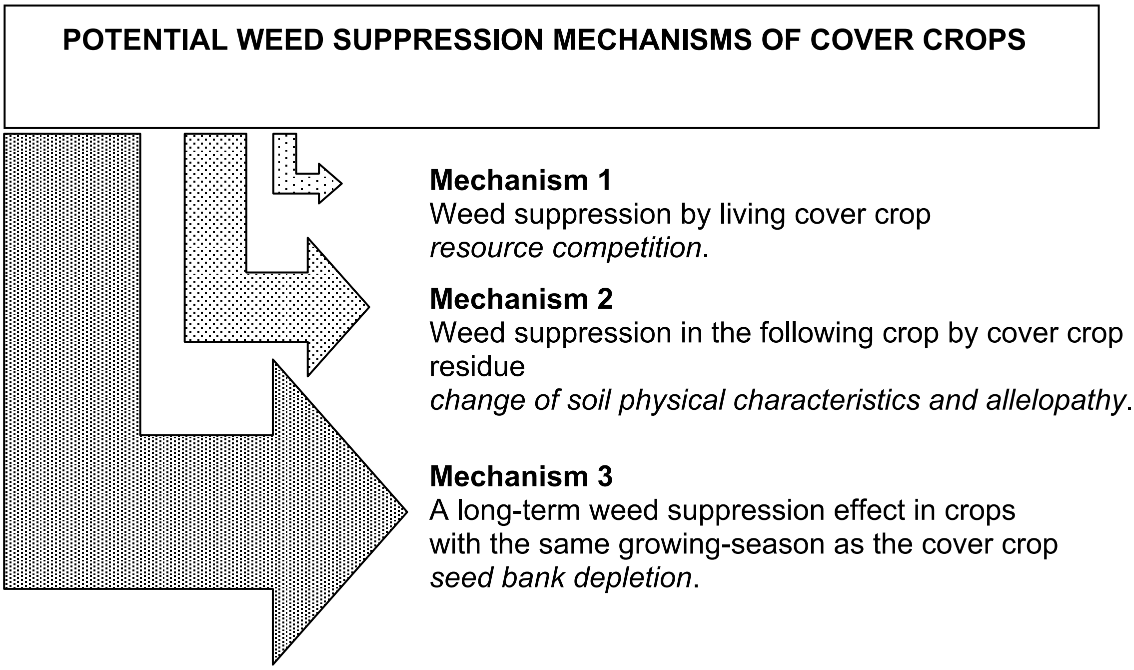

Figure 3. Potential cover crop-weed interaction mechanisms (from Moonen, 2004)).

IWM in a system approach context

Weed management typically requires a system approach for conceiving and evaluating innovative strategies, and this for at least 3 main reasons:

- Because alternative non-chemical techniques prove to have only limited efficacy so far as compared to the efficacy of herbicides, IWM should be based on the combination of different techniques to reach the objectives of (i) reducing the reliance on herbicides and (ii) succeeding in controlling weeds. Prototyping new strategies cannot be limited to the study of the efficiency of one single technical innovation. This feature was acknowledged in this joint study on IWM in maize, as the two integrated strategies (IIWM and AIWM) were based on combination of techniques (stale seed bed, adjusted crop density, mechanical weeding, etc.).
- The performance of IWM strategies cannot be based only on the observation of weed density, weed biomass and crop yield loss due to the competition with the weeds. Indeed the weed density and biomass within one single season is not a good indicator of the performance for weed management. In IWM strategies,

weed density might be higher than in systems relying heavily on herbicide applications, provided that the weed density (and biomass) remain low enough to avoid any significant yield loss. The most relevant indicator of weed management is the long-term evolution of the density of weed species in successive years. The main issue is to avoid any increase in the potential infestation level in the long term to avoid any yield loss or any increase in the required intensity of weed control in future crops. In this study, in the experiment at Flakkebjerg (DK), the efficiency of both IWM strategies were sufficient to avoid any yield loss in the current year, but the surviving weeds were denser than in the standard system (significantly in the AIWM). Consequently the potential weed infestation might increase in the long term after repeated application of the same strategy due to cumulative effects, if no compensatory measure is taken at the system level.

- IWM strategies involve deep changes in crop/weed management options. Therefore the evaluation of IWM prototypes cannot be based only on the evaluation of the efficiency of weed control. The consequences on other aspects of the farming should be considered (environmental impact, economics, feasibility at the farm scale). Those components of the assessment also require a system approach, at a larger scale than the field scale in a given cropping season.

The research group in Dijon is addressing these aspects of IWM with a system approach. The research is partly based on a long-term system experiment running since year 2000. The experiment was designed to assess the performances of different IWM-based cropping system prototypes. For weed control, the main criterion is based on the changes in density of weeds on the long term. Other criteria of system evaluation are considered, such as the reliance on herbicide, a range of potential environmental impact, economical return, and others (papers in preparation). This experiment demonstrated that it is possible to control weeds significantly over the whole duration of the experiment (8 years) with strong reduction in the reliance on herbicides, provided that many IWM techniques are combined at the system level. The experiment also gave indication of trade-offs between the environmental value of the cropping systems and different indicators of economical performance in the current economical context, thus providing information for debating about the fate of the agriculture in Europe.

Based on these considerations, the ENDURE-RA1-IWM group decided to continue the experimental work: the system-based experiments in Flakkebjerg and Pisa will be continued on the same plots with crop rotations based on maize and wheat. These experiments, and the currently running Dijon experiment, will provide data to assess the efficacy of weed control in IWM strategies on the long term. The principles of IWM inserted in the IWM systems will be discussed within the group, thus elaborating a common expertise on IWM at the system level. All 3 experiments will also provide data for a multi-sector evaluation with shared methods, most of them coming from the ENDURE-RA3 'Multicriteria assessment' group.

General conclusions and recommendations

The field studies and literature review undertaken have revealed a potential for markedly reducing both the herbicide input and environmental impact from herbicides in European maize cropping. The inclusion of preventive, cultural and mechanical methods reduces the necessity for herbicide application, apparently in a proportional manner; the more non-chemical measures are added the more can herbicide input be lowered. However, the amount of weeds surviving weed control is coincidently more likely to increase with limited reliance on herbicides. Moreover, mechanical methods applied directly in the crop may impact crop growth leading to yield losses that might impair their acceptability by the farmers.

Successful implementation of IWM in maize requires measures that reliably can replace full dose herbicide treatments and thereby preserve crop yield and prevent the continuous build-up of future weed populations. Non-chemical methods, new herbicide application techniques and reduced herbicide doses are all methods which need to suit the local conditions as well as the knowledge and skills of the operators. Clearly, appropriate timing of post-emergence herbicide application in a Mediterranean environment is more difficult, especially at reduced doses, as compared with a North European climate. Post-emergence weed harrowing is another example of a method associated with considerable risk of failures.

Given the fact that IWM occasionally might be less effective, IWM should be seen in a wider context that goes beyond the single crop. Weed control failures in one crop become less important if the whole cropping system is modified to counteract negative consequences (e.g. higher weed seed shed). Cover cropping and highly diversified crop rotations are measures presented in this report, which can reduce or prevent weed proliferation.

Unless successful IWM can be achieved by very simple means, for example a reduced herbicide dose combined with the growing of a more competitive variety, IWM would normally be more costly, especially in terms of time consumption when using mechanical methods. Cover cropping and changes in crop rotation are usually also more costly in the short term, as cover crops requires costs for seeds and extra treatments, and heterogeneous rotations could mean that less profitable crops have to be grown in some years. The potentially higher costs, the higher complexity of conducting IWM and the fact that the configuration of cropping systems is mainly driven by short-term economic factors (e.g. fluctuations in commodity prices) are probably the major reasons for the very limited use of IWM in European arable cropping. More research on IWM that could demonstrate the longer term benefits of IWM might help convince farmers. In the short term, however, financial support for implementing IWM is clearly a tool that can rapidly change farmers' and suppliers' choices, as seen with the Dutch experiences with promoting IWM in maize.

As a consequence of our work in the IWM case study, we have identified some recommendations for promoting and implementing IWM which we believe could come into action in the near future. These recommendations could reduce the environmental impact from herbicides and should also lead to a lower herbicide input in general. The recommendations are primarily formulated for silage and grain maize but may also have relevance many other crops.

- Farmer's awareness of the toxicology and environmental impact of the herbicides they chose could to be improved. The *Ipest* calculations in this case study have shown the significance of herbicide choice in relation the environmental impact.
- A stale seedbed should be established whenever possible. It can lower weed density, delay weed emergence and make the developmental growth stages of those eventually emerging more homogenous and more susceptible to post-emergence operations. A stale seedbed is preferably conducted with a weed

harrow but normal seedbed cultivators can also be used, meaning that farmers would not necessarily have to invest in new machinery.

- Inter-row cultivation should become a standard practise either to supplement band-spraying or to control weeds surviving previous weed control actions. Inter-row cultivation is easily conducted, may improve crop growth in general and can become an important factor in fighting herbicide resistance. Many farming enterprises already have inter-row cultivators, as this machinery is widely used in row crops.
- Band-spraying technology should be further improved and made available on a much wider scale than seen currently. Herbicide input on an area basis is drastically reduced without reducing the dose.
- Extension services are encouraged to motivate farmers more strongly to vary their crop rotations in order to overcome pest problems in a more sustainable manner. The growing of a less profitable crop in a single year may improve the economy in the long run, since pest problems are generally better managed while many other cropping factors are improved through diversification of the crop sequence.
- Policy makers should considered economic means to encourage farmers to adopt IWM programmes, somewhat similar to the actions taken in the Netherlands.

Future IWM research

The ENDURE RA1-Integrated Weed Management group has 2 main objectives: the first objective is to address practical recommendations for implementing IWM with satisfying weed control, improved environmental value and competitive economical profitability. These recommendations are presented above. Some of them are targeting public policy makers rather than farmers and extension services, particularly these recommendations about demonstrated trade-offs between the reliance on herbicides and the economics. The second objective is to contribute to future IWM research at the European level. The group is planning to contribute to this organisation by:

- continuing the running IWM experiments with a system approach of the 3 sites (Flakkebjerg, Pisa and Dijon), sharing a common analysis of data, and planning common publications of results;
- applying for a support from the EWRS for creating an IWM research group; the application will be submitted to the EWRS Executive Committee in September 2008
- organising an IWM workshop, partly funded by the EWRS support, that will be the occasion to expand the network with other European scientists;
- developing links with other ENDURE groups, namely
    - RA 4-5 Weed Biology and Management : the IWM experiments will provide important data to test the demography models developed by the participants to RA 4-5, and these models could be used to define more precisely decision rules at the system level (quantify the effects of crop rotation, sowing date, soil tillage, …).
    - Using emerging methods designed for cropping system evaluation in the RA 3 group, for a shared analysis of the consequences of IWM based or the experimental data from the 3 sites.
    - Developing a database grouping all the IWM practical recommendations based on the expertise of the participants and on the results of the experiments, published trough the ENDURE Information Centre (EIC) webpage.
- writing proposals for joint research actions, both at the European level and at the national level.

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