Distribution, significance and control of foxtail, *Setaria* spp. and crabgrass, *Digitaria* spp. in the Netherlands, and the situation within Europe

Verbreitung, Bedeutung und Bekämpfung von Unkrauthirsen der Gattungen Setaria und Digitaria in den Niederlanden und die Situation in Europa

Hilfred Huiting[1]*, Ton Rotteveel[2], Piet Spoorenberg[1] and Rommie van der Weide[1]

[1]Applied Plant Research, Wageningen UR / P.O. Box 430, NL-8200 AK Lelystad, the Netherlands
[2]Zutphenseweg 80, 7211 ED Eefde, the Netherlands
* Corresponding author, Hilfred.huiting@wur.nl

DOI 10.5073/jka.2014.443.085

Abstract

After its introduction in the early 1960s, maize (silage) became the largest arable crop in the Netherlands. It is often grown in monoculture or in rotation with grass leys as in a large part of Europe too. Its introduction and monoculture induced weed shifts. Although initially not considered problematic, the C4 species *Setaria viridis* and *Digitaria ischaemum* became more prominent due to changing crop husbandry systems since the mid 1990s. Tolerance of these weeds to triazines and metolachlor forced farmers to adapt weed control strategies, i.e. use of herbicides with other modes of action. Also, reduced nutrient input, earlier sowing dates, and low tillage caused a slower early crop development and increased the need for adequate weed control in general.

In today's herbicide portfolio in the Netherlands, control of *S. viridis* and *D. ischaemum* is marked as being most efficient with dimethenamide-P, isoxaflutole, S-metolachlor, and topramezone. The last one compound has a much higher degree of contact action than the predominant soil acting former three. This gives topramezone a rather unique position and, thus, Dutch crop advisors claim topramezone to be indispensable. In neighbouring countries the situation is comparable to the Dutch situation. In more Southern European countries (France, Spain) topramezone is not available, leading to a higher use of pre-emergence herbicide applications.

The different weed control strategies for *S. viridis* and *D. ischaemum*, including non-chemical alternatives, are discussed together with economic aspects.

Keywords: Control, *Digitaria*, distribution, Europe, *Setaria*, topramezone

Zusammenfassung

Nach seiner Einführung in den frühen 1960er Jahren wurde (Silo)Mais die bedeutendste landwirtschaftliche Kulturpflanze in den Niederlanden. Mais wird meist in Monokultur oder in Rotation mit Grünland angebaut, wie in großen Teilen Europas auch. Seine Einführung und die Monokultur induzierten Verschiebungen im Unkrautartenspektrum. Obwohl anfangs nicht als problematisch betrachtet, wurden die C4-Arten *Setaria viridis* und *Digitaria ischaemum* ab Mitte der 1990er Jahren aufgrund geänderter Ackerbausysteme bedeutender. Toleranz dieser Unkräuter gegen Triazine und Metolachlor nötigten Landwirte ihre Unkrautbekämpfungsstrategien anzupassen, d.h. Einsatz von Herbiziden mit anderen Wirkungsmechanismen. Darüber hinaus bedingte eine reduzierte Düngung, eine frühere Aussaat und reduzierte Bodenbearbeitung eine langsamere Jugendentwicklung der Kultur und erhöhte die Notwendigkeit einer angemessenen Unkrautbekämpfung

Im heutigen Herbizidportfolio der Niederlanden sind Dimethenamid-P, Isoxaflutole, S-Metolachlor und Topramezone am besten bewertet für die Kontrolle von *S. viridis* und *D. ischaemum*. Topramezone hat dabei eine vergleichsweise stärkere Kontaktwirkung als die vorherrschend über den Boden wirksamen anderen Wirkstoffe. Dies verleiht Topramezone eine verhältnismäßig einzigartige Position und Niederländische Berater bezeichnen Topramezone deshalb als unverzichtbar. In den Nachbarländern ist die Situation vergleichbar wie in den Niederlanden. In mehr südeuropäischen Ländern (Frankreich, Spanien) ist Topramezone allerdings nicht verfügbar, was die Nutzung von Vorauflaufherbiziden bedingt.

Die verschiedenen Unkrautbekämpfungsstrategien für *S. viridis* und *D. ischaemum* werden diskutiert, einschließlich nicht-chemischer Alternativen und wirtschaftlichen Aspekte.

Stichwörter: Bekämpfung, *Digitaria*, Europa, *Setaria*, Topramezone, Verbreitung

Introduction

After its introduction in the early 1960s maize today covers the largest cultivation area of all crops in the Netherlands (239,129 ha in 2012) and is mostly grown as silage maize. In practice, maize is often grown without rotation or in rotation with grass leys. Every crop is accompanied by a specific weed flora, whereupon the change in climate nowadays allows weeds with southern origin to colonize more northern areas. In the case of maize, colonization by the group of C4 grass weeds was particularly successful. Particularly successful recent invaders are *Setaria viridis* (L.) P. Beauv. (*Setaria*; foxtail) and *Digitaria ischaemum* (Schreb.) Schreb. Ex Muhl (*Digitaria*; cabgrass). Review papers by DOUGLAS *et al.* (1985), MITCH (1988), DEFELICE (2002), FRANKE *et al.* (2009), TURNER *et al.* (2012), OREJA *et al.* (2012) and MEHRTENS (2013) give an overview of the biology and life cycle of *Setaria* and *Digitaria* spp. Both genera are spread worldwide and are characterized by emergence in late-seeded spring crops (generally shortly after *Echinochloa crus-galli* (L.) P. Beauv. emergence) over a long period, rapid vegetative growth, seed production from July onwards, high seed rates, and a high phenotypic plasticity. Weed tolerance to triazines and metolachlor forced farmers to use herbicides with other modes of action, which is a continuous development. This paper describes the situation with *Setaria* and *Digitaria* spp. in the Netherlands and other countries in Europe. An overview of current control strategies and future developments and needs are presented, with special attention to the possible position of topramezone.

Emergence and distribution of *Setaria* and *Digitaria* spp. in the Netherlands and their current control

The oldest known findings of *Setaria* and *Digitaria* species in the Netherlands date back to the Iron Age, including *S. viridis* and *D. ischaemum* (WEEDA, 1994). Within their genera both are today the most common species. The shown recordings of *S. viridis* and *D. ischaemum* (Fig. 1) demonstrate that both species are especially important in southern and more continental regions of the Netherlands.

Although part of the Dutch flora for millennia, *S. viridis* and *D. ischaemum* seem to have become more important since 1994. Other *Setaria* species occurred since then that were not recognized before. The known presence of *Setaria faberi* Herrm. seems to be restricted to the east of the country, but its distribution may be much wider considering determination difficulties and possible lack of interest by (amateur) botanists (DIRKSE *et al.*, 2001). Furthermore *Setaria* species are closely related and hybrids occur (DEKKER, 2003). Although the within field genetic variation seems to be low (although no Dutch data available), the genetic variation between fields can be very high (USA data, personal communication Rotteveel). Therefore, the species group should be considered as very adaptable. Recent developments in Germany and Belgium (DIRKSE *et al.*, 2001; HOSTE *et al.*, 2001, 2006) are in line with the noticed increase in *Setaria* occurrence in the Netherlands over the last two decades.

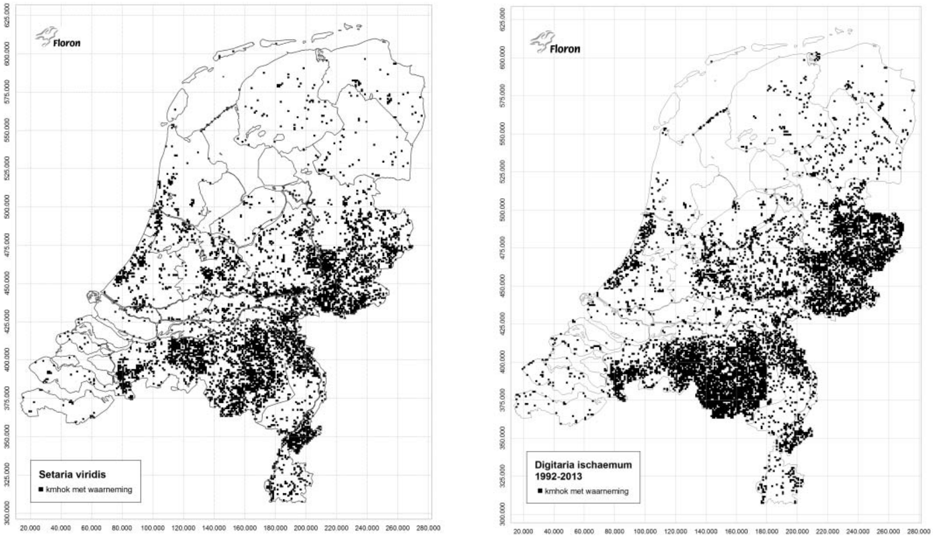

Fig. 1 Recordings of *Setaria viridis* and *Digitaria ischaemum* across the Netherlands in the period 1992-2013; 1 km grid cells (Floron/NDFF 2013).

Abb. 1 *Vorkommen von* Setaria viridis *und* Digitaria ischaemum *in den Niederlanden im Zeitraum 1992-2013; 1 km Raster (Floron/NDFF 2013).*

To date the exact reasons for the noted *Setaria* increase in the Netherlands have not been determined, but sufficient knowledge is available to interpret the influencing factors: crop rotation, fertilization, variety choice, chemical and mechanical control systems, farming scale, climate change, and time.

The introduction of silage maize marked a shift from traditional mixed farming systems with winter and root crops and *Centaurea* spp., *Papaver* spp. and *Chenopodium* spp. as the typical weed flora to specialised dairy farms with monocultures of maize for continuous years. After the era of atrazine – in which maize crops were dense due to over-manuring, leaving little space for weed competition – the maize growing systems changed halfway the 1980s, after restricting the use of manure. New maize varieties became available that ripened earlier and had less foliage. While *Setaria* and *Digitaria* were present in low numbers formerly, the new system promoted both species: favourable sowing conditions arrived earlier in spring and cultivars were more cold tolerant, moving up the sowing season (today approx. three weeks earlier than in the 1960's). Dicotyledon resistance and *Echinochloa* insensitivity to atrazine and label restrictions induced changes in chemical weed control to favouring metolachlor and bentazone. *Setaria* and *Digitaria* – rather sensitive to both, atrazine and metolachlor – did not benefit from these changes despite better conditions for germination.

Tab. 1 Active ingredients with registered efficacy towards grass species (GEWASBESCHERMINGSGIDS 2012, NVWA) and efficacy rating per active by DLV Plant (HANDLEIDING GEWASBESCHERMING AKKERBOUW EN VEEHOUDERIJ, 2012).

***Tab. 1** Registrierte Wirkstoffe mit Wirksamkeit gegen Ungräser (GEWASBESCHERMINGSGIDS 2012, NVWA) und Effektivitätsbewertung durch DLV Plant (HANDLEIDING GEWASBESCHERMING AKKERBOUW EN VEEHOUDERIJ, 2012).*

Active ingredient	**Trade name (Netherlands)**	***Setaria viridis***	***Digitaria ischaemum***
Bentazone	Basagran e.a.	*	*
+ terbuthylazine	Laddok N (+ oil)	-	-
Dimethenamide-P	Frontier Optima	+++	+++
+ iodosulfuron-methyl-sodium	MaïsTer	++	+
Glufosinate-ammonium	Finale (and others)	*	*
Isoxadifen-ethyl + tembotrione	Laudis WG	*	*
Isoxaflutole	Merlin	+++	+++
Mesotrione	Callisto	-	-
+ nicosulfuron	Elumis	*	*
+ terbuthylazine	Calaris	++	++
Nicosulfuron	Milagro/Samson	+	+
Pendimethalin	Stomp	*	*
Rimsulfuron	Titus	++	-
S-metolachlor	Dual Gold	+++	+++
+ terbuthylazine	Gardo Gold	+++	+++
Sulcotrione	Mikado	-	+
Tembotrione	Laudis	++	++
Topramezone	Clio	+++	+++

+++ = very sensitive; ++ = sensitive; + = moderately sensitive; - not sensitive; * = no information supplied

Today the herbicide portfolio used has changed further such that triazines and metolachlor are mostly avoided and an increased number of herbicides is included (with several label restrictions). Most maize in the Netherlands is grown on quickly drying sandy soils where typical soil herbicides do not perform well and despite early sowing (April 20-30) crop canopy closure is hardly earlier than before the end of July. These two aspects together promote competition by *Setaria* and *Digitaria*. At the current increased farming scale, maize cultivation is predominantly contractor work, implying an urge to control weeds in one pass, which creates increasing escape opportunities for weeds. Although operators are trained, distinguishing of grass weed species is often felt to be too time-consuming. This creates extra opportunities for *Setaria* and *Digitaria* species, which germinate after the main *Echinochloa* flux and are also able to germinate over an extended period of time.

Tab. 2 Possible tank mixtures to control maize weeds (after VAN DER WEIDE and HOGENKAMP, 2010).

Tab. 2 *Mögliche Herbiziden-Mischungen für die Unkrautbekämpfung in Mais, (nach VAN DER WEIDE und HOGENKAMP, 2010).*

Tank mix (application rates in kg or L formulated product per ha)	***Echinochloa crus-galli***	***Digitaria ischaemum***	***Setaria viridis***	***Poa annua***	***Agropyron repens***	***Geranium spp.***	**Polygonaceae**
Pre-emergence (sufficient moisture)							
0.1 Merlin (post-emergence mechanical hoeing)	+	++	++	-	-	+	-
0.075-0.1 Merlin + 0.5-1 Frontier Optima/Dual Gold*	++	++	++	++	-	+	+
2.0 Gardo Gold	++	++	++	++	-	++	+
Post-emergence							
1-2 Laddok N + 0.5 Promotor	-/+	-	-	+	-	+(+)	+
1.5 Mikado/Callisto	++	+	-	-	-	-	++
1 Laddok N + 0.5-1.0 Mikado/Callisto	++	+	-	+	-	+(+)	++
1 Laddok N + 0.5 Promotor + 0.2 Clio	++	++	++	+	-	+(+)	++
1 Laddok N + 0.75 Milagro/Samson	++	-	++	++	++	+(+)	+
1 Mikado/Callisto + 0.75 Milagro/Samson	++	+	++	++	++	-	++
0.5-1 Mikado/Callisto + 0.75 Milagro/Samson+ 0.5-1.0 Frontier Optima/Dual Gold	++	+	++	++	++	+	++
0.15 Maister + 2 Actirob	++	-	++	++	++	+	+
0.125 Maister +1.5 Actirob + 0.75 Mikado/Callisto	++	+	++	++	++	+	++
0.125 Maister +1.5 Actirob + 0.2 Clio	++	++	++	++	++	+	++
1.0 Calaris + 0.75 Milagro/Samson + 0.5-1.0 Frontier Optima/Dual Gold**	++	+(+)	++	++	++	++	++
2 Gardo Gold + 0.75 Milagro/Samson + 0.75-1 Mikado/Callisto	++	+(+)	++	++	++	++	++
0.2 Clio + 0.75 Milagro/Samson+ 0.5-1 Frontier Optima/Dual Gold**	++	++	++	++	++	+	+(+)
2 Gardo gold + 2 Laudis	++	++	++	++	-	++	++
2 Laudis + 0.5 Milagro/Samson + 0.5-1 Frontier Optima/Dual Gold**	++	++	++	++	++	+	++

Efficacy rated from - to ++
* Dual Gold needs 25% lower application rate compared with Frontier Optima with same efficacy
** Without pre-emergence harrowing rates may be lowered, possibly with somewhat higher rate of Frontier or Dual Gold

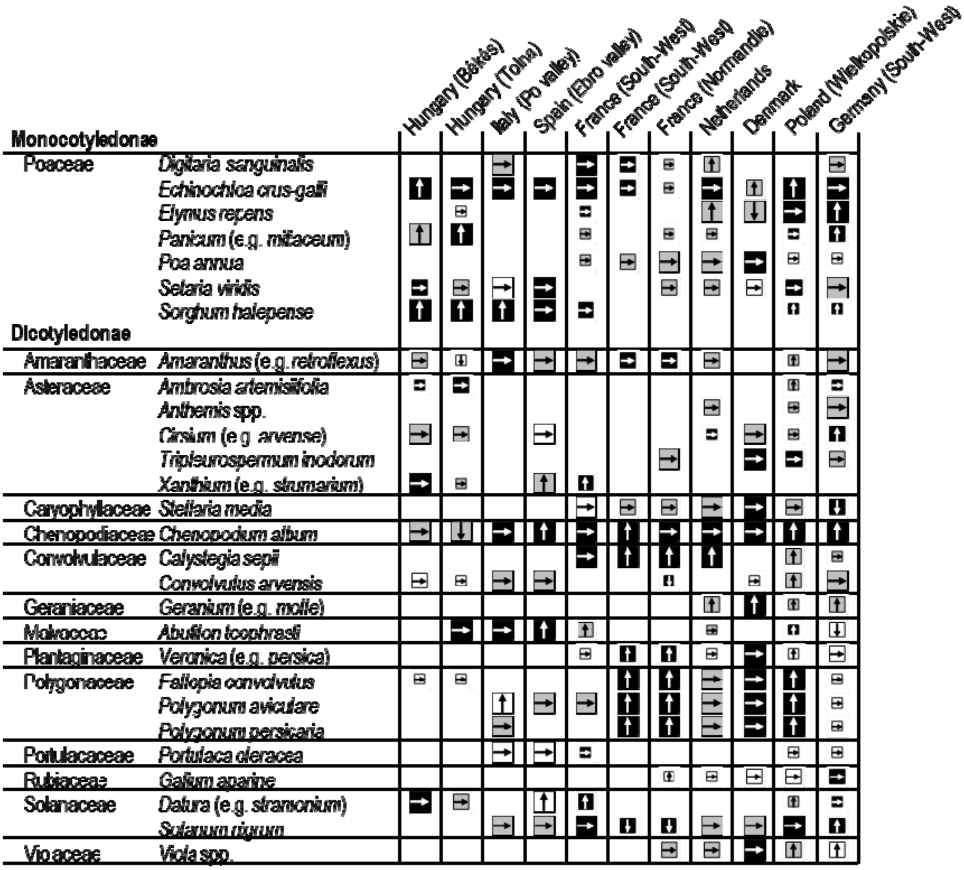

Fig. 2 Most important weeds in European maize production. Significance is represented by symbol colour: black = high, grey = medium, white = low. Occurrence is represented by symbol size: large = widespread and regularly, medium = widespread and occasionally, small = regionally and rare. The 5-year population development is represented by arrows: up = increasing, horizontal = stable, down = decreasing (after MEISSLE *et al.*, 2010).

Abb. 2 *Wichtigste Unkräuter und Ungräser im europäischen Maisanbau. Die Signifikanz ist dargestellt durch die Farbe der Symbole: Schwarz = hoch, Grau = mittel, Weiß = gering. Vorkommen ist dargestellt durch Größe: groß = weitverbreitet und häufig, mittel = weitverbreitet und gelegentlich, klein = regional und selten. Die fünfjährige Populationsentwicklung ist dargestellt durch Pfeile: aufwärts = zunehmend, horizontal = stabil, abwärts = abnehmend (nach MEISSLE et al., 2010).*

The contractor operated single pass weed control has access to approx. 20 active ingredients currently registered in the Netherlands, of which sixteen have an efficacy towards grasses in general (GEWASBESCHERMINGSGIDS 2012, NVWA). The highest rated active ingredients against S. viridis and D. ischaemum are dimethenamide-P, isoxaflutole, S-metolachlor, combined with terbuthylazine or not, and topramezone (HANDLEIDING GEWASBESCHERMING AKKERBOUW EN VEEHOUDERIJ, 2012). The selection of herbicides by contractors is based on an average occurrence and abundance of weeds including grasses in the treated fields. This situation asks for sophisticated tank mixtures of herbicides (Tab. 2). The tank mixture displayed in Table 2 have been discussed and agreed by the relevant chemical companies.

Distribution and importance of Setaria and Digitaria species in Europe and weed control strategies

Maize being an important crop within Europe, the research networks ENDURE and PURE used it as a case study of IPM implementation (MEISSLE *et al.*, 2010; VASILEIAS *et al.*, 2011 and 2013). Many maize cultivation factors were defined including herbicide use and weed abundance and importance from 11 European maize growing regions (MEISSLE *et al.*, 2010). Silage maize dominates in Northern Europe whereas grain production dominates in Central and Southern Europe. Several factors differ between areas, such as crop rotation, nitrogen level, and level of IPM implementation.

Tab. 3 Annual area (in % of total) of maize crop treated with pesticides in 11 European regions and mean number of applications in crop cultivation (in brackets) (from MEISSLE *et al.*, 2010).

Tab. 3 *Jährliche Maisanbaufläche (% von gesamt) die mit Pestiziden behandelt ist in 11 europäischen Regionen und durchschnittliche Anzahl der Anwendungen in der Anbau (in Klammern) (nach MEISSLE* et al.*, 2010).*

Country and region		**Herbicides**		**Insecticides**				**Fungicides**
		Spray[a]		**Soil application**	**Seed treatment**	**On-plant spray[b]**		**Seed treatment**
Hungary	Békés	100	(0.3 / 1)	50	20	40	(1)	100
	Tolna	95	(0.3 / 1.1)	60	40	20	(1)	100
Italy	Po Valley	96	(0.9 / 0.5)	5	80	11	(1)	100
Spain	Ebro Valley	100	(1.0 /1.0)	10	100	50	(1-2)	100
France	Southwest	98	(1.1 / 0.4)	42	0	6	(1)	100
	Grand-Ouest	99	(0.7 / 1.0)	32	0	5	(1)	100
	Normandie	100	(0.8 / 0.7)	33	0	2	(1)	100
Netherlands		99	(0.2 / 1.1)	0	50	0	-	95
Denmark		97	(0.1 / 2.3)	0	0	5	(1)	95
Germany	Southwest	90	(0.2 / 0.9)	?	100	?		100
Poland	Southwest	100	(0.1 / 1.3)	0	20	20	(1)	100

[a] number of applications pre-/ post-emergence in parenthesis
[b] number of applications in parenthesis

Among the more than 50 weed species recognised as important for maize, the monocotyledons *Echinochloa crus-galli* and *S. viridis* cause problems over all European countries (Fig. 2). *Sorghum halepense* (L.) *Pers*. is a major weed in southern regions, while *Elymus repens* (L.) Gould and *Poa annua* (L.) are important in northern regions. *Digitaria sanguinalis* (L.) Scop. causes problems only in some regions. Although *D. sanguinalis* is stated in Figure 2 and is the main species in the Southern countries, *D. ischaemum* is the main species for the Northern countries. However, a clear discrimination between both *Digitaria* species is in practice often not made. On being asked about the situation after publication of the paper, the Italian co-authors of MEISSLE *et al.* (2010) estimated the status of *Setaria* spp. today to be the same as *Digitaria* spp. reflecting its increased significance.

No (expected) changes of the analysis above were reported in Spain (ESCARIO *et al.*, 2013), Germany, and Hungary.

The Dutch chemical weed control situation is comparable to its neighbouring countries. Further south (France, Spain, Italy), pre-emergence applications are common practice (Tab. 3), dictated by the risk of yield reductions due to an insufficiently controlled first flush of weeds together with a lack of reliable post-emergence herbicides for the control of *Setaria* and *Digitaria* spp. (Tab. 4). In addition *Setaria* and *Digitaria* spp. may escape pre-emergence control as a result of a long emergence window, making post-emergence control options desirable. Figure 4 further demonstrates the increasing importance of *S. halepense* (L) Pers. in the Southern European countries, another C4 species that has been noted to migrate northwards including occasional recordings in the Netherlands. This monocotyledon is regarded to be one of the most noxious weeds (HOLM *et al.*, 1977). However, according to experiences from USA, *S. halepense* control is improved through post-emergence application of topramezone (BASF, 2011), which is likely to have an efficacy against seedlings. No specific data from Europe are available however.

Tab. 4 Overview of registered herbicidal active ingredients (Y = yes/N = no) in 13 European countries in 2013.

Tab. 4 *Übersicht zugelassener Herbizid-Wirkstoffe (Y = ja; N = nein) in 13 europäischen Ländern in 2013.*

Active ingredient	**Belgium**	**Czech Republic**	**Denmark**	**Spain**	**France**	**Greece**	**Italy**	**Netherlands**	**Poland**	**Romania**	**Sweden**	**Slovenia**	**Croatia**
Acetochlor	N	Y	N	Y	N	N	Y	N	Y	N	N	N	Y
Alachlor	N	N	N	N	N	N	N	N	N	N	N	N	N
Atrazine	N	N	N	N	N	N	N	N	N	N	N	N	N
Dimethenamid-P	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	N	Y	Y
Foramsulfuron	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Mesotrione	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Nicosulfuron	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	N	Y	Y
Pethoxamid	Y	Y	N	Y	Y	Y	Y	N	Y	Y	N	Y	Y
Rimsulfuron	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
S-metolachlor	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	N	Y	Y
Sulcotrione	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	N	N	N
Tembotrione	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	N	Y	Y
Terbutylazine	Y	N	N	Y	N	Y	Y	Y	Y	Y	N	Y	Y
Topramezone	Y	Y	N	N	N	Y	N	Y	Y	Y	N	N	N

A survey among the ENDURE and PURE members on the role and importance of topramezone for reliable weed control showed, that in Hungary the area of pre-emergence control appears to have decreased in recent years, due to unsatisfactory control in case of drought after application together with the new availability of several post-emergence herbicides; topramezone is used in several tank mixtures in Hungary. It seems that in countries with more reliable post-emergence options, including topramezone, the area of pre-emergence applications decreased (comparison of Tab. 3 and 4). In France and Spain, topramezone is not registered and sulfonylurea-based herbicides are still very important in post-emergence weed control. In Spain nicosulfuron is very important for control of *S. halepense* and there is much interest in new opportunities to control monocotyledons. Several international respondents stated the importance of the availability of herbicides with different modes of action and HRAC groups for resistance management.

Future outlook and discussion on control options of *Setaria* and *Digitaria* spp.

International developments

Some current developments are important towards the future of weed control in maize. To start with, weed control is depending on the cropping system and in many areas reduced tillage is increasingly practiced. A further increase depends on direct (energy and labour savings) and indirect economic constraints (erosion reduction, water retention, cover crops or double cropping, and new techniques such as strip tillage) (VAN DER WEIDE *et al.***,** 2008b; VAN DER WEIDE, 2011; RIEMENS *et al.*, 2013). Reduced tillage may increase weed abundance and hamper non-chemical weed control, calling for non-chemical innovations (MELANDER *et al.*, 2013). Particularly monocotyledonous weeds will benefit from reduced tillage. Meanwhile, availability of (new) herbicides to address monocotyledonous weed problems is far from being secure. Outside Europe weed control is much more based on the possibilities offered by GM crops, making the future introduction of new herbicides a rarity. Introduction of GM crops in Europe is unlikely in the short term. At the moment the EU is heading towards regulation of IPM through Regulation 2009/128/EC and current discussions relate to possible implementations. The IPM challenge is addressed by research programs like ENDURE and PURE, naming diversification of the crop rotation as a measure for maize (VASILEIADIS *et al.*, 2011). Generally, the uncontrolled presence of weeds in the early crop stages – until approx. 40 cm height – decreases the yield of maize. In these stages, weed competition is normally fierce as the early development of maize is rather slow making control measures unavoidable. Weed competition during the early developmental stages may lead to 5 to 10% yield reduction at moderate weed pressure and up to 25% or more at a high weed pressure (DEMEULEMEESTER, 2012). The direct economic losses would in the Netherlands add up to more than €500 per hectare at 25% yield loss (SCHREUDER *et al.*, 2009).

Chemical control alternatives

Maize growing is currently still largely dependent on the availability and use of herbicides, as farmers' considerations tend to weigh short-term economics over long-term sustainability. There are no signs that this will significantly change within the (near) future. Introduction of herbicide resistant GM crops will only increase this dependence, whereas the herbicides involved are equally prone to the evolution of resistance in weeds. In many regions maize crop rotations are often absent or narrow which together with the herbicide dependence indicates a considerable risk of herbicide resistance development (ROTTEVEEL *et al.*, 2011). After the triazines, this is now happening with ALS inhibitors in the countries surrounding the Netherlands, whilst sulfonylureas are an important tool for grass control in maize. To delay resistance development, alternations with other chemical groups are vital, together with mechanical control if possible. In this respect the inclusion of HPPD-acting herbicides such as topramezone can be very valuable. Especially regarding the control of *Setaria* and *Digitaria* spp. topramezone is claimed to be the most reliable contact herbicide by crop advisors, although more pronounced for *Setaria* spp. than for *Digitaria* spp. These independent advisors state topramezone to be effective against *Setaria* and *Digitaria* spp. until tillering whereas high efficacy ratings of dimethenamide-P, isoxaflutole and S-metolachlor (Tab. 1) are predominantly based on their soil activity in early weed stages under favourable conditions. So without the comparatively high efficacy of topramezone and in the presence of *Setaria* and *Digitaria* spp., weed control in maize will be more difficult, resulting in higher rates of other compounds or repeated applications, together with an increase of *Setaria* and *Digitaria* spp. populations in the near future. The selection pressure resulting from this development is likely to induce the development of metabolic resistance. Nevertheless, the control of *Setaria* and *Digitaria* spp. with less effective herbicides than topramezone may still sufficiently control weeds, but could increase cost level, besides environmental effects and the risk of crop failure. In the latter case, extensive weed seed production may even induce future weed control problems. Soil herbicides may intrinsically be effective against *Setaria* and *Digitaria* spp. However, should the control depend on soil herbicides, both soil moisture and the products´ persistence should be sufficient for the long emergence window of these species. If not, further costs have to be paid to prevent yield loss and the build-up of a seed bank, possibly without a secure control of grasses.

Non-chemical alternatives

To reduce both, environmental impact and the risk of resistance, wider crop rotations and/or more mechanical weed control will have to be applied. Widening crop rotation – with grass leys or (root) crops – will considerably slow down population build-up and resistance evolution, the former merely through competition and the latter through different options for weed control, even more so with root crops. Application of one or more of the available mechanical control techniques in maize (VAN DER SCHANS, 2006; VAN DER WEIDE *et al.*, 2008a, 2010 and 2011) brings a non-selective weed control component into the system. Mechanical weed control has the potential of keeping weeds under control in maize. However, it requires experience and skills to be applied effectively and cost-effective, more so than with chemical weed control. An effective purely mechanical strategy takes at least one or two passes with a harrow and one or two with a hoe – with (in case of little harrowing) or without finger or torsion weeders. Under Dutch conditions the cost per hectare of a mechanical strategy may be higher than a chemical strategy (SCHREUDER *et al.*, 2009). However, in other countries or based on other premises (e.g., rate of labour cost) the comparison may be quite even. Especially harrowing with its high capacity is a cost-effective way of mechanical weed control. Pre-emergence harrowing reduces the size and density of weeds without harming the maize crop. If combined with a herbicide application, these smaller weeds need a lower application rate or will still be completely controlled at the recommended rate. Besides harrowing, hoeing offers good possibilities, especially in combination with torsion or finger weeders and ridging. Nevertheless, it will be necessary to overcome the current prejudice that mechanical weed control is (too) labour-intensive and weather-dependent for large scale contractor operations. In the case of *Setaria* and *Digitaria* spp., their long emergence windows would dictate multiple passes. Nevertheless, incorporation of mechanical control into the control system should be considered to be a valuable tool in reducing resistance development. Moreover, the perceived higher weather sensitivity of mechanical weed control may in fact be merely different – not higher – compared to the sensitivity of spraying, emphasizing a need to build up farmer's experience.

Synthesis

If alternative weed control strategies lead to poorly controlled weed species, this will induce a shift in the weed flora and possible resistance development, as this is dependent on the left-over of resistant individuals that can set seeds. Crop rotation and alternation of weed control measures hamper the resistance development and may greatly influence herbicide input. However, the availability of effective post-emergence herbicides remains necessary to control weeds including *Setaria* and *Digitaria* spp. This need is created by the ineffective control by rotation and mechanical options under all circumstances and the often practical unsuitability of pre-emergence herbicides for long-lasting control under unfavourable conditions. Currently, countries without a topramezone registration (Spain, Italy and France) still depend on pre-emergence spraying illustrating that a varied choice of post-emergence products is necessary too when the different weed floras are taken into consideration. The current increases of both *Setaria* and *Digitaria* spp. in maize demands the availability of efficacious post-emergence herbicides with a wide window of application. Topramezone is a herbicide that could fill this niche because of its mode of action, its spectrum of activity, its window of application, and its suitability to be mixed with other products.

References

BASF, 2011: Armezon Herbicide Technical Information Brochure. Tough on Weeds. Safe on Corn.

CRIJNS, J., J. REMIJN, J. SALOMONS and G. SNIPPE, 2012: Handleiding gewasbescherming akkerbouw en veehouderij 2012. Assen, DLV Plant, 248 pp.

DEFELICE, M. S., 2002: Intriguing World of weeds: Green foxtail, *Setaria viridis* (L) P. Beauv. Weed Technol. **16**, 253-257.

DEKKER, J., 2003: The foxtail (*Setaria*) species group. Weed Sci. **51**, 641-656.

DEMEULEMEESTER, K., 2012: Praktijkgids landbouw en natuur. Depotnummer D/2012/3241/385.

DIRKSE G. M., A. I. REIJERSE and C. G. ABBINK-MEIJERINK, 2001: *Setaria faberi* (Chinese naaldaar) in Nederland over 't hoofd gezien. *Gorteria* **27** (5), 109-114.

DOUGLAS, B. J., A. G. THOMAS, I. A. MORRISON and M. G. MAY, 1985: The biology of Canadian Weeds 70. *Setaria viridis* (L) Beauv. Can. J. Plant Sci. **65**, 669-690.

ESCARIO, A. J., X. O. SOLD-SENAN, J. A. C. I MOR Y and J. R. GUINJUAN, 2013: Malas hierbas exóticas en cultivos de maiz en lleida, qué ha cambiodu en veinte anos. Vide rural 2013/1, 54-58.

FRANKE, A. C., C. J. VAN DIJK and M. M. RIEMENS, 2009: *Setaria verticillata*, *Digitaria ischaemum* and *Geranium molle*, biology and control, a review of literature. Nota 587, Plant Research International, Wageningen, 27 p.

HOSTE, I. , 2006: *Setaria viridis*. In: *Atlas van de flora van Vlaanderen en het Brussels gewest.* VAN LANDUYT W., HOSTE I., VANHECKE L., VAN DEN BREMT P., VERCRUYSSE W. and DE BEER D.,. Instituut voor Natuur- en Bosonderzoek, Nationale Plantentuin van België, 828.

HOSTE I. and F. VERLOOVE, 2001: De opgang van C_4-grassen (Poaceae-Paniceae) in de snel evoluerende onkruidvegetaties in maïsakkers tussen Brugge en Gent (Vlaanderen, België, *Dumortiera* **78**, 2-11.

MEHRTENS J., 2013: Artenvielfalt, Verbreitung und Bedeutung von Unkrauthirsen in Mais. Limburgerhof, 2013, BASF, 20 pp.

MEISSLE, M., P. MOURON, T. MUSA, F. BIGLER, X. PONS, V. P. VASILEIADIS, S. OTTO, D. ANTICHI, J. KISS, Z. PALINKAS, Z. DORNER, R. VAN DER WEIDE, J. GROTEN, E. CZEMBOR, J. ADAMCZYK, J.-B. THIBORD, B. MELANDER, G. CORDSEN NIELSEN, R. T. POULSEN, O. ZIMMERMANN, A. VERSCHWELE and E. OLDENBURG, 2010: Pests, pesticide use and alternative options in European maize production: current status and future prospects. J. Appl. Ent. **134**, 357-375.

MELANDER, B., N. M. MUNIER-JOLAIN, R. CHARLES, J. WIRTH, J. SCHWARZ, R. Y. VAN DER WEIDE, L. BONIN, P. K. JENSEN and P. K. KUDSK, 2013: European Perspectives on the Adoption of Nonchemical Weed Management in Reduced-Tillage Systems for Arable Crops. Weed Technol. **27** (1), 231-240.

MITCH, L., 1988: Intriguing world of weeds: crabgrass. Weed Technol. **2**, 114-115.

NVWA, 2012:. Gewasbeschermingsgids 2012. Wageningen, 2012, Wageningen Academic Publishers, 591 pp.

OREJA, F. H., F. BASTIDA and J. L. GONZALEZ-ANDUJAR, 2012: Simulation of control strategies for decision-making regarding *Digitaria sanguinalis* in glyphosate-resistant soybeans. Ciencia Investigation Agraria **39** (2), 299-308.

RIEMENS, M. M., H. F. HUITING, J. DERU, H. A. VAN SCHOOTEN, D. A. VAN DER SCHANS, J. VERLOOP, F. AARTS and R. Y. VAN DER WEIDE, 2013: Duurzaam bodembeheer maïs. Research report. 101 p.

ROTTEVEEL, T, L. N. JORGENSEN and U. HEIMBACH, 2011: Resistance management in Europe: a preliminary proposal for the determination of a minimum number of active substances necessary to manage resistance. EPPO bulletin volume **41** (3), 432-438.

SCHANS, D. A. VAN DER, P. O. BLEEKER, L. P. G. MOLENDIJK, M. C. PLENTINGER, R. Y. VAN DER WEIDE, L. A. P. LOTZ, R. BAUERMEISTER, R. TOTAL and D. T. BAUMANN, 2006: Practical weed control in arable farming and outdoor vegetable cultivation without chemicals Applied Plant Research, (PPO 352), 77 p.

SCHREUDER, R., M. VAN LEEUWEN, J. SPRUIJT, M. VAN DER VOORT, P. VAN ASPEREN and V. HENDRIKS-GOOSSENS, 2009: Kwantitatieve Informatie Akkerbouw en Vollegrondsgroenteteelt 2009. ISSN 1571-3059.

TURNER, F. A., K. S. JORDAN and R. C. VAN ACKER, 2012: Review: the recruitment biology and ecology of large and small crabgrass in turfgrass: implications for management in the context of a cosmetic pesticide ban. Can. J. Plant Sci. **92** (5), 829-845.

VAN DER WEIDE, R. Y., 2011: Geen structuurschade meer bij mais. Syscope 2011 (**29**), 6-7.

VAN DER WEIDE, R. Y., P. O. BLEEKER, V. T. J. M. ACHTEN, L. A. P. LOTZ., B. MELANDER and F. FOGELBERG, 2008(a): Innovation in mechanical weed control in crop rows. Weed Res. **48** (3), 215-224.

VAN DER WEIDE, R. Y., P. O. BLEEKER, M. M. RIEMENS, L. A. P. LOTZ, J. ASCARD and B. MELANDER, 2011: Tools and innovations in mechanical weed control in north-western Europe. Topics in Canadian Weed Science **6**, 91-102.

VAN DER WEIDE, R. Y. and W. HOGENKAMP, 2010: Maisteelt in beweging: Landschapsmais in plaats van 'gewone' mais? Boerderij 2010 (**26**), 44-47.

VAN DER WEIDE, R. Y., H. F. HUITING, P. O. BLEEKER and M. M. RIEMENS, 2011: Pro's and con's of reduced tillage in Maïze with respect to weeds. Proceedings 9th ERWS workshop on physical and cultural weed control, Samsun, Turkey, 28-30 March, 2011.

VAN DER WEIDE, R. Y., F. A. N. VAN ALEBEEK and R. C. F. M. VAN DEN BROEK, 2008(b): En de boer, hij ploegde niet meer?: literatuurstudie naar effecten van niet kerende grondbewerking versus ploegen. Lelystad : Praktijkonderzoek Plant & Omgeving, Sector Akkerbouw, Groene Ruimte en Vollegrondsgroenteteelt. 45 p.

VAN DER WEIDE, R. Y., D. J. M. VAN BALEN and G. J. H. M. MEUFFELS, 2010: Telen zonder ploeg. Kennisakker.nl 2010 (13-10-2010). Productschap Akkerbouw/Kennisakker.

VASILEIADIS, V. P., M. SATTIN, S. OTTO, A. VERES, Z. PÁLINKÁS, R. BAN, X. PONS, P. KUDSK, R. Y. VAN DER WEIDE, E. CZEMBOR, A.C. MOONEN and J. KISS, 2011: Crop protection in European maize-based cropping systems: current practices and recommendations for innovative integrated pest management. Agric. Syst. **104**, 533-540.

VASILEIADIS, V. P., A. C. MOONEN, M. SATTIN, S. OTTO, X. PONS, P. KUDSK, A. VERES, Z. DORNER, R. VAN DER WEIDE, E. MARRACCINI, E. PELZER, F. ANGEVIN and J. KISS, 2013: Sustainability of European maize-based cropping systems: Economic, environmental and social assessment of current and proposed innovative IPM-based systems. J. Agron. **48**, 1-11.

WEEDA, E. J., 1994: Nederlandse oecologische flora wilde planten en hun relaties, 5. ISBN no 90-6301-024-9.

HOLM, L. G., D. L. PLUCKNETT, J. V. PANCHO and J. P. HERBERGER, 1977. The World's Worst Weeds: Distribution and Biology. The University Press of Hawaii, Honolulu, Hawaii. 609 pp.