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Wirkung und Selektivität von Foramsulfuron + Thiencarbazone-methyl zur Unkrautkontrolle in Zuckerrüben

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Liste der Manuskripte

Die vorliegende Arbeit besteht aus vier Manuskripten, die in wissenschaftlichen Zeitschriften bereits publiziert oder zur Publikation angenommen sind:

WENDT, M.J.; WEGENER, M.; LADEWIG, E.; MÄRLÄNDER, B. (2016): Efficacy of *foramsulfuron + thiencarbazone-methyl* towards different development stages of weed species in sugar beet cultivation. Sugar Industry 141: 436-445.

WENDT, M.J.; KENTER, C.; LADEWIG, E.; WEGENER, M.; MÄRLÄNDER, B. (2016): Duration of Soil Activity of Foramsulfuron + Thiencarbazone-methyl applied to Weed Species typical of Sugar Beet Cultivation. Weed Technology (im Druck).

WENDT, M.J.; KENTER, C.; WEGENER, M.; MÄRLÄNDER, B. (2016): Efficacy of different strategies using an ALS-inhibitor herbicide for weed control in sugar beet. Journal für Kulturpflanzen 11/2016; 68: 338-343.

WENDT, M.J.; KENTER, C.; LADEWIG, E.; MÄRLÄNDER, B. (2016): Selectivity of foramsulfuron + thiencarbazone-methyl and classic herbicides in sensitive and non-sensitive sugar beet genotypes. Weed Research (im Druck).

Kapitel 1

Prolog

Prolog

Herbizidwirkstoffe, die in die Wirkstoffklasse „B“ des *Herbicide Resistance Action Commitee* (HRAC) eingeordnet werden, blockieren das Enzym Acetolactat-Synthase (ALS) von Pflanzen und sind daher unter dem Begriff ALS-Inhibitoren in der Literatur und Praxis bekannt.

Das Saatzuchtunternehmen *KWS Saat SE* und das Pflanzenschutzunternehmen *Bayer CropScience AG* arbeiten seit 2001 mit konventionellen Zuchtmethoden an der Züchtung gegenüber ALS-Inhibitoren nicht sensitiven Zuckerrübengenotypen (KWS 2012). Beim Anbau dieses Genotyps wäre ein breiter Einsatz von Herbiziden mit ALS-Inhibitoren möglich. Bislang ist nur der Wirkstoff Triflusulfuron-methyl aus dieser Herbizidgruppe in Zuckerrüben zugelassen. Das Dossier für ein entsprechendes Herbizid, das unter dem Namen Conviso® zugelassen werden soll, ist bereits eingereicht. Das Konzept eines Herbizids, das ALS-Inhibitoren enthält, mit einer komplementären Sorte zu kombinieren, wird voraussichtlich als Conviso Smart® Technologie eingeführt werden (KWS 2015). Eine komplementäre Sorte wurde 2016 zur Wertprüfung angemeldet und könnte 2018 für die Markteinführung zur Verfügung stehen.

Der breite Einsatz von ALS-Inhibitoren könnte zukünftig eine Erweiterung der Unkrautkontrolle in Zuckerrüben in Zentraleuropa bieten, die heute in einigen Punkten an ihre Grenzen stößt. Zu diesen zählt zum einen die mangelnde Selektivität an jungen Zuckerrübenpflanzen. Zum anderen ist der Anteil schwer bekämpfbarer Unkräuter in den letzten 15 Jahren gestiegen sowie weisen einige Unkräuter Resistenzen gegenüber den meist eingesetzten Wirkstoffen auf. Zudem ist eine Reduktion der hohen Pflanzenschutzintensität im Zuckerrübenanbau mit den heutigen Herbiziden nicht zu realisieren. Es gibt bisher keine wissenschaftlichen Daten darüber, ob die Conviso Smart® Technologie einen Beitrag zu einer innovativen Unkrautkontrolle in Zuckerrüben leisten kann.

Notwendigkeit der Unkrautkontrolle in Zuckerrüben

Der Hauptbestandteil des in der Europäischen Union (EU) verbrauchten Zuckers ist Rübenzucker aus der EU. Die Zuckerproduktion der EU betrug im Wirtschaftsjahr 2014/2015 19,27 Mio. Tonnen. Der Verbrauch betrug 19,22 Mio. Tonnen, was einem Pro-Kopf-Verbrauch von 38,1 kg entspricht, und war damit nur etwas geringer als die Produktion (WVZ 2016). Um die benötigte Zuckerproduktion gewährleisten zu können, ist es notwendig das Ertragspotenzial der Zuckerrüben auszuschöpfen. Die Unkrautkontrolle ist dabei eine der wesentlichen ackerbaulichen Maßnahmen. Zuckerrüben konkurrieren mit Unkräutern um Licht, Wasser und Nährstoffe (Hock et al. 1995). Neben vergleichsweise geringen Qualitätsverlusten, wie dem Anstieg des Natriumgehaltes, wird besonders der Rübenertrag negativ von Verunkrautung beeinflusst (Bräutigam 1998). Bei ausbleibender Unkrautkontrolle sind Ertragsverluste von bis zu über 90% (Jursik et al. 2008) oder gar ein Totalausfall durch unwirtschaftliche Erntebedingungen möglich.

Die wesentlichen Einflussmerkmale auf den Ertrag sind Zeitpunkt und Dauer des Auftretens sowie Dichte und Art der Verunkrautung. Aufgrund der langsamen Jugendentwicklung ist die Konkurrenzkraft junger Zuckerrüben gegenüber schnell und hoch wachsenden Unkräutern vergleichsweise gering. Eine frühe Verunkrautung in einem sich entwickelnden Zuckerrübenbestand verursacht höhere Ertragsverluste als eine Spätverunkrautung in einem geschlossenen Zuckerrübenbestand.

Besonders in der frühen Jugendentwicklung kann eine zeitliche Verzögerung des Auftretens von nur einer Woche signifikante Ertragsunterschiede mit sich bringen (Schäufele & Wellmann 1997, Wellmann 1999). Bei einer Spätverunkrautung sind zumeist keine Ertragsverluste mehr zu erwarten.

In Anlehnung an das zeitliche Auftreten der Verunkrautung nimmt die Dauer der Verunkrautung Einfluss auf den Ertrag. Zuckerrüben stehen bei Anwesenheit von Unkräutern in steter Konkurrenz zur Verunkrautung. So kann durch Ausbleiben einer Applikation der Unkrautdeckungsgrad zwischen 10 und 70% ansteigen und sich entsprechend negativ auf den Ertrag auswirken (Brandes 2000).

Die Unkrautarten unterscheiden sich hinsichtlich ihrer Konkurrenzkraft. So sind Ertragsverluste durch niedrig wachsende Unkräuter wie der Vogelmiere (*Stellaria media* (L.) *Vill.*), die unterhalb des Blattapparates der Zuckerrüben wächst, vergleichsweise gering (Schäufele 1991). Schnell und hoch wachsende Unkräuter, wie der Weiße Gänsefuß (*Chenopodium album* L.), können hingegen hohe Ertragsverluste verursachen, was in erster Linie auf die Konkurrenz um Licht zurückzuführen ist (Wellmann 1999). Auch die Unkrautart nimmt indirekt Einfluss auf den Zeitpunkt des Auftretens und die Dichte der Verunkrautung (Scott & Wilcockson 1976). Es treten verschiedene Unkrautarten zu unterschiedlichen Zeitpunkten im Jahresverlauf auf, wodurch Frühjahrskeimer im Zuckerrübenanbau eine besondere Rolle spielen. Noch dazu unterscheiden sie sich in der Unkrautdichte aufgrund unterschiedlicher Samenmengen im Boden. Hierdurch dominieren Unkräuter wie *C. album* und *Matricaria recutita* L. im Zuckerrübenanbau (Buhre et al. 2011).

Charakteristik der Unkrautkontrolle in Zuckerrüben

Zu Beginn des Zuckerrübenanbaus wurden Unkräuter durch das Hacken von Hand kontrolliert. In den 1890er Jahren kamen erstmalig Maschinenhacken und Sulfate zum Einsatz (Cioni & Maines 2011). Ab den 1930er Jahren wurden die ersten organisch chemischen Stoffe (Pentachlorphenol 1937, Propham 1946, Endothal 1951, Dalapon 1954) vor der Saat zur Unkrautkontrolle eingesetzt. Bis in die 1960er Jahre war das Hacken von Hand dennoch üblich, denn als Folge des bis dahin verwendeten multigermen Saatgutes war das Verziehen ein obligater Handarbeitsschritt, bei dem parallel das Unkraut gehackt werden konnte. Seitdem stieg die chemische Unkrautkontrolle mit der Zulassung von Ethofumesat, Chloridazon, Metamitron und Phenmedipham an. Mit diesen Wirkstoffen war erstmalig eine vielseitige Kontrolle von dikotylen Unkräutern möglich (Petersen 2003). Diese Wirkstoffe wurden vorrangig in hohen Aufwandmengen im Vorauflauf appliziert, was bis in die 1980er Jahre vorherrschend war. Aufgrund ökologischer und ökonomischer Aspekte wurden dann die Aufwandmengen um etwa zwei Drittel reduziert und auflaufende Unkräuter in mehreren Nachauflaufapplikationen behandelt (Cioni & Maines 2011). Dieses System wird bis heute üblicherweise im zentraleuropäischen Zuckerrübenanbau angewendet und hat sich seitdem bis auf wenige Wirkstoffe nicht verändert.

Die heutige Strategie der Unkrautkontrolle ist von Vasel et al. (2012) auf Datengrundlage einer deutschlandweiten Betriebsbefragung analysiert worden. Demnach wird auf etwa 50% der Zuckerrübenflächen in Deutschland Glyphosat vor der Aussaat appliziert. Je nach Verunkrautung und Bodenart werden Unkräuter ebenfalls durch eine Bodenbearbeitung vor der Aussaat beseitigt. Nach der

Zuckerrübenaussaat sind je nach Verunkrautung drei bis fünf Applikationen notwendig. Die Applikationen werden jeweils zum Auflaufen der Unkräuter terminiert. Eine präzise Applikation zum Keimblattstadium der Unkräuter ist notwendig (May & Wilson 2006). Im Durchschnitt wurden zwischen 2010 und 2014 jährlich 3,85 Applikationen je Schlag durchgeführt (PAPA, 2016a). Die Applikationen erfolgen bis die Zuckerrüben gegenüber den Unkräutern konkurrenzstark genug sind und eine weiteres Auflaufen oder etwaige Ertragseinbußen nicht mehr zu befürchten sind. In den ersten drei Applikationen werden etwa drei bis fünf und in den letzten beiden Applikationen ein bis drei Wirkstoffe je Applikation ausgebracht (Vasel et al. 2012). Es werden sowohl Wirkstoffe, die hauptsächlich über das Blatt aufgenommen und schnell wirksam sind (z. B. Phenmedipham) als auch Wirkstoffe, die hauptsächlich über die Wurzeln aufgenommen und länger im Boden aktiv sind (z. B. Metamitron), appliziert (Liehe & Pape 2015). Die Abstände zwischen den einzelnen Applikationen sind wiederum von der Verunkrautung aber besonders von der Witterung abhängig. Durchschnittlich betragen sie fünf bis 14 Tage (Cioni & Maines 2011, Petersen 2003, Vasel et al. 2012). Durch den Einsatz von ALS-Inhibitoren könnte der Applikationszeitpunkt flexibler sein und durch eine verlängerte Wirkung im Boden die Abstände zwischen den Applikationen vergrößert werden.

Selektivität

Neben der präzisen Applikation zum Keimblattstadium der Unkräuter ist es notwendig, die Witterungsverhältnisse sowie Vitalität der Zuckerrüben zu berücksichtigen. Bei hohen Aufwandmengen in Kombination mit ungünstigen Witterungsverhältnissen können phytotoxische Schäden an Zuckerrüben auftreten

(Hamouzová et al. 2013, May & Wilson 2006). Besonders bei hoher Lichtintensität oder bei kühler und feuchter Witterung über mehrere Tage kann es vermehrt zu Phytotoxizität kommen. Dieser Effekt kann sich bei schlechter Vitalität der Zuckerrüben verstärken. Deshalb werden Herbizide oftmals in den frühen Morgen- oder Abendstunden appliziert (Liehe & Pape 2015). Symptome der Phytotoxizität sind beispielsweise Vergilbungen, Verformungen, Nekrosen, Wuchsdepressionen und Pflanzenverluste (EPPO 1/135 (3)). Im Vergleich zu den leichten Schäden wie Vergilbungen und Verformungen, können Wuchsdepressionen und Pflanzenverluste den Ertrag je nach Aufwandmenge und Schädigung zwischen 2 – 30% verringern (Beißner 2000, Pfleiderer et al. 2001). Die Schonung einer Kulturpflanze bei gleichzeitiger Kontrolle der Unkräuter durch eine Herbizidanwendung wird als Selektivität bezeichnet (Aust et al. 2005). Die Wirkstoffe sowie Produkte unterscheiden sich in ihrer Selektivität bereits durch ihre Formulierung. Um eine möglichst hohe Selektivität zu erzielen ist bei der Unkrautkontrolle durch Herbizide auf Wirkstoffe, Produkte, Witterung, Vitalität und Applikationszeitpunkt zu achten. Mit dem Einsatz von nicht sensitiven Sorten gegenüber ALS-Inhibitoren ist eine hohe Selektivität zu erwarten. Bei hoher Selektivität könnte zum einen die Flexibilität der Applikationen steigen und zum anderen das Risiko von Ertragsverlusten vermindert werden.

Resistenzen

Die bereits in den 1960er Jahren eingeführten Wirkstoffe Ethofumesat, Phenmedipham und Metamitron werden heute bei nahezu jeder Applikation (99,9%) angewendet. Desmedipham findet in 72,4% aller Applikation Anwendung (Vasel et al. 2012). Metamitron blockiert das Photosystem II der Unkräuter und Ethofumesat, Phenmedipham und Desmedipham blockieren die Lipid-Synthese (nicht ACCase). Eine über Jahrzehnte fast unveränderte Strategie der Unkrautkontrolle und der hohe Aufwand von Wirkstoffen mit nur zwei Wirkorten erhöht das Risiko Herbizid resistente Unkräuter zu selektieren (Balgheim 2006). Fälle von Weißem Gänsefuß (*Chenopodium album* L.), der weniger anfällig gegenüber Metamitron ist, sind bereits in Zuckerrüben aufgetreten (Mechant et al. 2008, Varrelmann & Kalfa 2013). Die Erweiterung der eingesetzten Wirkstoffgruppen, wie es bei einer Zulassung von Conviso® der Fall wäre, könnte das Resistenzrisiko vermindern. Untersuchungen zu Resistenzen sind nicht Bestandteil dieser Arbeit.

Unkrautauftreten und Intensität des Herbizideinsatzes in Deutschland

Parallel zu der breiten Anwendung der Herbizid-Strategie hat sich die Unkrautzusammensetzung in den letzten 20 Jahren verändert. So ist der Anteil von Gänsefußgewächsen (z.B. *C. album*) von 47 auf 79%, Kamillearten (*Matricaria* ssp.) von 16 auf 34%, Einjährigem Bingelkraut (*Mercurialis annua* L.) von 9 auf 25% und Knötericharten (*Polygonum* ssp.) von 35 auf 86% der Zuckerrübenflächen in Deutschland von 1996 zu 2010 gestiegen (Buhre et al. 2011). Gänsefußgewächse und Knötericharten sind die dominierenden Unkrautarten im Zuckerrübenanbau. Einjähriges Bingelkraut, Kamillearten und Knötericharten sind als schwer bekämpfbar eingestuft (Vasel et al. 2012). Das bedeutet, dass mit der üblichen (wie oben beschriebenen) Herbizid-Strategie eine vollständige Kontrolle dieser Unkrautarten nicht gewährleistet ist. ALS-Inhibitoren könnten jedoch Wirkungslücken der schwer bekämpfbaren Unkräuter schließen.

Eine Quantifizierung der Intensität des Pflanzenschutzmitteleinsatzes in Deutschland erfolgt über die Berechnung des Behandlungsindex (BI) (Roßberg et al. 2009). Dieser wird mit folgender Formel (1) berechnet:

(1)

$$\text{Behandlungsindex} = \sum \left(\frac{\text{Aufwandmenge}}{\text{Zugelassene Aufwandmenge}} \times \frac{\text{Behandelte Fläche}}{\text{Totale Fläche}} \right)$$

Es steigt mit jeder Applikation oder mit steigenden Aufwandmengen auch die Intensität. Eine Reduktion der Intensität wäre also durch eine Reduktion der Anzahl der Applikationen oder durch die Reduktion der applizierten Wirkstoffe möglich. In den Jahren 2010 bis 2014 lag der BI von Herbiziden in Zuckerrüben durchschnittlich bei 2,64 (PAPA, 2016b). Diese Intensität ist im Vergleich zu anderen Pflanzenschutzmitteln wie Fungiziden und Insektiziden, die einen BI von 1,00 bzw. 0,18 in diesen Jahren hatten, relativ hoch.

Der Nationale Aktionsplan Pflanzenschutz (NAP) ist Teil der Umsetzung der EU-Pflanzenschutz-Rahmenrichtlinie 2009/128/EG. Im NAP ist gefordert, dass die Risiken der Anwendung von Pflanzenschutzmitteln bis 2023 um 30% zu den Mittelwerten aus 1996 – 2005 reduziert werden sollen. Eine Reduktion des Pflanzenschutzmitteleinsatzes bei Zuckerrüben wäre bei einem Vergleich der Pflanzenschutzmittel für Herbizide am effektivsten und bezüglich der Umsetzung am wahrscheinlichsten. In Anbetracht der heutigen Herbizid-Strategie erscheint weder eine Reduktion der Wirkstoffmengen noch der Anzahl der Applikationen mit den bisher eingesetzten Herbiziden möglich. Mit einer Reduktion der Wirkstoffmenge oder der Anzahl der Applikationen durch die Conviso Smart®-Technologie könnte sich zumindest die Intensität gemessen am BI verringern.

ALS-Inhibitoren zur Unkrautkontrolle

Die Firma DuPont forschte in den 1970er Jahren mit Sulfonylharnstoffen als ALS-Inhibitoren zur Unkrautkontrolle. Anfang der 1980er Jahre kam der erste Wirkstoff dieser Wirkstoffklasse in den USA auf den Markt (Drobny et al. 2012). Seitdem werden ALS-Inhibitoren vorrangig gegen dikotyle aber auch monokotyle Unkräuter im Ackerbau eingesetzt. Es reichen vergleichsweise geringe Mengen von 5 bis 60 g ha^{-1} aus. Heutzutage werden ALS-Inhibitoren auch in Europa in den Hauptackerbaukulturen wie Getreide, Mais und Kartoffeln zur Unkrautkontrolle eingesetzt. Die durch die Herbizide blockierten Aminosäuren sind für den menschlichen Organismus essentiell. Das wiederum bedeutet, dass der menschliche Organismus diesen Wirkort nicht besitzt und diese Herbizide entsprechend eine besonders geringe Humantoxizität mit sich bringen (Drobny et al. 2012).

Wirkmechanismus von ALS-Inhibitoren

Die verzweigten Aminosäuren Valin, Leucin und Isoleucin sind wichtige Bausteine für den Stoffwechsel innerhalb der Pflanze (Duggleby & Pang 2000). Das Enzym ALS katalysiert den jeweils ersten Schritt von zwei Synthesepfaden in der Biosynthese der Aminosäuren. Aus zwei Molekülen Pyruvat wird Acetolactat gebildet, das als Ausgangsstoff für Valin und Leucin fungiert. Oder aus je einem Molekül Pyruvat und Ketobutyrat wird Aceto-hydroxybutyrat gebildet, welches als Ausgangsstoff für

Isoleucin fungiert. Nach weiteren katalysierten Schritten werden schließlich die Endprodukte Valin, Leucin und Isoleucin synthetisiert (Duke 1990, Hallmann et al. 2007). Eine Blockade von ALS unterbindet die Synthese dieser Aminosäuren und es kommt zu einer Anreicherung wachstumshemmender Stoffe wie Oxybutyrat und Aminobutyrat und die Pflanze stirbt ab (Heitefuß 2000).

Die Aufnahme der Wirkstoffe erfolgt über das Blatt und über die Wurzel, ist aber von den jeweiligen Wirkstoffen abhängig. Sie werden sowohl akropetal als auch basipetal in der Pflanze verteilt, was eine schnelle Wirksamkeit fördert. So kommt der Stoffwechsel der behandelten Unkräuter bereits einige Stunden nach der Applikation zum Erliegen, so dass ihre Konkurrenzkraft zur Kulturpflanze abnimmt, auch wenn sie optisch noch nicht abgestorben sind. Die artspezifischen Symptomausprägungen setzen jedoch erst später ein und das vollständige Absterben der Pflanzen kann bis zu drei Wochen andauern (Drobny et al. 2012).

Es sind insgesamt fünf chemische Verbindungsklassen, die als ALS-Inhibitoren dienen, bekannt. Die Hauptgruppe bilden die Sulfonylharnstoffe, die im praktischen Gebrauch fälschlicher Weise oftmals als Synonym für ALS-Inhibitoren gebraucht werden. Den Imidazolinonen gehören die zweitmeisten Wirkstoffe der ALS-Inhibitoren an, wobei diese hauptsächlich in Nordamerika im Soja- und Maisanbau zugelassen sind. Weiterhin sind Pyrimidinylbenzoate, Triazolopyrimidine und Sulfonylamino-Carbonyl-Triazolinone bekannt (Drobny et al. 2012).

ALS-Inhibitoren zur Unkrautkontrolle in Zuckerrüben

Im Maisanbau sind seit 1991 ALS-Inhibitoren zur Unkrautkontrolle in Deutschland zugelassen (Drobny et al. 2012). Die Unkrautflora in Mais ähnelt der in Zuckerrüben (de Mol et al. 2012), da beide Kulturen im Frühjahr ausgesät werden und entsprechend Frühjahrskeimer an Unkräutern begünstigen. Außerdem handelt es sich bei beiden um Reihenkulturen, die eine spezifische Unkrautflora selektieren. Der Reihenschluss von Mais erfolgt etwa zwei Wochen nach dem der Zuckerrüben. Die Reihenweiten sind außerdem mit 70 cm weiter als die 45 bis 50 cm der Zuckerrüben. Dadurch und durch den steileren Wuchs ist die Lichteinstrahlung auf den Boden im Mais gegenüber Zuckerrüben für das Unkrautwachstum von Vorteil. Trotzdem ist es z. B. mit dem ALS-Inhibitor Thiencarbazone-methyl möglich, mit nur zwei Applikationen Unkräuter in Mais zu kontrollieren (Santel 2012). Weitere Produkte, die ALS-Inhibitoren enthalten, weisen eine ähnliche Wirkung auf (Wegener & Balz 2014). Da mit diesen Wirkstoffen eine ähnliche Unkrautflora wie in Zuckerrüben hoch effizient kontrolliert werden kann, könnten ALS-Inhibitoren auch zur effektiven Unkrautkontrolle in Zuckerrüben eingesetzt werden. Die hohe Sensitivität von Zuckerrüben gegenüber dieser Wirkstoffklasse hat das jedoch bisher verhindert.

Züchtung einer gegenüber ALS-Inhibitoren nicht sensitiven Zuckerrübensorte

Kulturarten wie Weizen und Mais sind gegenüber ALS-Inhibitoren nicht sensitiv. Die natürliche Selektivität dieser Kulturarten gegenüber den ALS-Inhibitoren resultiert aus einem schneller ablaufenden Metabolismus des Wirkstoffes als in den meisten Unkräutern. Momentan ist Triflusulfuron-methyl der einzige ALS-Inhibitor, der so von Zuckerrüben metabolisiert wird, dass er zur Unkrautkontrolle zugelassen ist (Wittenbach et al. 1994). Eine breitere Nutzung von ALS-Inhibitoren zur Unkrautkontrolle in Zuckerrüben würde jedoch eine Sorte erfordern, die gegenüber dieser Wirkstoffklasse nicht sensitiv ist. Aus politischen Gründen ist eine derartige

Bearbeitung durch Gentechnik in Europa nicht möglich (Tencalla 2006). Deshalb wurden in Europa bereits Kulturarten wie Sonnenblumen, Raps und Mais auf konventionelle Weise so gezüchtet, dass sie gegenüber ALS-Inhibitoren oder anderen Wirkstoffklassen nicht sensitiv sind (Beckert et al. 2011).

In einer Kooperation von KWS Saat SE und Bayer CropScience AG wurden Zuckerrübenzellen in-vitro kultiviert und mit einem entsprechenden Selektionsmedium (ALS-Inhibitoren) behandelt. Es wurden vorrangig Foramsulfuron aber auch andere ALS-Inhibitoren getestet (WO 2012/049268 A1). Die überlebenden Zellen wurden zu Zuckerrübenpflanzen kultiviert und anschließend rückgekreuzt. Ausgangspunkt der Nicht-Sensitivität ist eine spontan aufgetretene Mutation des ALS-Gens am Tryptophan 569 Kodon. Das heißt, dass an dieser Stelle eine andere Aminosäure als Tryptophan vorliegt, wodurch eine Bindung von ALS-Inhibitoren nicht mehr möglich ist. Durch ein Marker gestütztes Rückkreuzungsverfahren wurde die aufwändige Selektion im Feld umgangen und der Züchtungsprozess beschleunigt (Wegener et al. 2015).

Das Herbizid Conviso® wird die beiden Wirkstoffe Foramsulfuron und Thiencarbazone-methyl enthalten. Beide sind ALS-Inhibitoren und bereits zur Unkrautkontrolle in Mais zugelassen. Je Liter Conviso® werden 50 g Foramsulfuron und 30 g Thiencarbazone-methyl enthalten sein. Foramsulfuron ist ein Sulfonylharnstoff und wird über das Blatt aufgenommen. Thiencarbazone-methyl ist ein Sulfonylamino-Carbonyl-Triazolinon und wird hauptsächlich über die Wurzel aufgenommen. Conviso® wird als ölige Dispersion formuliert (Balgheim et al. 2016). Ein Antrag zur Zulassung von Conviso® ist für die Zulassungszone Mitteleuropa in Deutschland in 2015 erfolgt.

Ziele der Arbeit

Die Registrierung einer nicht-sensitiven Sorte gegenüber ALS-Inhibitoren und die Zulassung eines Komplementärherbizids wären für den Zuckerrübenanbau eine technologische Neuerung, zu der es keine belastbaren Daten gibt. Grundkenntnisse über die Charakterisierung dieses Systems sind für die Anwendung von großer Bedeutung. Es stehen durch die Anwendung von Conviso® vier Kernpunkte, die Unkrautkontrolle im Vergleich zum heutigen System zu optimieren, im Fokus. Diese sollen in der vorliegenden Arbeit untersucht werden (Tabelle 1):

Tabelle 1: Untersuchungen der Conviso Smart® Technologie in der vorliegenden Arbeit

Untersuchungen* der Conviso Smart® Technologie
1. Flexiblerer Applikationszeitpunkt
2. Längere Dauer der Wirkung im Boden
3. Gleiche oder höhere Wirksamkeit bei geringerer Applikationsanzahl
4. Höhere Selektivität
* im Vergleich zu klassischen Herbizid-Strategien

1.) Durch einen flexibleren Applikationszeitpunkt könnte zu einem späteren Zeitpunkt als zum Keimblattstadium der Unkräuter appliziert werden. 2.) Die Intervalle zwischen den Applikationen könnten durch eine längere Dauer der Wirkung im Boden vergrößert werden. Eine Kombination der ersten beiden Punkte könnte insgesamt eine geringere Anzahl an Applikationen und niedrigere Aufwandmenge ermöglichen. 3.) Die Wirksamkeit von Conviso® soll in verschiedenen Strategien untersucht werden. 4.) Die Selektivität von der Conviso Smart® Technologie soll mit der Selektivität von klassischen Herbiziden verglichen werden. Eine möglicherweise höhere Selektivität könnte sowohl die Flexibilität der Anwendungszeitpunkte steigern als auch das Risiko von Ertragsverlusten minimieren. Mit diesen Untersuchungen werden grundlegende Kenntnisse zur Charakterisierung der Conviso Smart® Technologie geschaffen. Es sind Rahmenbedingungen, die Grenzen und Möglichkeiten dieses Systems aufzeigen und einen Vergleich zu derzeitigen Herbizidstrategien zulassen. Gleichzeitig werden Grundlagen für weiterführende Untersuchungen geschaffen.

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Kapitel 2

Efficacy of *foramsulfuron* + *thiencarbazone-methyl* towards different development stages of weed species in sugar beet cultivation

Efficacy of *foramsulfuron* + *thiencarbazone-methyl* towards different development stages of weed species in sugar beet cultivation

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Sugar Industry 141: 436-445

Abstract

The currently available weed control system in sugar beet cultivation has low flexibility due to the necessity of applications at the cotyledon stage of the weeds. The aim of the present study was to evaluate a new herbicide providing more flexibility in terms of application time. In 2013 and 2014, efficacy of an ALS-inhibiting herbicide (*foramsulfuron* + *thiencarbazone-methyl*) was evaluated in six field trials in Germany. Sugar beet varieties not sensitive to ALS-inhibiting herbicides are currently in the breeding process. The herbicide was tested on five weed species in different development stages (later than cotyledon stage). In the trials, only weeds but no sugar beet were sown. The herbicide was applied with three dosages at five development stages of the weeds. Efficacy towards *Brassica napus* L. and *Galium aparine* L. was nearly 100%. Efficacy towards *Chenopodium album* L., *Matricaria chamomilla* L. and *Polygonum convolvulus* L. was reduced due to unfavorable weather conditions and with decreasing dosages and increasing development stages. Efficacy was lowest in case of *Chenopodium album* being close to 95% at BBCH 14 and 16 with 0.50 l/ha and 1.00 l/ha, respectively. It was thus concluded that the herbicide can be applied later than at cotyledon stage. This implies more flexibility of application timing than current herbicides. To develop a comprehensive evaluation of the weed control system, further studies regarding selectivity, duration of efficacy and resistance risks are necessary.

Key words: ALS-inhibiting herbicide, *Brassica napus* L., *Chenopodium album* L., *Galium aparine* L., *Matricaria chamomilla* L.*, Polygonum convolvulus* L.*, Polygonum aviculare* L., *Aethusa cynapium* L., herbicides, development stage, dosage

1 Introduction

Weed control is one of the most important factors to achieve yield potential in sugar beet cultivation. Sugar beet plants compete with weeds for light, water and nutrients (*El Titi*, 1986). Particularly, competitiveness of young sugar beet plants against weeds is low. Therefore, weed control at early crop development stages is important (*Wellmann*, 1999). Until herbicides became available, weeds were controlled by hand hoeing up into the 1960s of sugar beet cultivation.

Since the 1960s, new active ingredients like *metamitron*, *phenmedipham* and *ethofumesate* were launched and chemical weed control has become the main method of weed control due to broad efficacy against mono- and dicotyledonous weeds. High dosages of active ingredients in pre-emergence and post-emergence treatments were common. Starting in the 1980s, for economical and ecological reasons, the main applications were shifted to lower dosages in post-emergence treatments. Reduced dosages, however, require application at the cotyledon stage of weeds which is the most sensitive development stage (*Petersen*, 2003).

Today, the system of split applications with a combination of different active ingredients in reduced dosage is the main herbicide strategy for weed control in sugar beet. Due to its broad use in practice, the composition of common weed species in sugar beet cultivation shifted over time. Furthermore, the control of

Brassica napus L., *Chenopodium album* L., *Galium aparine* L., *Matricaria chamomilla* L., *Polygonum convolvulus* L., *Polygonum aviculare* L., *Aethusa cynapium* L. and other species has become increasingly difficult (*Vasel* et al., 2012). The current system has low flexibility concerning the application timing. Unfavorable application conditions restrict this low flexibility even more.

Herbicide efficacy is depending on a multitude of factors and their interactions, e.g. weather conditions before, during and after the application (*Blair* and *Martin*, 1988), application technique (*Prokop* and *Veverka*, 2003; *Skuterud* et al., 1988) and herbicide sensitivity of the target weeds (*Heap*, 2014). Temperature, light, precipitation and humidity influence photosynthesis which drives uptake, translocation and metabolism of the active ingredients by stomata regulation, transpiration and plant growth (*Baker*, 1974; *DiTomaso*, 2002; *Bethlenfalvay* and *Norris*, 1977). These processes are also depending on the weed species, development stage and leaf anatomy (cuticula, leaf wax, leaf hair, phyllotaxy) (*Hock* et al., 1995).

These factors can reduce efficacy and a precise timing of application becomes necessary (*May* and *Wilson*, 2006; *Cioni* and *Maines*, 2010). To apply reduced dosages of herbicides is well established (*Kudsk* and *Streibig*, 2003). However, especially unfavorable weather conditions may necessitate higher dosages for effective weed control (*Lundkvist*, 1997).

Since the 1980s, the *acetolactate-synthase* (ALS) inhibiting herbicides have been used in agricultural crops. This group of herbicides is characterized by high efficacy at low total amounts of active ingredients (*Drobny* et al., 2012). In maize cultivation, ALS-inhibiting herbicides are widely used. In this case the composition of weed flora is similar to sugar beet cultivation (*Keller* et al., 2014). Application in maize cultivation is later than cotyledon stage of the weeds and is often defined by the development stage of the maize crop (*Wegener* and *Balz*, 2014). This demonstrates high efficacy which could also be advantageous in sugar beet cultivation to achieve more flexibility in application timing. It could furthermore reduce the influence of weather conditions on the weed control system with post-emergence treatments and improve efficacy towards weeds.

ALS-inhibiting herbicides may provide a new system to control common weeds in sugar beet cultivation. Due to high phytotoxic effects of ALS-inhibiting herbicides on sugar beet, non-sensitive sugar beet varieties in cultivation are necessary. At present, such varieties are in the breeding process and will presumably be registered in a few years (*Bayer CropScience AG, KWS Saat AG*, 2012; *KWS Saat AG*, 2012).

To assess the potential and limitations of the system, a field trial series with six environments was conducted. For an investigation of efficacy, a special field trial setup was used and no sugar beet but five weed species most widespread in sugar beet cultivation (*Vasel* et al., 2012) were selected and sown at each environment. These weed species were treated by an ALS-inhibiting herbicide. The objectives of the present study were (I) to assess the influence of environment on efficacy of the herbicide, (II) to quantify the effect of herbicide dosage on efficacy of the herbicide and (III) to identify the development stages of the weeds at which the herbicide has to be applied for adequate weed control.

2 Material and Methods

A field trial series was conducted at six sites across northern Germany in 2013 and 2014. Two sites were located at Göttingen; two sites were located near Göttingen (Angerstein, Niedernjesa) and two sites were located east of Hanover (2x Schwüblingsen). In the following, the combination of site x year will be referred to as environment. Precrops were potato in Schwüblingsen 2013 and summer barley in Schwüblingsen 2014. Precrop in the other environments was winter wheat. Local weather data (air and soil temperature, humidity, precipitation and wind speed and direction) were recorded by weather stations at every environment (Figure 1).

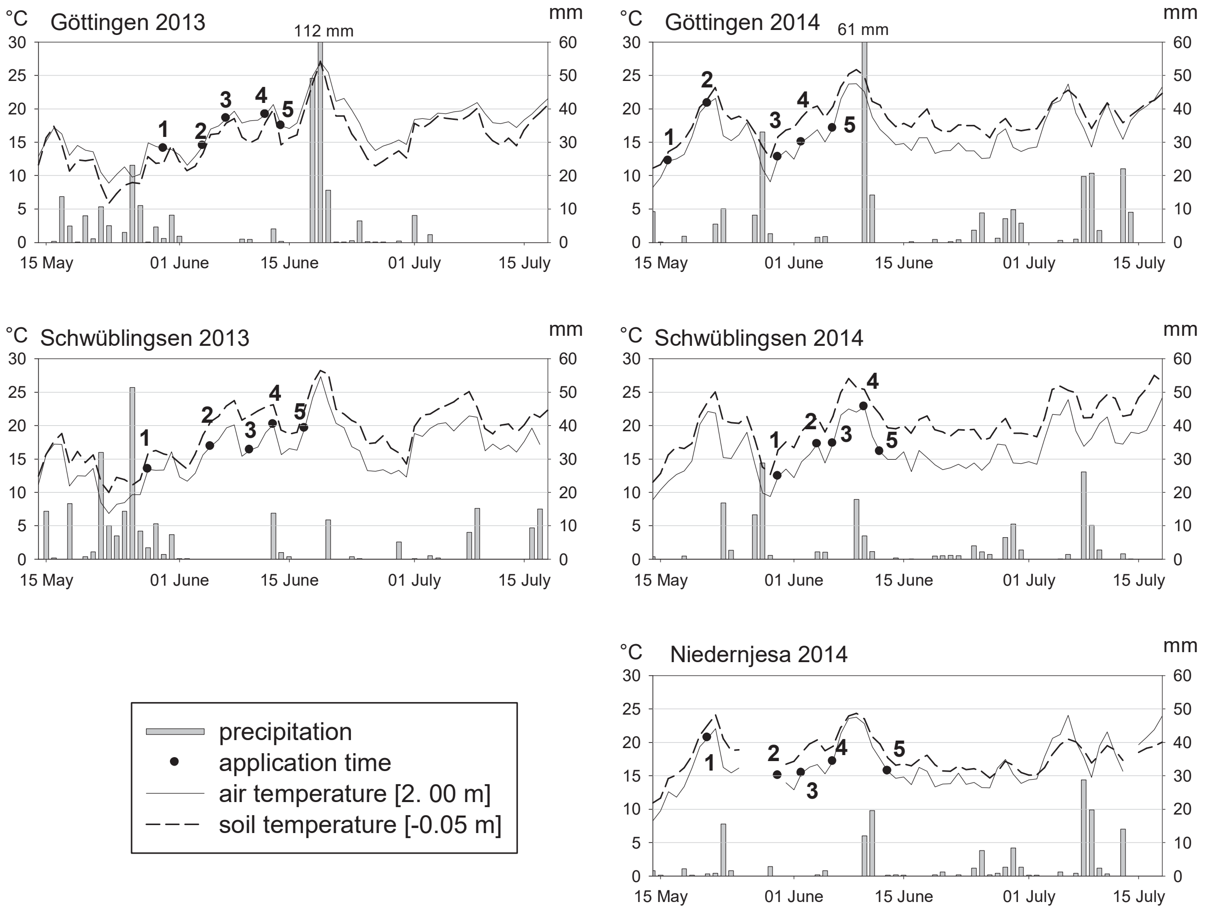

Figure 1: Weather conditions (average daytime temperature [°C] and precipitation [mm] at five environments in Germany, 2013 and 2014 from 15 May to 15 July. Dots indicate application times of ALS-inhibiting herbicide.

Additionally, soil moisture and soil structure, dew and sky cover during treatments were documented (not shown). The ALS-inhibiting herbicide includes two active ingredients, *foramsulfuron* and *thiencarbazone-methyl* (*Bayer CropScience AG,* 2012). Both belong to the HRAC Group "B", at which *foramsulfuron* is a sulfonylurea and *thiencarbazone-methyl* is a sulfonylamino-carbonyl-triazolinone. *Foramsulfuron* will be taken up mainly via the leaves whereas the absorption of *thiencarbazone-methyl* takes place via leaves and roots. Both compounds are afterwards systemically translocated in the plants (*Wegener* and *Balz*, 2014).

The weed species sown in this trial are known as common for sugar beet cultivation (*Vasel* et al., 2012): *Brassica napus* L., *Chenopodium album* L., *Galium aparine* L., *Matricaria chamomilla* L., *Polygonum convolvulus* L., *Polygonum aviculare* L. and *Aethusa cynapium* L.. Four weed species were sown at all environments and three species were sown site-specifically (Table 1).

Table 2: Trial sites, soil texture and sown weed species, 2013 and 2014. + = was sown at this site, (-) = determination of efficacy impossible due to low plant density.

year	site	soil texture	*Brassica napus*	*Cheno-podium album*	*Galium aparine*	*Matricaria chamomilla*	*Polygonum convolvulus*	*Polygonum aviculare*	*Aethusa cynapium*
2013	Angerstein	clay	+ (-)	+ (-)	+ (-)	+ (-)		+ (-)	
	Göttingen	loam	+	+	+	+			+ (-)
	Schwüblingsen	sand	+	+	+	+	+		
2014	Niedernjesa	clay	+ (-)	+	+	+		+ (-)	
	Göttingen	loam	+	+	+	+			+ (-)
	Schwüblingsen	sand	+	+	+	+	+		

2.1 Sowing and Application

Soil cultivation and seed bed preparation was carried out site-specifically and according to standard practice in sugar beet cultivation by plough, cultivator and harrow. Seeds were provided by a specialized company for weed seeds in England (Herbiseed). Weed species were sown in parallel strips (Figure 2) and were randomized between the sites but not within the sites due to technical requirements. The sowing machine (Sembdner GSD) is normally used for fine seeds in horticulture and the settings of each sowing unit could be adapted independently.

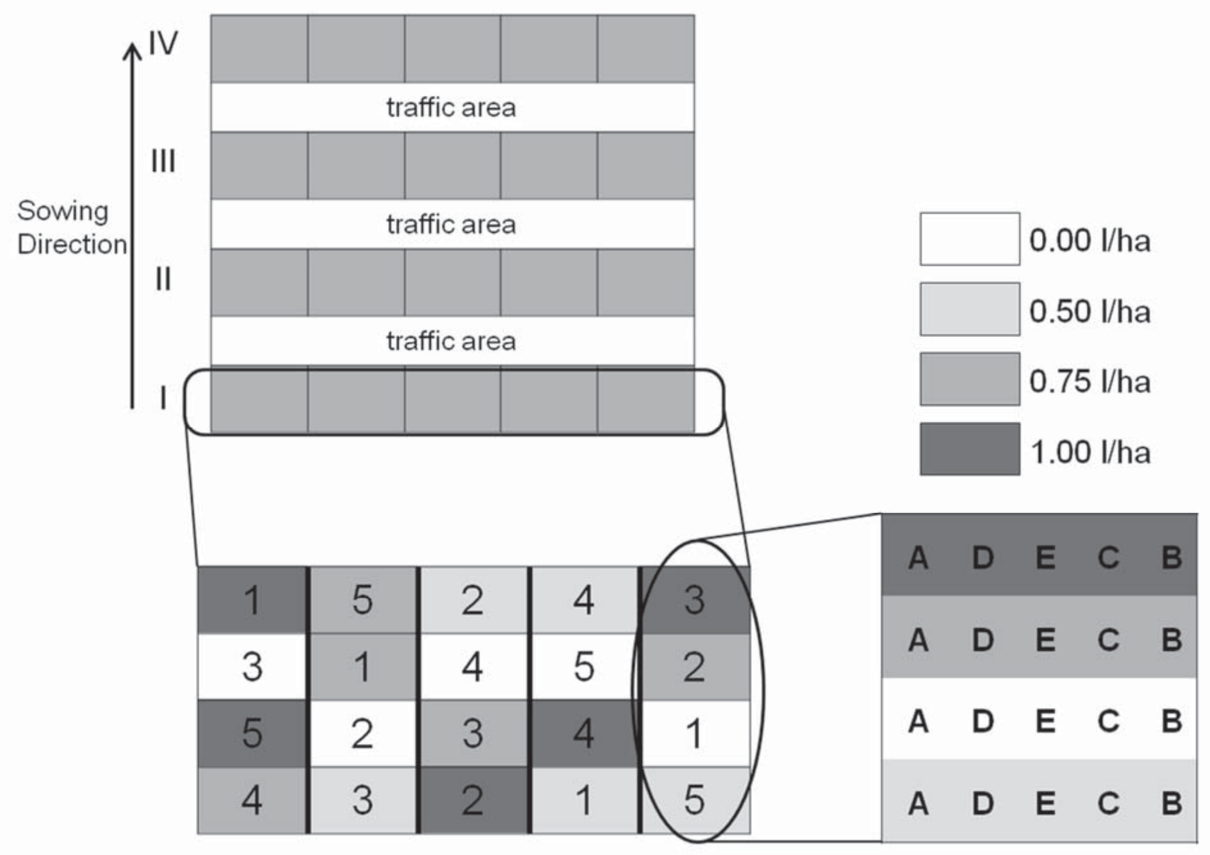

Figure 2: Field trial design to investigate efficacy of an ALS-inhibiting herbicide towards important weed species in sugar beet cultivation at different development stages. Different capital letters indicate different weed species; different numbers indicate different development stages at application times; Roman numerals indicate repetition blocks, 2013 and 2014

The seeded area was divided into four replication blocks. The blocks were divided into 20 plots and every plot included each weed species that was sown at the respective site. Sowing depths were set to the optimum of each weed species (*Kästner* et al., 2001; *Zwerger* and *Ammon*, 2002; *Partzsch* et al., 2006) and was adapted to drill the seeds into a wet soil layer. Actual seeding depths were: *B. napus* 1.0 to 2.0 cm, *C. album* 0.5 to 1.5 cm, *G. aparine* 1.0 to 2.0 cm, *M. chamomilla* 0.0 to 0.5 cm*, P. convolvulus* 0.5 to 1.5 cm*, P. aviculare* 0.5 to 1.0 and *A. cynapium* 0.5 to 1.5 cm*.* Seeding rates were set to 50 germinating plants per meter. Germination rates had been determined in the greenhouse before. For this purpose, 100 seeds of each species were sown in pots filled with sterilized standard potting mixture (75% sandy clay and 25% sand) at the above mentioned depths. The climate conditions in the greenhouse were 22/18 °C (day/night) with a period of 12 h (*Christ* et al., 2011). In 2013, sowing was done in the beginning of May. In 2014, sowing was done in the middle of April in Göttingen and Niedernjesa. At the end of April sowing in Schwüblingsen followed.

Applications were done with a pneumatic plot sprayer (type *Schachtner PSG,* nozzle type Air Induced (low pressure) flat fan - 110 02, water volume 200 l/ha, pressure 2.5 bar, velocity 4.5 km/h) orthogonally to the sowing direction.

Plots were treated with several dosages at defined development stages of *C. album* (Figure 2). For technical reasons it was not possible to treat each species separately. This is why they were treated independently of their own development stages along with *C. album.* Accordingly to results by *Wegener* and *Balz* (2014), who worked with a similar herbicide (*foramsulfuron*, *iodosulfuron*, *thiencarbazone-methyl* and *cyprosulfamide*) in maize cultivation, the application times in the present field trial series were set later than cotyledon stage. Furthermore, it was assumed that efficacy would be the lowest towards *C. album*. Defined development stages of *C. album* were BBCH 12, 14, 16, 18 and 20 (Table 2) (*Hess* et al., 1997). Every plot was treated only once per stage. The defined dosages were 0.50, 0.75 and 1.00 l/ha.

Table 3: Development stages of weed species treated with an ALS-inhibiting herbicide at defined application times at five environments in Germany, 2013 and 2014. (n.a.: not available).

weed species	defined application time	Göttingen 2013	Schwüblingsen 2013	Göttingen 2014	Schwüblingsen 2014	Niedernjesa 2014
Brassica napus	1	14	14	14	19	n.a.
	2	14-16	14-16	14	19	n.a.
	3	16-17	16-17	16	29	n.a.
	4	16-17	18	19	29	n.a.
	5	18	18	19	29	n.a.
Chenopodium album	1	12	12	12	14-16	12
	2	14	14	14	16-19	14
	3	16	16	16-18	18-19	14-18
	4	18	18	18-31	19	18-19
	5	19	19	32	31	19-32
Galium aparine	1	10-11	10	10	11	10
	2	12	11-12	11	12-22	13-14
	3	13-22	12-22	13-14	29	32
	4	13-22	23-31	14-32	33	33
	5	35	25-32	35	35	35
Matricaria chamomilla	1	16-18	12-14	19	19	14
	2	18	16-19	29	29	16
	3	19	19	29	32	16
	4	19	19	29	32	18
	5	19-51	19-51	32	61	18
Polygonum convolvulus	1	n.a.	10	n.a.	11-12	n.a.
	2	n.a.	11-12	n.a.	14	n.a.
	3	n.a.	12-13	n.a.	19	n.a.
	4	n.a.	15	n.a.	19	n.a.
	5	n.a.	15-19	n.a.	31	n.a.

2.2 Assessments

Three to five assessments of efficacy per plot were made. The final assessment was made about four weeks after the last application. This assessment was used to evaluate the efficacy of the herbicide. It was done by separately assessing the phytotoxic damage of each weed species. Recorded symptoms were bleaching, yellowing, necrosis, thinning, deformation and growth depression according to EPPO guideline PP 1/135 (*EPPO*, 2014). Symptoms were rated on a 0 to 100% scale by steps of with 0% = no effects observed and 100% = dead plants. From 100 to 85%, steps of 2.5 percentage points and from 85 to 0% steps of 5.0 percentage points were rated.

It was not possible to accomplish the intended plant density of 50 plants per meter (see 2.1) for every weed species and environment. This is why in some cases a determination of the efficacy was impossible (Table 1). The results of Angerstein 2013 were not included in the evaluation, because dry soil surface lead to an inhomogeneous emergence and a slow growth with a low plant density of all weeds. Furthermore, plant density of *P. aviculare* was too low to determine herbicide efficacy at Niedernjesa 2014. At Niedernjesa, *B. napus* was affected by slugs and diseases which highly thinned plant density. Therefore, this environment was not included into the results evaluation for *B. napus*. *A. cynapium* did neither germinate in the greenhouse nor in the field.

2.3 Statistical Analysis

The statistical analysis was carried out with the statistic program SAS version 9.4 (SAS Institute Inc., Cary, NC, USA). The data were tested for normal distribution and variance homogeneity. The data were modified by an angular transformation to allow the use of relative figures. In all tables and figures, original data are shown.

The statistical analysis was carried out with two different methods. The first method was used to analyze efficacy towards each weed separately. Therefore, the procedure "*MIXED*" was used. The second method was applied to compare efficacy towards the different weed species. Due to the missing randomization of the weed species within environments (see 2.1), data of repetitions of each site were averaged and environments were set as repetitions. Afterwards, the procedure "*MIXED*" was applied.

3 Results

Weed growth differed between species and environments. Development stages of the weed species differed between environments at the defined application times of *C. album* (Table 2). In 2013, applications were carried out at defined development stages of *C. album*. Due to unfavorable weather conditions in 2014, actual development stages at the application times of *C. album* were sometimes beyond the defined development stages. At some environments, the same development stages of weeds occurred at consecutive application times. This did not necessarily mean no continued weed growth. It rather meant no further development of phenotypic attributes (e.g. new leaves) to identify a new development stage.

3.1 Efficacy towards different weed species

Dosage and application time significantly influenced the efficacy of the herbicide across all weeds except *B. napus* and *G. aparine* (Table 3). For the other weed species, significant effects occurred within the different environments, dosages and application times. Among weed species, efficacy was significantly different towards *C. album* than towards the other weed species. On average, it was lower than towards other weed species (data not shown).

Table 3: Efficacy of an ALS-inhibiting herbicide towards weed species at five environments in Germany, 2013 and 2014. (*: significant at p≤0.0001; **: significant at p≤0.001; *: significant at p≤0.05; n.s.: not significant; / = calculation not possible).**

	mean of all weeds	*Brassica napus* (n=4)	*Chenopodium album* (n=5)	*Galium aparine* (n=5)	*Matricaria chamomilla* (n=5)	*Polygonum convolvulus* (n=2)
environment	n.s.	n.s.	***	n.s.	*	n.s.
dosage	***	n.s.	***	n.s.	*	*
application time	***	n.s.	***	n.s.	***	*
environment x dosage	/	n.s.	***	n.s.	***	n.s.
environment x application time	/	n.s.	n.s.	n.s.	***	***
dosage x application time	n.s.	n.s.	n.s.	n.s.	**	n.s.
weeds	*	a	b	a	a	a

Efficacy increased with higher dosage of the herbicide (Figure 3). The later the application time the lower the efficacy was across all species. Interactions between dosage, application times and environment concerning the efficacy towards *M. chamomilla* and *P. convolvulus* occurred. Therefore, statistical analysis of efficacy towards both weed species regarding dosage and application time in mean of environments was not possible. However, they showed a slightly decreasing efficacy depending on application time.

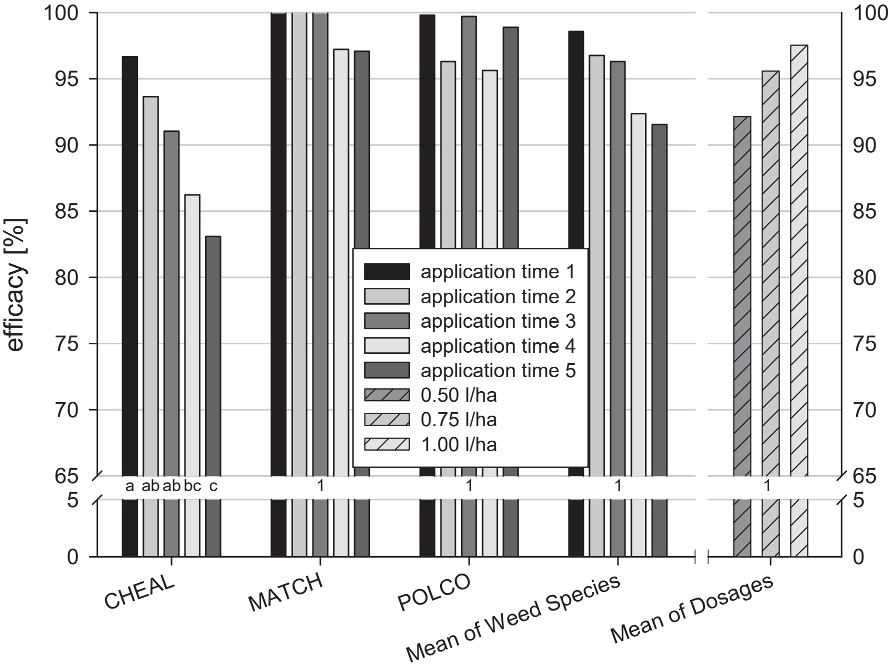

Figure 3: Efficacy [%] of an ALS-inhibiting herbicide towards weed species depending on dosage and application time. CHEAL = *Chenopodium album*, MATCH = *Matricaria chamomilla*, POLCO = *Polygonum convolvulus*. Mean of five environments in Germany, 2013 and 2014. Different letters indicate significant differences (Tukey, p≤0.05) (1= significant differences not calculated due to environment specific interactions).

3.1.1 *Chenopodium album*

Efficacy towards *C. album* significantly increased at higher dosage (Figure 4). Furthermore, efficacy differed significantly between the environments. The highest efficacy was observed at Göttingen 2013 and the lowest at Schwüblingsen 2014. Influence of dosage on efficacy was also different between the environments. Dosage had no significant influence at Göttingen 2013, but a highly significant influence at Schwüblingsen 2014.

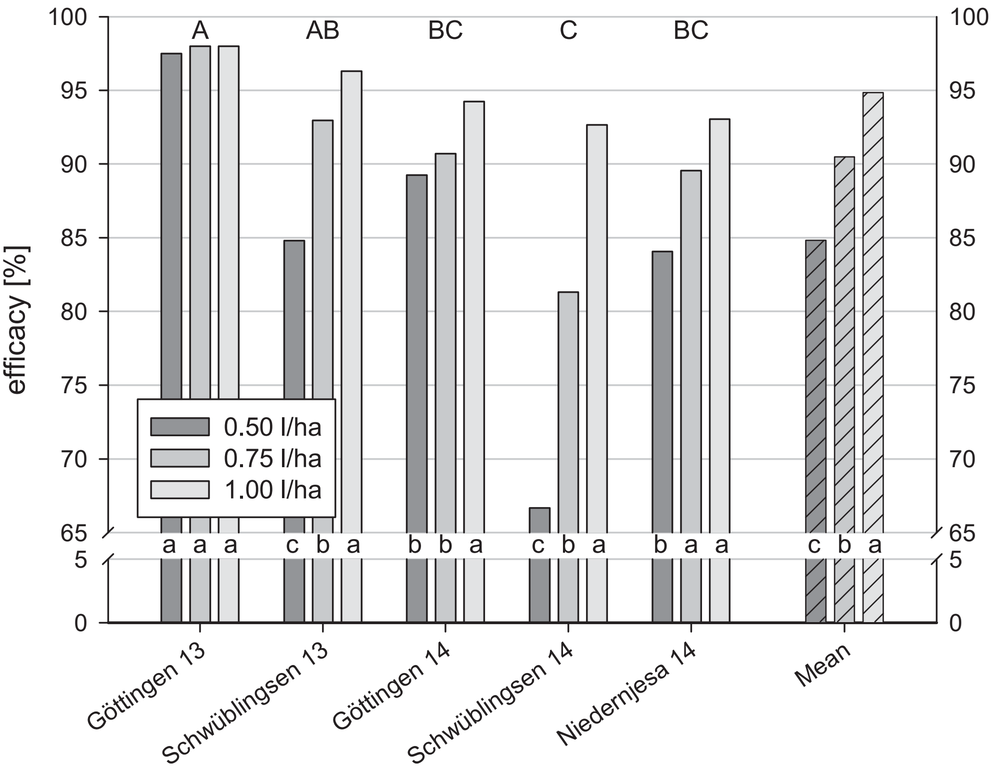

Figure 4: Efficacy [%] of an ALS-inhibiting herbicide towards *Chenopodium album* depending on dosages at five environments in Germany, 2013 and 2014. Different capital letters indicate significant differences between environments (Tukey, p≤0.05). Different small letters indicate significant differences of dosages among dosages within each environment and among means of the environments (Tukey, p≤0.05).

3.1.2 *Matricaria chamomilla*

Efficacy towards *M. chamomilla* was not significantly influenced by dosage (Figure 5). Until the third application time (BBCH 16 - 32) efficacy was 100%. Efficacy towards *M. chamomilla* was significantly influenced by environment (Table 3). At Schwüblingsen 2013 and 2014, efficacy was lower than at the other environments. At Göttingen 2013 and Niedernjesa 2014 decreases of efficacy at the later application times were not significant.

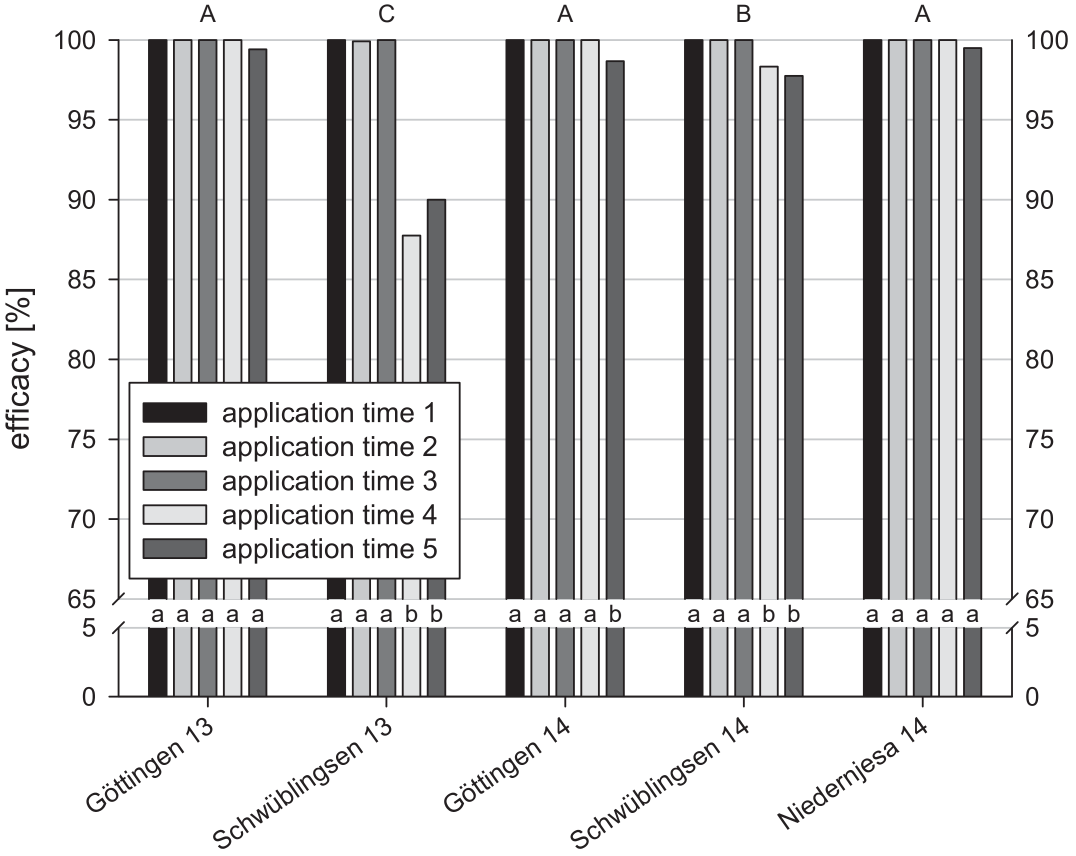

Figure 5: Efficacy [%] of an ALS-inhibiting herbicide towards *Matricaria chamomilla* depending on application time at five environments in Germany, 2013 and 2014. Different capital letters indicate significant differences of environments (Tukey, p≤0.05). Different small letters indicate significant differences among application times within each environment (Tukey, p≤0.05).

Only at Schwüblingsen 2013, efficacy was significantly influenced by dosage (Figure 6). The 0.50 l/ha dosage had a very low efficacy at the fourth application time (BBCH 19) in comparison to the other application times (Figure 6a). Decrease of efficacy at the fourth and fifth application time (BBCH 32 and 61) was lower at Schwüblingsen 2014 (Figure 6b) than at Schwüblingsen 2013.

Only at Schwüblingsen 2013, efficacy was significantly influenced by dosage (Figure 6). The 0.50 l/ha dosage had a very low efficacy at the fourth application time (BBCH 19) in comparison to the other application times (Figure 6a). Decrease of efficacy at the fourth and fifth application time (BBCH 32 and 61) was lower at Schwüblingsen 2014 (Figure 6b) than at Schwüblingsen 2013.

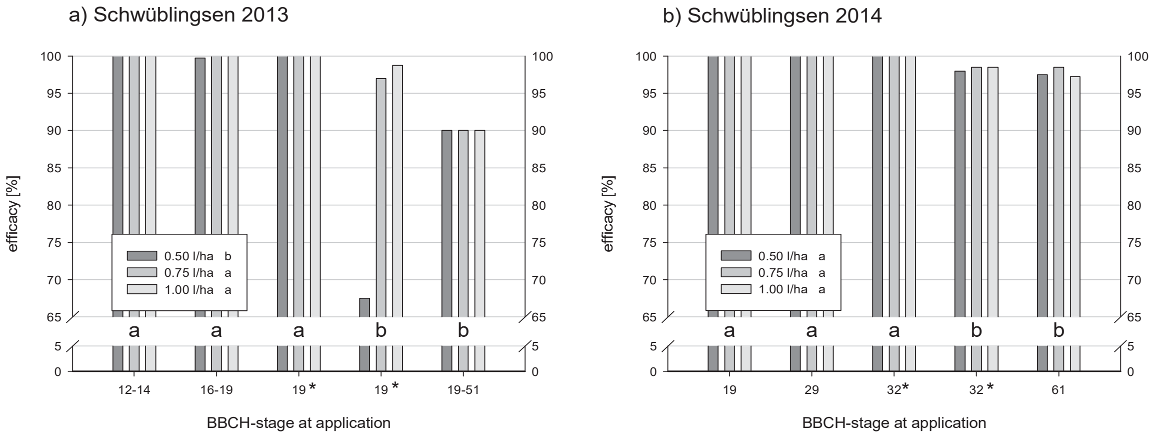

Figure 6: Efficacy [%] of an ALS-inhibiting herbicide towards *Matricaria chamomilla* depending on dosage at different application times at a) Schwüblingsen in 2013 and b) Schwüblingsen in 2014. * = crop growth continued, but no further development stages occurred. Small letters indicate significant differences (Tukey, p≤0.05).

3.1.3 *Polygonum convolvulus*

Efficacy towards *P. convolvulus* was significantly influenced by dosage and application time. An interaction of environment x application time occurred (Table 3). At Schwüblingsen 2013, efficacy towards *P. convolvulus* was lower at the fourth application time (BBCH 15). This effect was only significant for 0.50 l/ha dosage (Figure 7). At Schwüblingsen 2014, a similar effect occurred at application time two (BBCH 14), whereas efficacy of the 0.50 l/ha dosage was varying between 40 and 100% across the repetitions (not shown).

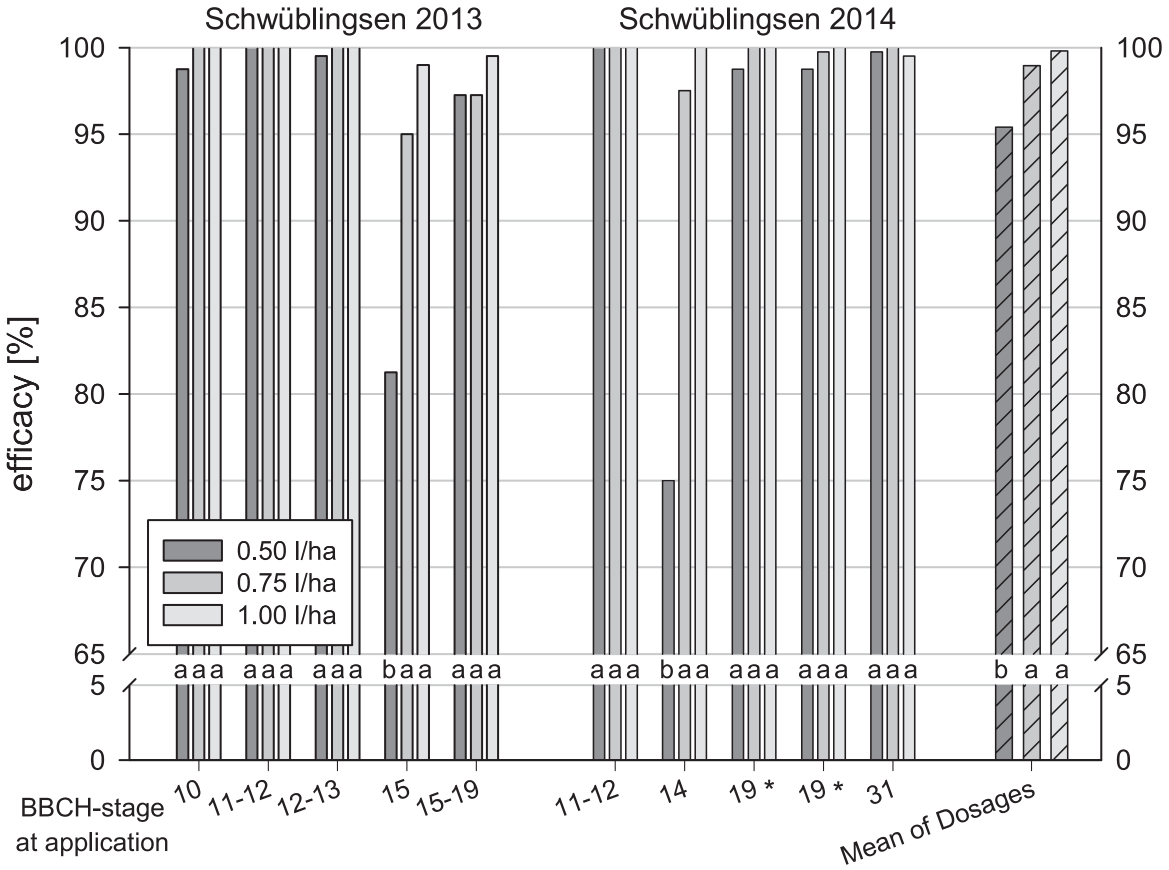

Figure 7: Efficacy [%] of an ALS-inhibiting herbicide towards *Polygonum convolvulus* depending on application time and dosage at two environments in Germany, 2013 and 2014. * = crop growth continued, but no further development stage occurred. Different letters indicate significant differences among dosages within each environment and among means of the dosages (Tukey, p≤0.05).

3.2 Weather conditions

Both air and soil temperatures were higher at Schwüblingsen 2013 and Schwüblingsen 2014 than at the other environments (Figure 1). At Göttingen 2013, precipitation and moderate temperatures before, during and after the application period were constant. Conditions were similar at Göttingen 2014 and Niedernjesa 2014. At Schwüblingsen 2013, a period with high precipitation before the first two applications occurred. Ten days before the fourth application no rainfall occurred. Furthermore, temperatures were high and soil was very dry. At Schwüblingsen 2014, soil temperatures were higher than at the other environments. Actual weather data during applications were recorded (data not shown).

4 Discussion

The field trial series was performed to investigate efficacy of the ALS-inhibiting herbicide towards weed species in sugar beet cultivation at later development stages than cotyledon stage. Furthermore, effects of different dosages on efficacy were determined. For a possible interpretation of environmental interactions, weather data were recorded. In the following, the effects of dosage, development stage and weather conditions on efficacy will be discussed.

4.1 Weed species, dosage and development stage

Efficacy of the ALS-inhibiting herbicide was weed specific. In our field trial series, efficacy towards *C. album* and *P. convolvulus* was lower compared to the other tested weeds. In 2009-2012, 188 field trials were conducted in the maritime EPPO zone (*Bouma*, 2005) for weed control in maize with a similar herbicide (*foramsulfuron, iodosulfuron, thiencarbazone-methyl*, and *cyprosulfamide*) (*Wegener* and *Balz*, 2014). In this study, efficacy towards *C. album* and *P. convolvulus* was also lower compared to *G. aparine*, *Stellaria media* L. and other weeds. The difficulty of controlling *P. convolvulus* by ALS-inhibiting herbicides was similar to *C. album* in this study. Efficacy towards *B. napus* and *G. aparine* was also high in the present field trial series. Especially *B. napus* is difficult to control with the common weed control system due to its fast growth. Efficacy of the common active ingredients apart from *triflusulfuron-methyl* is almost low (*May* and *Wilson*, 2006). Therefore, the ALS-inhibiting herbicide is able to improve the control of volunteer rape. *Nurse* et al. (2007) applied *foramsulfuron* to control weeds in maize cropping. Efficacy towards *C. album* was also significantly lower than towards *Amaranthus retroflexus* L., *Ambrosia artemisiifolia* L. and other weed species in this study.

Dosage had a significant influence on efficacy. The present results confirm the expectation that higher dosages increase efficacy (*Talgre* et al., 2008; *Kieloch* and *Domaradzki*, 2011; *Faccini* and *Puricelli*, 2007). Furthermore, efficacy was significantly influenced by application time. In general, a trend of decreasing efficacy by later application times, which was along with higher development stages, was observed. *Chauhan* and *Abugho* (2012), *Zhang* et al. (2013) and *Kieloch* and *Domaradzki* (2011) found similar effects in different weed species like *C. album*, *Stellaria media* and *Amaranthus retroflexus*. Due to a more active metabolism in younger plants, efficacy at earlier development stages is higher than in later development stages (*Hennigh* et al., 2005). This is one of the reasons identified for higher efficacy at lower development stages in the present field trial series. The herbicide uptake seems to be nearly independent of the development stage. The amount of active ingredients per unit weight of tissue is essential for efficacy (*Schuster* et al., 2007). The concentration of active ingredients in the plant tissue is higher at early development stages. This results in a higher efficacy. Furthermore, these investigations are according to the increasing efficacy by higher dosage.

The efficacy at the fourth application time was too low for an adequate weed control. This was limited by the development stage of BBCH 16 of *C. album*. However, the differences concerning environment and weed species require a further analysis of the results.

4.2 *Chenopodium album*

Differences in efficacy among the environments concerning dosage and application time occurred. Efficacy was significantly lower in 2014 than in 2013. This effect was due to the later development stages within the comparable application times. Particularly at Schwüblingsen 2014, development stages were higher than at Göttingen 2013 at all application times.

While dosage had no significant influence on efficacy at Göttingen 2013, influence of dosage was significant at all other environments. At Schwüblingsen 2014, the low efficacy was probably due to the later development stages at application. Whereby efficacy towards *C. album* was reduced by lower dosages (see 4.1). At Schwüblingsen 2013, especially at the application times one and four (BBCH 14 and 18), efficacy of 0.50 l/ha was low (data not shown). This was presumably due to low temperatures at application time one. *Kelly* (1949) observed that higher temperatures increased the susceptibility of plants to a herbicide. This effect was confirmed in other studies (*Kudsk* and *Kristensen*, 1992). In consequence, at this application time the low temperatures could have reduced efficacy. High precipitation of 74 mm within three days before application amplified this effect. High and low soil moisture can reduce rates of transpiration and photosynthesis (*Qaderi* et al., 2011). Thereby, translocation and metabolism are reduced and herbicide efficacy decreases (*Caseley*, 1987). Another aspect for reduced efficacy is the lower mobility of herbicides in dry soils (*Pätzold* and *Brümmer*, 2003). Ten days before the fourth application time it was not raining and temperatures were high. The consequently low soil moisture probably reduced efficacy at this application time due to similar effects at application time one (*Kudsk* and *Kristensen*, 1992).

At Niedernjesa 2014, high air temperature (>25.0 °C) and low humidity (28.2%) were measured at application time four (BBCH 18-19). This could have reduced efficacy in addition to the late development stages. Temperature optimum for photosynthesis of most C3-plants is between 20 and 30 °C. Higher temperatures can cause lower rates of photosynthesis due to closed stomata and reduced transpiration. Temperatures above 25 °C during application can reduce efficacy of herbicides (*Brown*, 2001). Furthermore, low humidity (< 35%) can reduce herbicide uptake by closed stomata (*Kudsk* et al., 1990), high developed leaf wax layer (*Baker*, 1974) and a very fast evaporation of spray droplets (*Kudsk* and *Kristensen*, 1992).

A lower efficacy towards *C. album* in comparison to the other weeds was assumed. This was confirmed by the results of the present field trial series. Efficacy was higher than 90% in spite of application time at later stages than cotyledon stage using 1.00 l/ha. At the second application time, plants were in BBCH 14 apart from Schwüblingsen 2014. Efficacy was 93.5% on average at this application time. Efficacy at the third application time was 91% on average. At this application time, development stages were between BBCH 16 and 19. This efficacy values are similar to efficacy of the currently used herbicides (*Deveikyte* and *Seibutis*, 2006) where application at cotyledon stage is necessary (*Cioni* and *Maines*, 2010). This is not necessary due to the high efficacy of the ALS-inhibiting herbicide. Using the dosage of 0.50 l/ha at BBCH 14 and dosage of 1.00 l/ha at BBCH 16 of *C. album*, efficacy was nearly 95%.

4.3 *Matricaria chamomilla*

The significantly lower efficacy at Schwüblingsen 2013 and Schwüblingsen 2014 leads to the assumption that efficacy towards *M. chamomilla* is reduced on sandy soils. In spite of earlier development stages at Schwüblingsen 2013 and 2014, efficacy at Göttingen 2014 also decreased at the last application time (BBCH 32). Furthermore, decrease of efficacy at Schwüblingsen 2014 was only 2-3% in spite of the late BBCH 32 and 61. In comparison, efficacy at Schwüblingsen 2013 decreased by about 10% in spite of the late development stages BBCH 19 and 51. Thus, efficacy was only reduced at one sandy environment compared to the other environments. Application time four at Schwüblingsen 2013 also showed lower efficacy towards *C. album*. This was according to the reduction by unfavorable weather conditions (see 4.2). High temperatures (> 25 °C) and low humidity (42%) during treatment could be the reason for the lower efficacy at application time five at Schwüblingsen 2013. The same was observed for *C. album* at application time four at Niedernjesa 2014. In comparison to currently used herbicides, the determined efficacy of the ALS-inhibiting herbicide is an increase of flexibility. While current herbicides have to be applied at cotyledon stage, the ALS-inhibiting herbicide could be applied at BBCH 19-51 with an efficacy of about 90%.

4.4 *Polygonum convolvulus*

Efficacy towards *P. convolvulus* only showed a slight decrease by later application times. In comparison to the other treatments a decrease of about 15% occurred at the fourth application time at Schwüblingsen 2013 (BBCH 15) when using a dosage of 0.50 l/ha. A similar effect was found for *C. album* and *M. chamomilla* at the same application time at Schwüblingsen 2013. This was possibly caused by the weather conditions during application. A similar decrease of efficacy was observed at application time two at Schwüblingsen 2014 (BBCH 14). During application, air temperature was high (22.7 °C) and humidity was low (48.0%). Efficacy towards *C. album* was relatively low in this treatment. Thus, efficacy of dosage 0.50 l/ha at this treatment towards *P. convolvulus* could also be reduced. Though, efficacy was highly variable. This is why a precise determination of efficacy is difficult. In comparison to the weed control by currently used herbicides, efficacy was higher (*Deveikyte* and *Seibutis*, 2008). In consideration of the two application times with low efficacy at 0.50 l/ha, an adequate weed control of the ALS-inhibiting herbicide on *P. convolvulus* is depending on the weather conditions during the applications.

5 Conclusions and Outlook

In the present field trial series, the influence of environment, dosage and development stage on efficacy of an ALS-inhibiting herbicide towards selected weed species in sugar beet was evaluated. On average, efficacy of the ALS-inhibiting herbicide towards the tested weed species was high. Differences among the environments regarding efficacy occurred. This effect has to be distinguished between weather conditions and soil texture. Even though no influence of soil texture was detected, certain decreases of efficacy were caused by unfavorable weather conditions like high temperatures or low humidity during the treatments. Furthermore, differences in efficacy towards the different weed species occurred. *B. napus* and *G. aparine* were controlled at 100% independently of dosage and development stage. Thus, control of volunteer rape seed is improved in comparison to currently used herbicides. Efficacy towards *C. album* was lowest. The lower efficacy mainly occurred at lower dosage and later development stages. On average, lower dosage led to lower efficacy. In *C. album*, *M. chamomilla* and *P. convolvulus,* efficacy was decreased by application at later development stages. The limiting development stages of *C. album* for an adequate weed control were BBCH 14 with 0.50 l/ha and BBCH 16 with 1.00 l/ha.

In conclusion, new aspects concerning influence of environment, dosage and development stage on efficacy of an ALS-inhibiting herbicide were detected. In comparison to current weed control systems, the ALS-inhibiting herbicide promises an even more flexible system by controlling weeds at increased development stages.

However, the use of a weed control system in sugar beet with ALS-inhibiting herbicide is depending on more factors than efficacy and flexibility. An advantage concerning integrated pest management is expected due to high efficacy and the possibility to use herbicides with a broader weed spectrum. The ALS-inhibiting herbicides are classified as *high* for resistance risk by *Herbicide Resistance Action Committee* and resistance of weed species to these herbicides has been identified worldwide (*Heap*, 2014). Therefore, a strategy for resistance management has to be developed. Furthermore, non-sensitive sugar beet varieties have to be registered. Efficacy towards weeds in sugar beet plots as well as duration of efficacy have to be evaluated to get more information about possibilities and limitations of this system.

Acknowledgments

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Kapitel 3

Duration of Soil Activity of Foramsulfuron + Thiencarbazone-methyl applied to Weed Species typical of Sugar Beet Cultivation

Duration of Soil Activity of Foramsulfuron + Thiencarbazone-methyl applied to Weed Species typical of Sugar Beet Cultivation

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Weed Technology (im Druck)

Abstract

The duration of the soil activity of an acetolactate-synthase (ALS) inhibiting herbicide which is currently under approval for sugar beet cultivation was determined in a field trial series in Germany in 2013 and 2014. The herbicide containing foramsulfuron (FSN; 50 g L^{-1}) and thiencarbazone-methyl (TCM; 30 g L^{-1}) was applied in different dosages (25 + 15, 37.5 + 22.5 and 50 + 30 g FSN + TCM ha^{-1}) to the bare soil. Five weed species (rapeseed, common lambsquarters, wild chamomile, blackgrass, barnyardgrass) were sown at 5, 10, 15 and 20 days after application. The duration of the soil activity was assessed by determining percent weed control in the treated plots. The longest duration was observed after applying 50 + 30 g FSN + TCM ha^{-1}, but the influence of environment was much stronger than the dosage effect. The mean duration of soil activity was 10 to 15 days in 2013 and longer than 20 days in 2014. Differences among weed species in their response to the herbicide treatments were small.

Nomenclature: foramsulfuron; thiencarbazone-methyl; barnyardgrass, *Echinochloa crus galli* L.; blackgrass, *Alopecurus myosuroides* Huds.; common lambsquarters, *Chenopodium album* L.; rapeseed, *Brassica napus* L.; wild chamomile, *Matricaria recutita* L.; sugar beet, *Beta vulgaris* L. ssp. *vulgaris* var. *altissima* Döll

Keywords: percent weed control, herbicide dosage, sowing time.

In sugar beet cultivation, weed control is essential to achieve high yields, because the competition with weeds for light, water and nutrients reduces yield and quality (Schweizer 1981 and 1983). Further negative impacts of weeds are harvest difficulties caused by weed residues, enhanced future weed infestation by increasing the seed bank in the soil and co-hosting of insects and diseases (Petersen 2003; Cioni and Maines 2011). As the early development of young sugar beet plants is slow and competitiveness with fast growing weeds is low, weed control must take place at early growth stages of the beet (May and Wilson 2006). Chemical weed control requires a precise application timing of herbicides starting at the cotyledon stage of the weeds (May and Wilson 2006).

Currently, three to five active ingredients (ai) with reduced dosages (relative to authorized application rate) are applied per treatment in sugar beet cultivation in Germany. On average, 3.5 treatments are necessary until competitiveness of sugar beet plants is high enough to suppress weed growth (Vasel et al. 2012). Plants usually absorb ai via roots and/or foliage. Herbicides that are taken up via roots and/or hypocotyl soon after germination can decelerate further weed emergence. This time delay is hereinafter referred to as soil activity. Continuous decrease of soil activity and further germination of weeds necessitate repeated treatments (Andr et al. 2014). The treatment interval depends on the duration of soil activity which is influenced by environment and herbicide properties (Andr et al. 2014). The intervals usually vary between five (Cioni and Maines 2011) and 14 days (Petersen 2003). In the 1980s, the described weed control strategy was enhanced. The benefit was a reduction of about two-thirds of applied ai and less pre-emergence applications compared to the former strategy (May and Wilson, 2006), but this was the last basic advancement and no new ai have been registered since (Petersen 2003). Parallel to the current weed control strategy, a shift to a higher infestation with difficult to control weeds like *Chenopodium album* L., *Matricaria recutita* L. and *Galium aparine* L. occurred (Vasel et al. 2012). Furthermore, the risk of resistant weed species increases by consistent use of the same chemical products (Heap 2013).

A possible improvement is using herbicide tolerant crops. One approach was the use of genetic modification by insertion of relevant genes into sugar beet crops. This was developed and introduced in North America in the early 2000s (Beckie and Hall 2014). Due to political reasons, this technology is not available in the European Union (Tencalla 2006). Genotypes that are non-sensitive to *acetolactate-synthase* (ALS) inhibitor herbicides could be a further option. This trait can naturally occur in crops and was conventionally selected for sunflowers and rapeseed and both crops are grown in Europe today (Lamichhane et al. 2016). Sugar beet is naturally sensitive towards ALS-inhibitor herbicides and triflusulfuron-methyl is the only ai of this mode of action that is registered for weed control in sugar beet cultivation (Wittenbach et al. 1994). Cultivars that are non-sensitive to the ALS-inhibitors foramsulfuron (FSN) and thiencarbazone-methyl (TCM) of the complementary herbicide Conviso® are currently under development (KWS 2015). In the following, the herbicide is referred to as ‘F/T’. F/T contains 50 g FSN L^{-1} and 30 g TCM L^{-1}. FSN belongs to the sulfonylurea (SU) and TCM to the sulfonyl-amino-carbonyl-triazolinones. FSN is absorbed through foliage, TCM is mainly absorbed by roots and both ai are transported in the xylem and phloem. F/T is formulated as an oily dispersion.

In Central Europe, the spectrum of weeds in maize cultivation is similar to that in sugar beet cultivation (de Mol et al. 2015). Both foramsulfuron and thiencarbazone-methyl are registered in maize cultivation, where only two applications of thiencarbazone-methyl are necessary to control weeds (Sulewska et al. 2012; Pannacci and Onofri 2016). The utilization of F/T on sugar beet could thus improve efficacy and reduce the number of herbicide applications due to a longer lasting soil activity. Nevertheless, in the case of intensive use of ALS inhibitors as the only mode of action, the possibility of increasing development of ALS resistant weeds has to be considered.

Flexibility of application timing and efficacy increase by using F/T (Wendt et al. 2016). However, there is no data on the effect of environment and dosage on the duration of soil activity of F/T or on the duration itself. To assess whether the utilization of F/T would prolong the interval between herbicide treatments in sugar beet cultivation, data on the duration of soil activity of F/T are necessary. A comparison of F/T with classic herbicides was not intended due to the high workload connected with the scope of the present study. Data for classic herbicides are available from the literature (e.g. Kucharski and Sadowski 2009; Janaki et al. 2013).

The data by other authors on FSN and TCM in maize cultivation do not describe the duration of soil activity of F/T in detail (Sulewska et al. 2012; Pannacci and Onofri 2016). Performance of F/T regarding dosage and environmental effects and furthermore the soil activity against different weed species are unknown. The aim of the present study was thus to evaluate the influence of (i) environment and (ii) dosage on soil activity of F/T and (iii) its maximum duration. A field trial series was conducted in northern Germany in 2013 and 2014 with three sites each year (six environments) where different weed species but no sugar beets were sown.

Materials and Methods

Field Trials. Four field trials were located near Göttingen (Table 1), three on loamy soils (Göttingen 2013, Göttingen 2014, Niedernjesa 2014) and one on clay soil (Angerstein 2013). Two were located on sandy soils near Hanover (Schwüblingsen 2013, Schwüblingsen 2014). The trial sites represent typical environments for sugar beet cultivation covering soil and climatic differences that can be found in Central Europe.

Table 1. Environmental attributes of the trial sites and date of herbicide application, Germany 2013 and 2014. (Weather conditions from 20th April to 31st May of each year, corresponding to the period of weed sowing).

	Göttingen		Schwüblingsen		Niedernjesa
	2013	2014	2013	2014	2014
Soil type	Stagnic luvisol		Haplic cambisol		Fluvisol
Soil texture	Silt loam		Loamy sand		Loam
pH value	6.6	6.4	5.6	6.0	7.1
Organic matter [%]	1 - < 2	1 - < 2	2 - < 4	2 - < 4	1 - < 2
Total precipitation [mm]	116	127	210	124	67
Mean air temperature [°C at 2.00m]	12.8	13.1	12.3	13.1	13.1
Mean soil temperature [°C at -0.05m]	11.7	15.2	14.6	16.1	15.7
Application date	13-04-25	14-04-23	13-04-29	14-04-24	14-04-23

Angerstein 2013: cancelled due to too low weed densities

Soil was prepared similar to sugar beet cultivation. The fields near Göttingen were plowed in autumn and the fields near Hanover were tilled with a cultivator in spring. Five days after application of F/T, the following common weed species in sugar beet cultivation (Vasel et al. 2012) were sown at different dates: *Amaranthus retroflexus* L., *Brassica napus* L., *Chenopodium album* L., *Matricaria recutita* L., *Alopecurus myosuroides* Huds. and *Echinochloa crus-galli* (L.) Beauv..

Herbicide Application. The herbicide was applied in parallel strips with dosages of 0 (untreated check), 25 + 25, 37.5 + 22.5 and 50 + 30 g FSN + TCM ha^{-1}. The strips were randomized in four replications per environment (Figure 1). The treated stripes extended to the whole width of the area prepared for the subsequent sowing times of the weeds. Application was carried out with a pneumatic plot sprayer (type *Schachtner PSG,* nozzle type Air Induced (low pressure) flat fan - 110 02, water volume 200 L ha^{-1}, pressure 250 kPa, velocity 4.5 km h^{-1}) with an effective spraying width of 1.8 m.

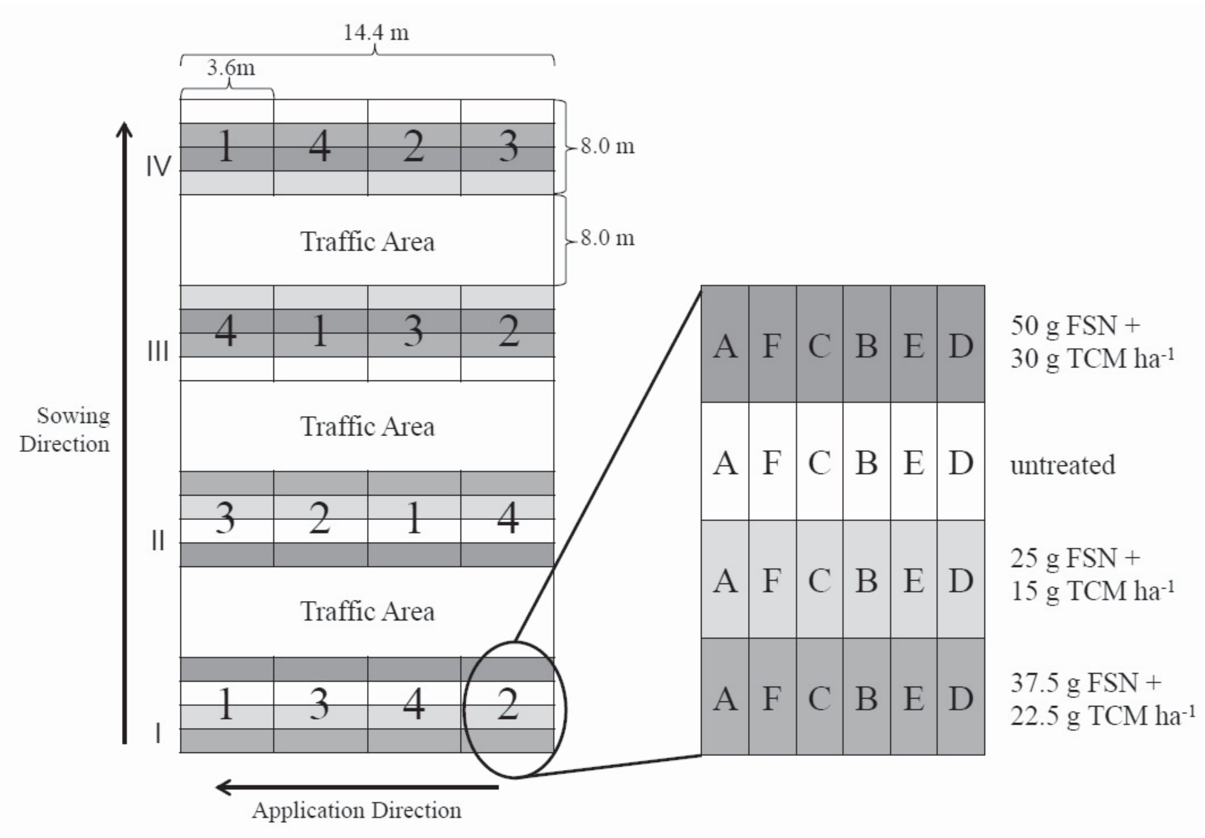

Figure 1. Field trial design to assess duration of soil activity of foramsulfuron (FSN) + thiencarbazone-methyl (TCM) against important weed species typical of sugar beet cultivation. Different numbers indicate different sowing times after application of foramsulfuron + thiencarbazone-methyl; different capital letters indicate different weed species, Roman numerals indicate replications. Sowing times and weed species were randomized in each environment.

Weed Sowing and Assessments. Herbicide strips were divided into four blocks to sow weeds at four different times: Weeds (no sugar beet) were sown during the usual time of sugar beet sowing (end of April) at 5, 10, 15 and 20 days after application (DAA). In 2014, a fifth sowing time (40 DAA) was added, because residual soil activity was found to last longer than 20 DAA in 2013. Altogether, one plot included one sowing time, one dosage and the six weed species. The weed seeds (purchased from Herbiseed, Mire Lane West End, Twyford, RG10 0NJ, England) were drilled at right angles to the application direction in parallel rows with a distance between the rows of 20 cm (Figure 1) with a Sembdner GSD sowing machine (SEMBDNER Maschinenbau GmbH, Liebigstrasse 16, 82256 Fürstenfeldbruck, Germany).

Each sowing unit of the drilling machine was set to the specific optimum seeding rate and sowing depth of each species (Nichols et al. 2015) and adapted to soil conditions to ensure drilling into a humid soil horizon. The sowing depths were: *A. retroflexus* 1.0 to 2.0 cm, *B. napus* 1.0 to 2.0 cm, *C. album* 0.5 to 1.5 cm, *M. recutita* 0.0 to 0.5 cm, *A. myosuroides* 1.0 to 2.0 cm and *E. crus-galli* 1.0 to 2.0 cm.

The seeding rates were set to achieve a plant density of 50 growing plants per meter within a row. The specific germination rates were tested in the greenhouse before: 100 seeds of each weed species were sown in pots filled with sterilized standard soil mixture (75% sandy clay and 25% sand). Day/night temperatures were 22/18 °C with a period of 12 h (Christ et al. 2011).

In the plots, the arrangement of the weed species was randomized among sowing times. Sowing times and herbicide strips were also randomized (Figure 1). Due to technical reasons, weed species were not randomized between replications and herbicide dosages.

Soil activity of F/T was evaluated by assessing percent control of each weed species related to the untreated check. Weed coverage as plant density (emerged plants per meter seeded) and plant growth (estimated biomass and development stage) were visually assessed in each plot for each sowing time according to EPPO (2007). Consequently, the lower the weed coverage in the treated plots, the higher were weed control and thus soil activity. Weed control was graded from 0 to 100% in two assessments at 35 and 55 days after application. In 2014, the newly introduced fifth sowing time (40 DAA) could thus not be evaluated at the first assessment.

At Angerstein 2013, the evaluation of weed control was not possible, because very low soil moisture caused poor plant density. As *A. retroflexus* had a poor plant density at every environment, no data for this weed are available. At Göttingen 2013, *A. myosuroides* had not yet emerged at the first assessment.

Air and soil temperature, precipitation, air humidity, wind direction and wind speed were recorded by weather stations at each site (Figure 2). Actual weather conditions during applications were additionally recorded.

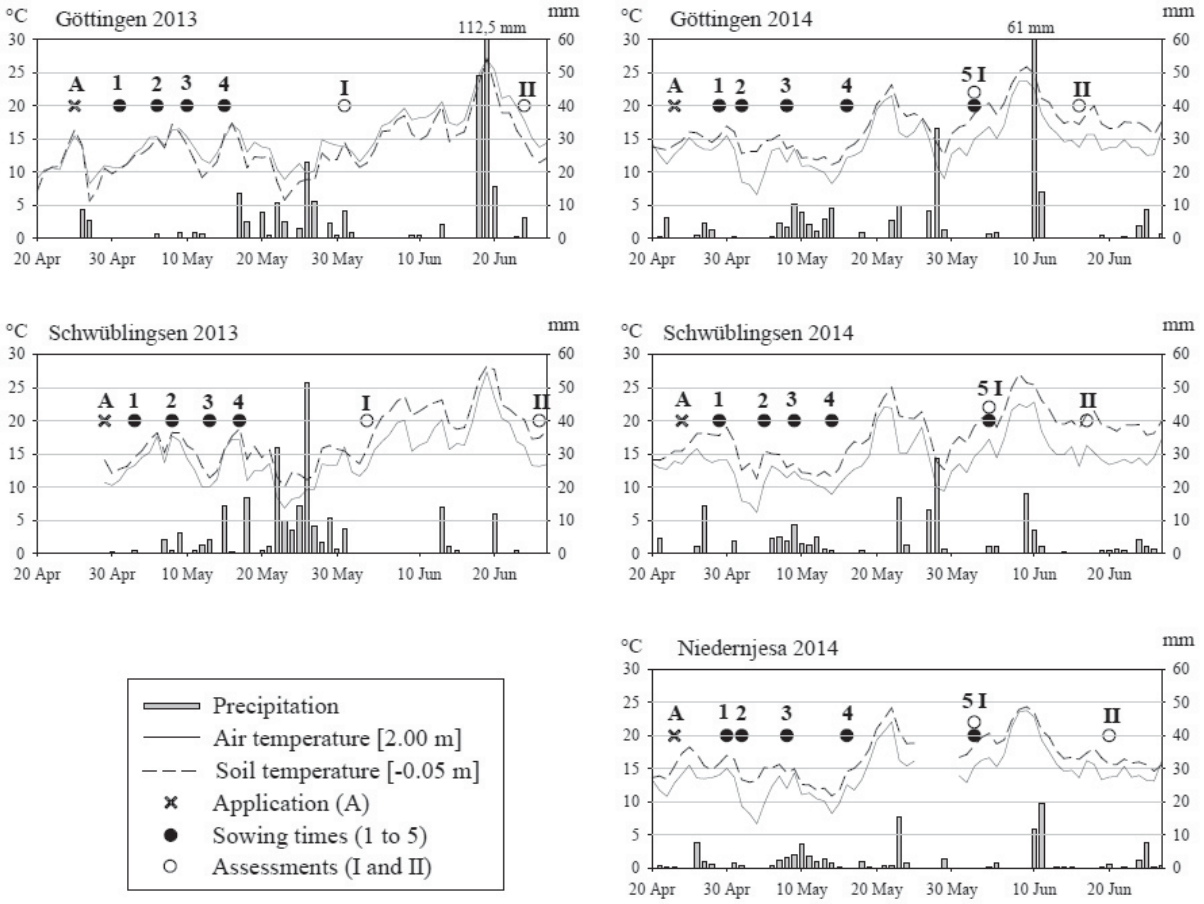

Figure 2. Weather conditions (average daytime temperature [°C] and precipitation [mm] in five environments in Germany, 2013 and 2014 from 20 April to 27 June). Dots indicate sowing times of weed species.

Statistical Analysis*.* The statistical analysis was carried out with the statistic program SAS version 9.4 (SAS Institute Inc., Cary, NC, USA). The data were tested for variance homogeneity and normal distribution. Due to the use of relative figures, the data were altered by an angular transformation (EPPO 2013). All tables and figures include the original data.

Data were subject to analysis of variance using PROC MIXED and a multiple post-hoc Tukey test (p≤0.05) was applied to compare parameter means. The untreated checks were excluded from the analysis, because values in these plots were generally zero. The influence of weed species on weed control could not be assessed in this analysis due to the missing randomization of the weeds (Figure 1). Replications at each environment were thus averaged and environments were set as replications in a second ANOVA. The fifth sowing time (40 DAA) was excluded from the evaluation due to the missing values in 2013.

Results and Discussion

Factors affecting Soil Activity. Weed control was influenced by environment, herbicide dosage, sowing time and weed species and their interactions at both assessment dates (Table 2). At the first assessment, environment and sowing time and at the second assessment, environment and dosage had the strongest influence on weed control.

Table 2. Factors influencing relative weed coverage of five weed species (*Brassica napus*, *Chenopodium album*, *Matricaria recutita*, *Alopecurus myosuroides*, *Echinochloa crus-galli*) treated with different dosages of foramsulfuron + thiencarbazone-methyl prior to sowing in five field trials in Germany, 2013 and 2014. Assessments: 1st at 35, 2nd at 55 days after application. (*, ** and *: significant at p≤0.05, p≤0.001 and p≤0.0001; n.s.: not significant). DF: degrees of freedom.**

		1st assessment		2nd assessment	
Factor	Number of DF	F Value		F Value	
Environment	4	365.16	***	161.48	***
Herbicide dosage	2	19.66	***	51.57	***
Sowing time	3	58.39	***	12.21	***
Weed	4	25.55	***	41.94	***
Environment x dosage	8	3.26	**	20.83	***
Environment x sowing time	12	22.24	***	7.53	***
Dosage x sowing time	6	1.35	n.s.	0.72	n.s.
Weed x environment	16	18.28	***	21.16	***
Weed x dosage	8	1.51	n.s.	2.58	*
Weed x sowing time	12	4.64	***	2.87	**

Environment. The lower weed control at the first assessment (35 DAA) compared to the second one (55 DAA) (Figure 3) was caused by the exponential weed growth in the untreated checks in comparison to the treated plots as described before (Jursik et al. 2008). Therefore, differences in weed control between untreated and treated plots were smaller in the earlier assessments.

Nevertheless, weed control differed significantly among environments at both assessments (Figure 3a). It was significantly lower in 2013 than in 2014 and lower at Göttingen 2013 than at Schwüblingsen 2013. In 2014, no significant differences in weed control among environments occurred until 20 DAA.

The strong year effect was most likely caused by temperature differences. Soil and air temperatures were about 1 °C higher in 2014 than in 2013 (Table 1). Especially soil temperatures until 15 DAA were about 2 °C higher in 2014 than in 2013. This probably enhanced soil activity of F/T in 2014 compared to 2013. Plant availability of herbicides including sulfonylureas is also increased by increasing temperature (Eleftherohorinos et al, 2004), resulting in higher uptake and metabolism (Kudsk and Kristensen 1992). In 2013, especially the low soil temperatures of about 7 °C two days after application at Göttingen (Figure 2) may have reduced soil activity in comparison to Schwüblingsen.

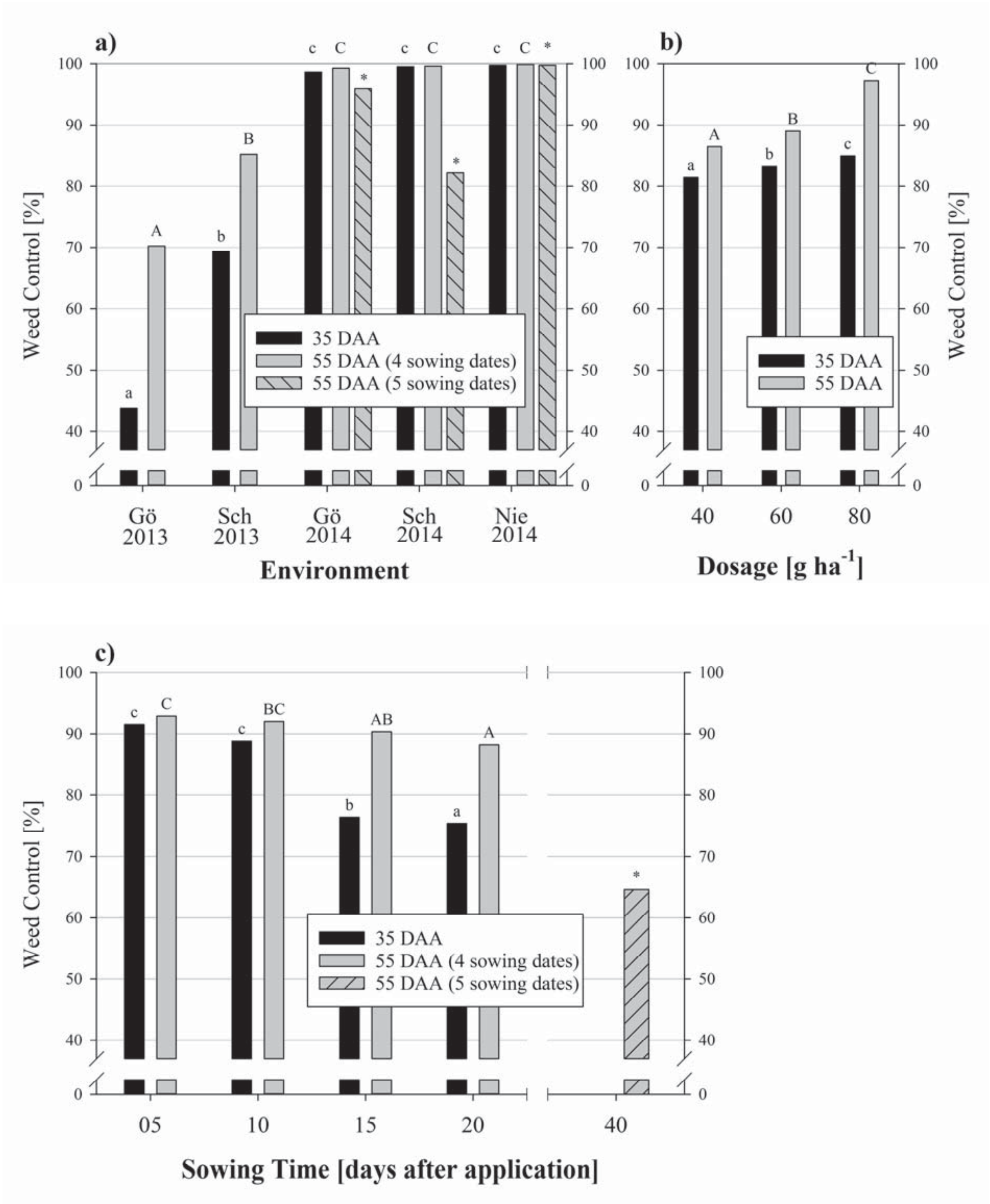

Figure 3. Mean relative weed control [%] of five weed species treated with foramsulfuron + thiencarbazone-methyl prior to emergence as influenced by a) environment, b) dosage and c) sowing time. Assessments at 35 and 55 days after application (DAA) for four sowing dates (5, 10, 15 and 20 DAA) and at 55 DAA (2014 only) for five sowing dates (5, 10, 15, 20 and 40 DAA). a) and c) summarize five sowing times (5 to 40 DAA). Significant differences among environments, dosages and sowing times are indicated by different small letters for the 35 DAA and by different capital letters for the 55 DAA assessment (Tukey, p≤0.05), n = 16-20. *= statistical evaluation not possible due to missing values in 2013. Gö: Göttingen; Sch: Schwüblingsen; Nie: Niedernjesa.

Differences in soil moisture also affect weed control. The first step in degradation of sulfonylurea is hydrolysis followed by (less effective) microbial degradation (Grey and McCullough 2012). Furthermore, increased soil moisture was described to enhance the degradation of herbicides such as sulfometuron-methyl (sulfonylurea) and isoxaflutole (cyclopropylisoxazole) (Anderson and Dulka 1985; Taylor-Lovell et al. 2002) due to lower sorption, higher bioavailability and faster diffusion kinetics and transport (Cupples et al. 2000). However, different rainfall patterns hardly explain the lower weed control rates in 2013 compared to 2014, as neither hydrolysis nor leaching out of the germination zone seem likely during the first 19-20 DAA at Göttingen or Schwüblingsen 2013 (Sondhia 2009; Stewart et al. 2012). In 2014, significant environmental differences were found in the 55 DAA assessment when the latest sowing date (40 DAA) was included. The precipitation data show that leaching of the ai out of the germination zone of the weeds due to heavy rainfall is unlikely for the first three sowing dates 5-15 DAA (Figure 2). After the 4th sowing at 20 DAA, heavy rainfall events within one day (30-35 DAA) at Göttingen and Schwüblingsen 2014 could have caused leaching at these sites, whereas this is less likely for Niedernjesa. Later than 20 DAA, leaching seems likely but this is also related to degradation over the time. In consequence, leaching was just one factor for the reduced control of the weeds sown at 40 DAA. At Niedernjesa 2014, leaching was unlikely due to the soil texture and the relatively low precipitation (Sondhia 2009; Stewart et al. 2012).

By contrast, the higher precipitation of 210 mm at Schwüblingsen 2013 (Table 1) in comparison to 116 mm at Göttingen 2013 could have enhanced soil activity at this environment. In studies by Stewart et al. (2010, 2012), efficacy of soil active herbicides was increased by increasing soil moisture due to the faster absorption of ai by weed seeds. This effect most likely outbalanced the aforementioned effect of faster degradation at increased soil moisture. Furthermore, plant availability was presumably higher at Schwüblingsen due to lower soil pH (5.6, Table 1) than at Göttingen (6.6), because plant availability of TCM increases at lower soil pH whereas degradation of FSN and TCM is not influenced by the soil pH (Szmigielski et al. 2012). Although FSN and TCM are weakly adsorbed to soil (Grey and McCullough 2012), soil activity of F/T may have been higher at Schwüblingsen with sandy soil than at Göttingen where clay content was higher (Barriuso and Calvet 1992; Villaverde et al. 2008). All influencing factors are interacting and it is difficult to quantify the importance of every factor. Furthermore, this might be of particular relevance concerning soil organic matter which was highest at Schwüblingsen necessitating further studies.

Dosage. Higher herbicide dosages are often necessary to achieve an adequate weed control (Talgre et al. 2008). In the present study, weed control significantly increased with increasing herbicide dosage (Figure 3b) as also shown in earlier studies for both pre- and post-emergence application of herbicides (Raimondi et al. 2015). This is mainly due to a higher amount of ai in the plant tissue per unit weight at higher dosages (Schuster et al. 2007).

Sowing Time. Weed control significantly decreased with later sowing times being less distinctive in the second than in the first assessment (Figure 3c). This decrease can be explained by several factors such as soil binding, leaching and degradation which are interacting. As discussed above, leaching was not likely until 20 DAA and decreasing soil activity of the herbicide was presumably caused by degradation of ai in relation to temperature (Sarmah and Sabadie 2002). Due to the significant decrease of weed control between 10 and 15 DAA at the first assessment, maximum duration of soil activity of F/T can be expected around this time. This is in line with studies indicating the degradation in soil (at 20 °C) at 1.5 - 12.7 days for FSN (Haas 2001) and at 3.2 - 53.2 days for TCM (EFSA 2013). The DT_{50} (period for 50 percent dissipation) by hydrolysis (at 25 °C) is 3.7 to 132.0 and 50.0 to 153.0 days in FSN and TCM, respectively (BVL 2009, 2010). Due to the different response of the weed species to the application of F/T and the interactions of environment and dosage influencing soil activity, a more detailed evaluation of weed species and environments is given.

Maximum Duration of Soil Activity. In the present study, mean weed control rate significantly decreased between the second and third sowing time (10 and 15 DAA) for all weed species (except *M. recutita*) at the first assessment (Figure 4a). Differences in control among the weed species rarely occurred. Only the control of *C. album* and *M. recutita* decreased more slowly than control of the other weeds, but there was a strong environmental effect. In the 2014 trials, weed control hardly differed among the 5 to 20 DAA sowing times in the first assessment. In the second assessment, weed control was considerably lower in the plots sown 40 DAA than in the plots with earlier sowing times (Figure 4b).

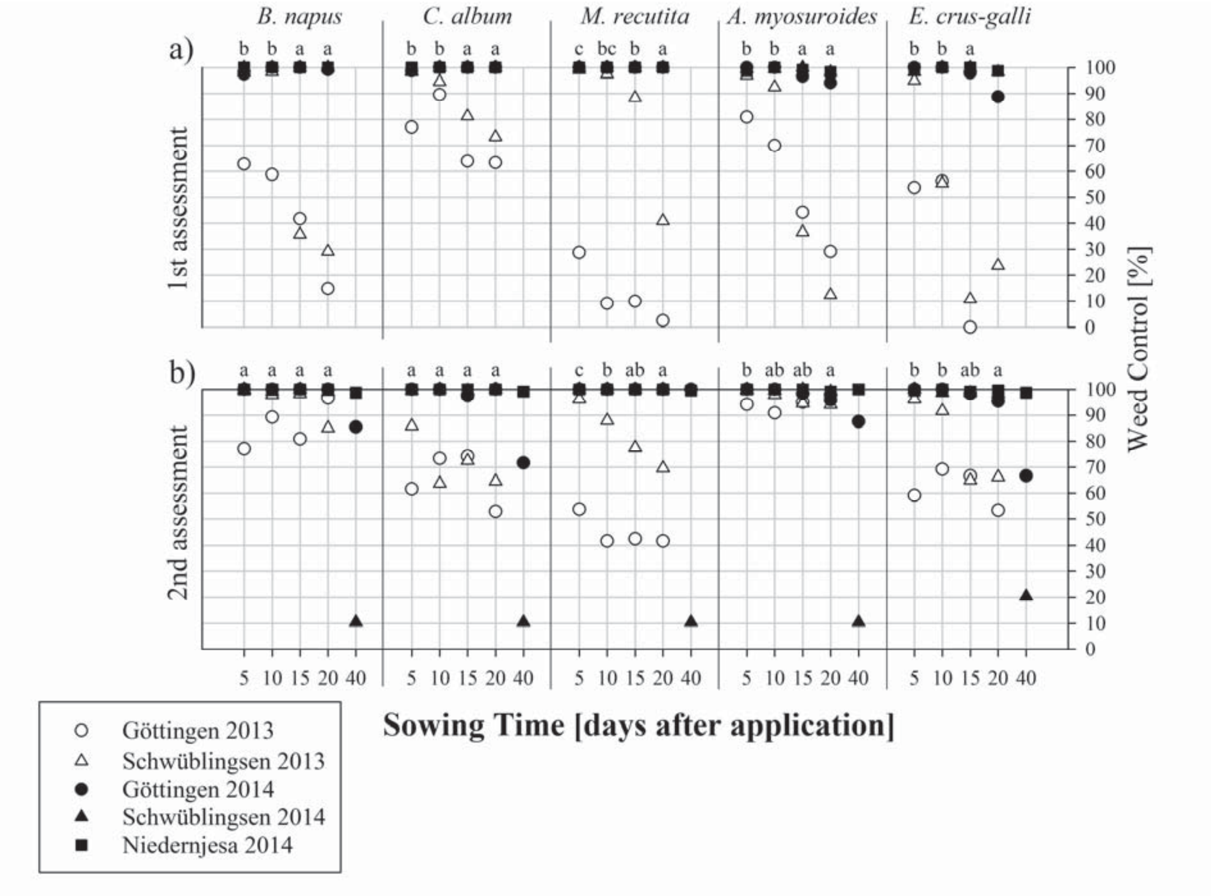

Figure 4. Relative weed coverage rate [%] of five weed species treated with foramsulfuron + thiencarbazone-methyl prior to emergence (mean of dosages: 0.50, 0.75, 1.00 l/ha) as affected by sowing time and environment. Untreated check was set as 100. Assessments made a) 35 days and b) 55 days after application. Different letters indicate significant differences among sowing times (Tukey, p≤0.05), n = 12. *Echinochloa crus-galli* sown 20 days after application had not yet emerged at the first assessment at Göttingen 2013; fifth sowing time (40 days after application) only in trials in 2014.

At Göttingen 2013, the control of all weeds decreased almost constantly in comparison to Schwüblingsen 2013 where a stronger decrease occurred at 15 DAA. At Göttingen 2013, only low and constant precipitation of about 6.9 mm between 6 and 13 May (10 and 18 DAA) occurred between the sowing times (Figure 2). Furthermore, temperatures were constant between 15 and 17 °C. Presumably, degradation of the ai was also constant and soil activity against weeds decreased continuously. In contrast, after a period with low precipitation of only 6.6 mm until the second sowing time (10 DAA), 19.2 mm fell between the 7 and 13 May (8 and 15 DAA) at Schwüblingsen 2013. In a study by Graebing et al. (2003), environmental factors (temperature and soil moisture) were constant and degradation of herbicides also remained constant. Saha and Kulshrestha (2002) found that the degradation rate of sulfosulfuron was nearly constant between 10 and 25 °C. Furthermore, the degradation rate of prosulfuron markedly increased after rewetting a dry soil 17 days after application (Hultgren et al. 2002). As discussed above, the soil activity was not reduced by leaching in the 2013 trials (Sondhia 2009; Stewart et al. 2012). Especially at Schwüblingsen 2013, the high precipitation between 30-35 DAA caused fast dissipation by leaching and hydrolysis leading to the significant decrease in weed control at this site.

In 2014, the control of all weeds did not decrease until 20 DAA at any environment (Figure 4). Regarding the DT_{50} values of soil degradation of FSN and TCM being more than 50 days, soil activity lasting longer than 20 days with high weed control is possible in relation to the weather conditions which differed between years. In previous studies, the half-lives of SU herbicides ranged from days to months depending on factors like pH-value and temperature (Grey and McCullough 2012). The strongest influence on the duration of soil activity of F/T in our study was thus caused by environment. Soil activity lasted 10 to 15 days in 2013 and longer than 20 days in 2014. For currently used herbicides, duration of soil activity against weeds was indicated at five to 14 days (Cioni and Maines 2011; Petersen 2003) being shorter than the estimated soil activity of F/T. Further studies including classic herbicides have to prove whether this implies a longer duration of soil activity of F/T.

Outlook. As the duration of soil activity of F/T was more than 10 to 20 DAA, the treatment interval between two applications in practical weed control could be prolonged and the number of herbicide treatments might decrease in comparison with classic herbicides. A further aspect of evaluating weed control systems is the application timing which was determined by Wendt et al. (2016) for F/T at BBCH 14 to 16 of *C. album* applying 25 + 15 or 50 + 30 g FSN + TCM ha^{-1} complementing the present data on duration of soil activity. Basic determinations and further studies comparing efficacy and selectivity of F/T to classic herbicides are necessary to specify possibilities and limits of the system. Field trials in further Central European environments could be conducted to broaden the data on environmental effects. As the number of weed species resistant against ALS inhibitor herbicides has increased during the last two decades (Heap 2013), a weed and crop rotation specific weed resistance management is essential.

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Kapitel 4

Efficacy of different strategies using an ALS-inhibitor herbicide for weed control in sugar beet

Efficacy of different strategies using an ALS-inhibitor herbicide for weed control in sugar beet

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Abstract

In 2013 and 2014, field trials were conducted at six environments in Germany to evaluate the efficacy of a new ALS-inhibiting herbicide containing foramsulfuron and thiencarbazone-methyl (F/T) for weed control in sugar beet cultivation. Five herbicide strategies with different application frequencies of F/T (50 g foramsulfuron ha^{-1} + 30 g thiencarbazone-methyl ha^{-1}) and a classic herbicide strategy with three applications of phenmedipham (75 g ai ha^{-1}), desmedipham (59 g ai ha^{-1}), ethofumesate (94 g ai ha^{-1}), lenacil (34 g ai ha^{-1}) and metamitron (700 g ai ha^{-1}) were compared. The efficacy of the classic herbicide strategy was between 84 and 99% due to surviving *Chenopodium album* L., *Matricaria recutita* L., *Mercurialis annua* L. and *Solanum tuberosum* L.. Average efficacy of F/T was 95% in the single application treatment. Strategies with two applications combining classic herbicides and F/T achieved an efficacy beyond 97%. This points to an increased flexibility of weed control in sugar beet.

Keywords: foramsulfuron, thiencarbazone-methyl, application frequency, standardized treatment index

Introduction

In sugar beet cultivation, high yield strongly depends on an effective weed control (May and Wilson, 2006). In Germany, the classic weed control strategy comprises on average 3.5 applications of three to five active ingredients (ai) at the cotyledon stage of the weeds (Vasel et al., 2012). The summation of all applied ai in relation to their authorised dosages and the treated area results in the standardised treatment index (STI) which is an indicator for the use intensity of plant protection products (Sattler et al., 2007). In Germany, the mean STI for herbicide use in sugar beet was 2.64 in 2010-2014 (PAPA, 2016). As increasing occurrence of weeds that are difficult to control, e.g. *Chenopodium album* L., *Matricaria* spp. and *Polygonum* spp., was observed in Germany during the last 15 years (Buhre et al., 2011; Vasel et al., 2012), a future increase of STI can be assumed.

Currently, a new herbicide (Conviso®) containing foramsulfuron and thiencarbazone-methyl is under approval for sugar beet cultivation. In the following, it is referred to as ‘F/T’. Both ai belong to the HRAC-group “B” and inhibit the acetolactate-synthase (ALS). Due to the susceptibility of sugar beet to this mode of action, a non-sensitive genotype is currently being developed (Wegener et al., 2015). Wegener et al. (2015) determined the efficacy of F/T as part of the approval procedure. They compared F/T in two application strategies as requested for registration with classic herbicides, but without presenting cumulated efficacy results. Thus, the present study was conducted to compare the cumulated efficacy of five weed control strategies with F/T for possible use in commercial practice and a classic herbicide strategy.

Material and methods

Experimental setup

Three sugar beet field trials were conducted in Northern Germany each in 2013 and 2014 (six environments, Table 1). The trial sites were selected for different soils and weed compositions. Soil texture was silt loam at Göttingen, clay loam at Angerstein, loam at Niedernjesa and loamy sand at Schwüblingsen. Schwüblingsen was especially selected to test efficacy towards *Mercurialis annua* L. and volunteer potatoes (*Solanum tuberosum* L.) which are difficult to control in sugar beet (May and Wilson, 2006).

Table 1. Site specific weed composition in field trials with sugar beet assessed in untreated plots (BBCH 39 of sugar beet in herbicide treated plots). Six environments, Germany 2013 and 2014.

Environment	Canopy ground cover	Site specific weed composition (percentage of all weeds)
Göttingen 2013	100%	*Chenopodium album* L. (60%), *Matricaria recutita* L. (20%), *Solanum nigrum* L. (10%), *Urtica urens* L. (5%)
Göttingen 2014	100%	*C. album* (70%), *M. recutita* (20%), *Hordeum vulgare* L. (5%)
Angerstein 2013	10%	*C. album* (40%), *M. recutita* (20%), *Sonchus arvensis* L. (10%), *Alopecurus myosuroides* Huds. (30%)
Niedernjesa 2014	40%	*C. album* (70%), *M. recutita* (10%), *A. myosuroides* (10%), *Galium aparine* L. (5%)
Schwüblingsen 2013	90%	*C. album* (40%), *M. recutita* (20%), *Mercurialis annua* L. (20%), *Solanum tuberosum* L. (10%), *Polygonum convolvulus* L. (10%)
Schwüblingsen 2014	100%	*C. album* (30%), *M. recutita* (10%), *M. annua* (20%), *S. tuberosum* (15%), *Senecio vulgaris* L. (20%)

Seedbed was prepared site-specifically. Seeds of a sugar beet genotype non-sensitive to ALS-inhibitor herbicides were provided by KWS Saat SE (Einbeck, Germany). The experimental setup was a four times replicated randomized block design. The size of the six row plots was 21.8 m² with 0.45 m distance between the rows and 0.18 m within the rows. Sugar beets were not harvested and tilled into the soil in the end of October.

Herbicide applications

Herbicides were applied with pneumatic plot sprayers type *Schachtner PSG,* nozzle type Air Induced (low pressure) flat fan - 110-02 (Göttingen, Angerstein, Niedernjesa); type *Agrartest*, nozzle type Agrotop Airmix 110-02 (Schwüblingsen). Used water volume was 200-300 L ha^{-1}, pressure was 250 kPa and velocity was 4.5 km/h.

The requested authorized application rate of F/T (foramsulfuron + thiencarbazone-methyl, 50 g ai L^{-1} + 30 g ai L^{-1}) is 1.00 L ha^{-1} for a single and 0.5 L ha^{-1} for a two time application (Wegener et al. 2015). Treatments 2, 3 and 5 represent possible weed control strategies with F/T (Table 2). Treatment 4 represents the classic weed control strategy including the four most frequently applied ai in Germany: 75 g ai ha^{-1} phenmedipham (PMP), 59 g ai ha^{-1} desmedipham (DMP), 94 g ai ha^{-1} ethofumesate (ETO), 700 g ai ha^{-1} metamitron (MET) (Vasel et al., 2012) and 34 g ai ha^{-1} lenacil (LEN). Active ingredients against monocotyledonous weeds were not included. Treatments 6 and 7 are alternative application strategies for weed control with F/T. Note: registration is requested for treatments 5 and 7. STI was calculated according to Sattler et al. (2007).

Table 2. Application timing, number of applications and standardised treatment index (STI) of different herbicide strategies tested in field trials with sugar beet to evaluate efficacy of an ALS-inhibitor herbicide (F/T)[1] and classic herbicides[2], six environments in Germany in 2013 and 2014.

Treatment	Strategy	Application Code	Number of Applications	STI
1	Untreated		0	0.00
2	1x classic + 1x 1.0 L ha^{-1} F/T	A B*	2	1.47
3	1x 1.0 L ha^{-1} F/T + 1x classic	B A*	2	1.47
4	3x classic	A A* A*	3	1.43
5	2x 0.5 L ha^{-1} F/T	B B*	2	1.00
6	1x 1.0 L ha^{-1} F/T + classic (tankmix)	C	1	1.47
7	1x 1.0 L ha^{-1} F/T	C	1	1.00

A	BBCH 10 of most developed weeds
B	BBCH 12 of CHEAL
C	BBCH 14 of CHEAL
*	or weed regrowth after prior treatment

[1] F/T: 50 g foramsulfuron L^{-1} + 30 g thiencarbazone-methyl L^{-1}

[2] Classic: 1.25 L ha^{-1} Betanal® maxxPro (94 g ai ha^{-1} ethofumesate, 75 g ai ha^{-1} phenmedipham, 59 g ai ha^{-1} desmedipham, 34 g ai ha^{-1} lenacil) + 1.00 L ha^{-1} Goltix® Gold (700 g ai ha^{-1} metamitron)

Assessments of herbicide efficacy

Efficacy was assessed two weeks after herbicide applications. It is indicated as percentage of controlled weeds relatively to the untreated check. It was rated from 0-100%. Final efficacy was assessed at canopy closure (BBCH 39) of the sugar beet. Efficacy was not evaluated for single weed species due to the limited number of environments and their varying weed compositions.

Statistical evaluation

Statistical analysis was carried out with the statistic program SAS version 9.4 (SAS Institute Inc., Cary, NC, USA). The data were tested for normal distribution and variance homogeneity. The data were transformed into angular values. ANOVA and Tukey test ($p \leq 0.05$) were carried out with the procedure PROC GLM. Original data are shown in the figure.

Results

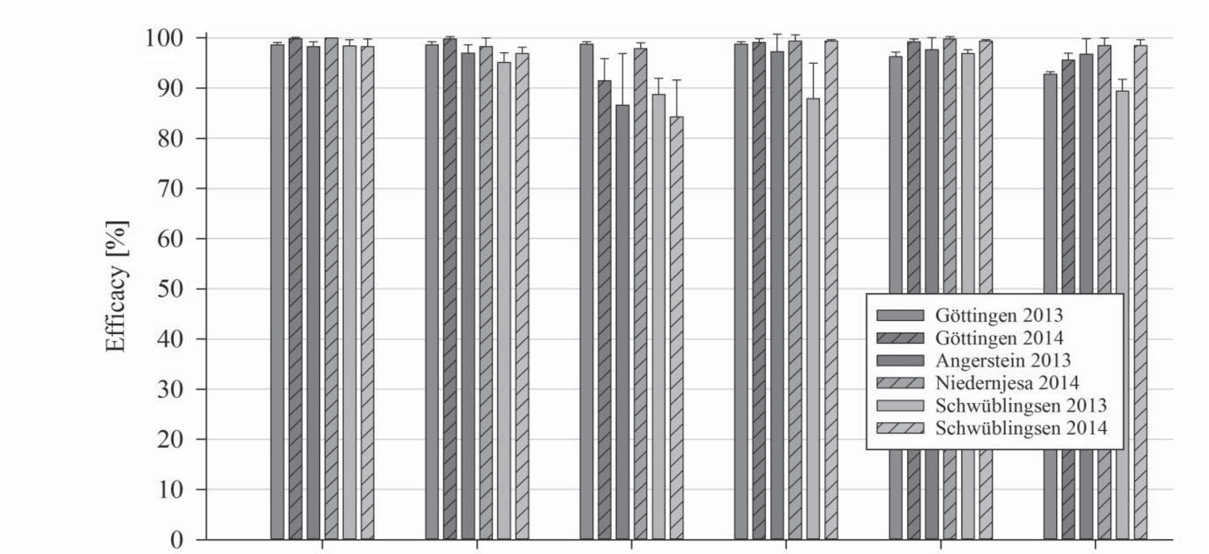
At all environments, *Chenopodium album* L. and *Matricaria recutita* L. occurred and accounted for 40-90% of all weeds (Tab. 1). Site specific weed species also emerged. Weed density was highest at Göttingen 2013, Göttingen 2014 and Schwüblingsen 2014 and lowest at Angerstein 2013 and Niedernjesa 2014.

Herbicide efficacy

Efficacy was significantly influenced by treatment, environment and their interaction (Table 3). Due to the interaction of treatment x environment, a comparison of means for the main factor treatment was not made. Efficacy was highest in treatments 2, 3, 5 and 6 (97% and higher), second highest in treatment 7 (95%) and lowest in treatment 4 (91%) (Figure 1). Lowest efficacy of F/T was observed in treatments 5 and 7 at Schwüblingsen 2013 (88 and 89%) and in treatment 7 at Göttingen 2013 (93%). Highest variation among environments occurred in treatment 4 (classic herbicides) with efficacy being 98% at Göttingen 2013 and Niedernjesa 2014 and 84-92% at the other environments.

Table 3. Analysis of variance for factors influencing efficacy of herbicide strategies in field trials with sugar beet, six environments in Germany 2013 and 2014. *: significant at p≤0.0001; DF: degrees of freedom.**

	DF	F-Value	Pr > F
Treatment	5	34.17	***
Environment	5	32.27	***
Treatment x environment	25	7.56	***



Treatment	2	3	4	5	6	7
No. of Applications	2	2	3	2	1	1
Herbicide	BG_F/T	F/T_BG	BG	F/T	BG+F/T	F/T

Figure 1. Efficacy of herbicide treatments with foramsulfuron + thiencarbazone-methyl (F/T) and classic herbicides (BG) in various combinations assessed in field trials with sugar beet (BBCH 39). Six environments, Germany 2013 and 2014, n = 4. 1x F/T: 50 g foramsulfuron ha^{-1} + 30 g thiencarbazone-methyl ha^{-1}; 1x classic herbicides: 94 g ai ha^{-1} ethofumesate, 75 g ai ha^{-1} phenmedipham, 59 g ai ha^{-1} desmedipham, 34 g ai ha^{-1} lenacil + 700 g ai ha^{-1} metamitron. For details see Table 2.

Efficacy against *C. album* was highest in treatments 2, 3, 5 and 6, in treatment 5 with exception of Schwüblingsen 2013 (Figure 2). *M. annua* and *S. tuberosum* occurred at Schwüblingsen 2013 and 2014 (Table 1). Efficacy of treatments 2, 3, 5, 6 and 7 against both was 96% and higher in both years (Figure 3). Mean efficacy of treatment 4 (3 applications of classic herbicides) was 90 and 72% against *M. annua* and 89 and 96% against *S. tuberosum* in 2013 and 2014, respectively.

Standardised treatment indexes were 1.00 when only F/T was applied, 1.43 in the classic strategy and 1.47 when F/T and classic herbicides were combined (Table 2).

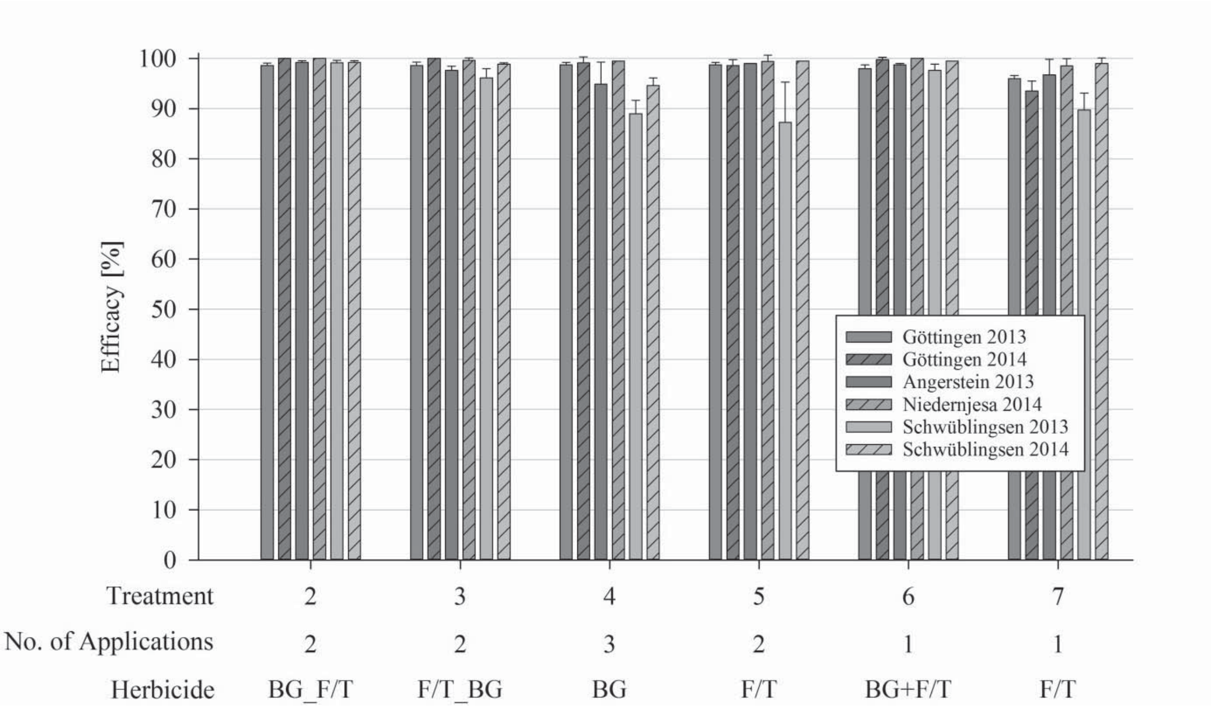


Figure 2. Efficacy of herbicide treatments with foramsulfuron + thiencarbazone-methyl (F/T) and classic herbicides (BG) in various combinations against *Chenopodium album* L. assessed in field trials with sugar beet (BBCH 39). Six environments, Germany 2013 and 2014, n = 4. 1x F/T: 50 g foramsulfuron ha^{-1} + 30 g thiencarbazone-methyl ha^{-1}; 1x classic herbicides: 94 g ai ha^{-1} ethofumesate, 75 g ai ha^{-1} phenmedipham, 59 g ai ha^{-1} desmedipham, 34 g ai ha^{-1} lenacil + 700 g ai ha^{-1} metamitron. For details see Table 2.

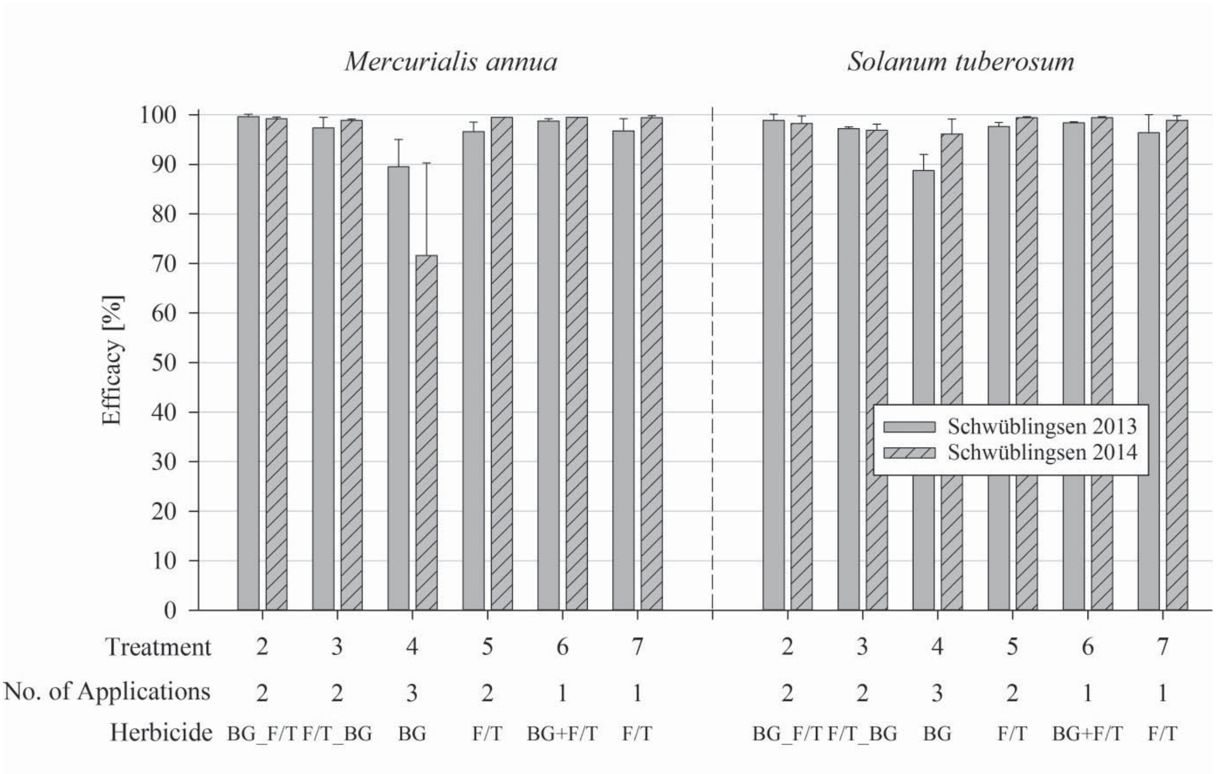


Figure 3. Efficacy of herbicide treatments with foramsulfuron + thiencarbazone-methyl (F/T) and classic herbicides (BG) in various combinations against *Mercurialis annua* L. (left) and *Solanum tuberosum* L. (right) assessed in field trials with sugar beet (BBCH 39), Schwüblingsen 2013 and 2014, n = 4. 1x F/T: 50 g foramsulfuron ha^{-1} + 30 g thiencarbazone-methyl ha^{-1}; 1x classic herbicides: 94 g ai ha^{-1} ethofumesate, 75 g ai ha^{-1} phenmedipham, 59 g ai ha^{-1} desmedipham, 34 g ai ha^{-1} lenacil + 700 g ai ha^{-1} metamitron. For details see Table 2.

Discussion

Weed control strategies with F/T had higher efficacy than classic herbicides as also described by Wegener et al. (2015). Efficacy was relatively low in treatments 5 (2x F/T) and 7 (1x F/T) at Schwüblingsen 2013 which resulted from a too late application as BBCH of *C. album* was beyond 12-14 in treatment 5 and beyond 14-16 in treatment 7 (data not shown). A similar effect was observed for treatment 7 at Göttingen 2013 and 2014, where single plants of *C. album* were beyond BBCH 16 and could not be controlled. This is in accordance with results by Wendt et al. (2016), who determined BBCH 14 and 16 of *C. album* as the latest development stage for weed control with 0.50 or 1.00 L ha^{-1} F/T, respectively. This has to be considered in herbicide strategies with F/T. The connection between overall efficacy and efficacy against *C. album* points to the high importance of application timing and makes *C. album* to the key species for F/T strategies.

Limitations of the classic herbicide strategy (treatment 4) became obvious at four environments. Its efficacy was insufficient against the severe infestation with *C. album* and *M. recutita* at Göttingen 2014. Another aspect was that no ai against monocotyledonous weeds (e.g. propaquizafop or fluazifop-P) were included which caused the high occurrence rate of *Alopecurus myosuroides* Huds. at Angerstein 2013. These finds are supported by studies with similar classic herbicide strategies. In experiments by Abdollahi and Ghadiri (2004), control of *Amaranthus retroflexus* L. and *C. album* was 96 and 97% compared to 90-94% of *Echinochloa crus-galli* L. when 230 g ai ha^{-1} each of PMP, DMP and ETO were applied. In studies by Deveikyte and Seibutis (2008, 2015), the maximum control of *C. album* was 91%. It was achieved with 91 g ai ha^{-1} PMP, 71 g ai ha^{-1} DMP, 112 g ai ha^{-1} ETO and 525 g ai ha^{-1} MET.

The low efficacy against *M. annua* in treatment 4 is in accordance with results of the coordinated herbicide trials in Germany in 2014 and 2015 where three applications of only two herbicides also had a low efficacy against this fast growing weed species (IfZ, 2014, 2015). Furthermore, the control of *S. tuberosum* is difficult (May and Wilson (2006). To date, chemical treatments have low efficacy and an improvement of mechanical methods was suggested (Nieuwenhuizen et al., 2007).

It is thus concluded that either an additional ai or a fourth application is necessary for a constantly high weed control with a classic herbicide strategy. In this case, efficacy of classic herbicides towards *C. album* and *Polygonum convolvulus* L. can be beyond 97% (IfZ, 2014, 2015). Compared to the classic treatments, efficacy of strategies with F/T was higher at Schwüblingsen 2013 and 2014 showing an improved weed control on sandy soils. In general, strategies including FT should also be site-specifically adapted for different weed populations and densities.

Conclusions and Outlook

The high efficacy of F/T points to an option for a more flexible and easier weed control in sugar beet cultivation (Wegener et al., 2015; Wendt et al., 2016). This could be of importance as the populations of the dominant weeds in Germany (*C. album*, *M. annua* and *M. recutita*) have increased (Buhre et al., 2011; Vasel et al., 2012). Furthermore, the treatments with F/T indicated advantages for the control of volunteer potato and provide an option to control weed beet as well (Wegener et al., 2015). Additionally, this is accompanied by a reduction of the plant protection intensity as the STI of F/T treatments was lower (1.00-1.47) than the current mean in Germany (2.64; PAPA, 2016). Further studies are necessary to gain more data on efficacy against different weed populations and densities. However, potential risks of a weed control system with F/T, e.g. gene flow and development of weed resistance (Kudsk and Streibig, 2003), must be preventively excluded necessitating full control of volunteers of non-sensitive sugar beet. First, an effective resistance management is required due to the increasing number of weed species resistant against ALS-inhibitors (Heap, 2013). Thus, herbicide strategies with F/T only should not be applied.

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Kapitel 5

Selectivity of foramsulfuron + thiencarbazone-methyl and classic herbicides in sensitive and non-sensitive sugar beet genotypes

Selectivity of foramsulfuron + thiencarbazone-methyl and classic herbicides in sensitive and non-sensitive sugar beet genotypes

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Weed Research (im Druck)

Summary

A new herbicide for sugar beet cultivation using the ALS-inhibiting active ingredients foramsulfuron and thiencarbazone-methyl is under approval in the EU member states. Genotypes that are non-sensitive to this herbicide are currently under development. Selectivity of the ALS-inhibiting herbicide and yield response of the non-sensitive genotypes might be relevant to meet the requirements for variety registration. To evaluate these issues, six field trials were conducted in Germany in 2013 and 2014. Classic herbicides and the ALS-inhibitor herbicide were applied in dosages of up to fourfold the authorized (or applied for) application rates. The ALS-inhibitor herbicide did not cause any significant phytotoxicity and had no effect on leaf area index at a single, double or fourfold dosage. By contrast, classic herbicides had significant negative effects as early as at single dosage. At fourfold dosage, they caused 41% phytotoxicity and reduced leaf area index by 35%. The relative yield difference between ALS-inhibitor and classic herbicide treatments was 8.6 and 17.4 percentage points of white sugar yield at double and fourfold dosage, respectively. The ALS-inhibitor herbicide thus showed higher selectivity than the classic herbicides. In the registration process, the resulting yield advantage could balance a possible yield penalty of non-sensitive genotypes. The introduction of a new system for weed control could improve application flexibility and control of troublesome weeds in sugar beet.

Keywords: ALS-inhibitors, phytotoxicity, leaf area index, yield, root quality, white sugar yield

Introduction

Weed control is one of the central measures to prevent yield losses in sugar beet (*Beta vulgaris* L. ssp. *vulgaris* var. *altissima* Döll) cultivation. Apart from introducing new combinations or formulations of already available active ingredients (a.i.), the strategy of weed control in sugar beet has not changed in Central Europe since the 1980s (Petersen, 2003). In the classic herbicide strategy, three to five a.i. are applied, starting at the cotyledon stage of the weeds. Application is repeated three to four times at 5 to 14 day intervals (Cioni & Maines, 2011; Vasel *et al.*, 2012) until competitiveness of the sugar beet is sufficient to suppress further weed development.

A system with more flexibility in application timing, an overall lower number of applications and high efficacy against weeds would overcome disadvantages of the classic herbicide strategy in sugar beet cultivation. One option is the use of acetolactate synthase (ALS)-inhibitor herbicides. This mode of action comprises five chemical groups with varying efficacy against dicotyledonous and monocotyledonous weeds in many crops. Two applications of thiencarbazone-methyl suffice to achieve high efficacy in maize cultivation (Santel, 2012), where weed composition is similar to that in sugar beet (Keller *et al.*, 2014; Wegener & Balz, 2014). The use of ALS-inhibitors in sugar beet has been limited up to now, as classic sugar beet are sensitive to ALS-inhibitors, and even low concentrations remaining from previous applications on pre-crops can damage the crop (Azimi *et al.*, 2014). A new herbicide for sugar beet cultivation containing the ALS-inhibitors foramsulfuron and thiencarbazone-methyl – referred to in the following as 'F/T' – is currently being reviewed for EU-wide approval (KWS, 2015). Compared to classic herbicides, applications of F/T can start later (beyond the cotyledon stage of the weeds) and the duration of soil activity is longer (Santel, 2012; Wendt *et al.*, 2016 and 2017).

F/T can only be used on genotypes that are non-sensitive to the herbicide, and these are currently under development (KWS, 2015). Prior to registration, the performance of new sugar beet genotypes is compared to varieties that are already registered. Varieties with new traits such as non-sensitivity to herbicides are expected to have a yield penalty due to a time delay in the breeding process (Märländer, 1996) and thus might need further beneficial features to meet the requirements for registration. The selectivity of F/T used on non-sensitive genotypes is expected to be high (Wegener *et al.*, 2015), and this might be considered in the registration process to be an advantageous characteristic that balances the lower yield performance.

Selectivity is the property of herbicides to control weeds without damaging the crop (Aust *et al.*, 2005). If selectivity is too low, herbicide applications cause phytotoxicity to the crop. Particularly at early stages, sugar beet is susceptible to high dosages of herbicides (Dale *et al.*, 2006; Hamouzová *et al.*, 2013), and thus herbicide applications require precise timing. Phytotoxicity can range from slight reversible symptoms like bleaching to plant loss, and is often linked to yield losses (Pfleiderer *et al.*, 2001). The anticipated high selectivity of F/T in combination with a non-sensitive variety (Wegener *et al.*, 2015) might have yield advantages over the application of classic herbicides with lower selectivity.

The aim of the present study was thus to examine differences between F/T and classic herbicides in field trials with sugar beet regarding i) phytotoxicity and ii) leaf area index and iii) to measure quality and yield effects of F/T dosage in comparison to classic sugar beet herbicides. The field trial was, for this reason, set up in such way as to induce phytotoxicity in order to make it possible to assess the selectivity effect, which is usually difficult to determine.

Materials and Methods

Six hand weeded sugar beet field trials were conducted in Northern Germany in 2013 and 2014. Four trials were located on loamy soils, two near Göttingen and two near Einbeck, and two trials were located on sandy soils near Hanover (Table 1).

Table 1. Trial sites, soil data and cultivation measures in sugar beet field trials for evaluation of selectivity of foramsulfuron (50 g ha^{-1}) + thiencarbazone-methyl (30 g ha^{-1}), Germany 2013 and 2014.

	Soil		Date of		
	Texture	pH value	Sowing	Applications	Harvest
2013					
Göttingen	loam	6.6	25.4.	14.5. - 12.6.	24.10.
Schwüblingsen	sand	5.8	30.4.	17.5. - 19.6.	23.10.
Einbeck	loam	6.9	21.4.	14.5. - 18.6.	25.10.
2014					
Göttingen	loam	6.9	24.3.	17.4. - 21.5.	29.10.
Schwüblingsen	sand	6.0	01.4.	24.4. - 30.5.	30.10.
Einbeck	loam	6.9	03.4.	29.4. - 30.5.	28.10.

Seedbed was prepared according to local practice. Seeds of a sugar beet genotype non-sensitive to the F/T herbicide (experimental hybrid, not registered) were provided by KWS SAAT SE, Einbeck. Field trials were set up with four replications in a randomized complete block design using six row plots with a size of 21.8 m² (Einbeck 20.0 m²). Row distance was 0.45 m and seeding distance within the rows 0.06 to 0.07 m. To ensure a homogenous plant population, sugar beets were singled to 0.18 m distance at BBCH (Meier *et al.*, 1993) stage 10 to 14. This sugar beet specific trial layout is essential to minimise variation caused by differences in plant density, which would presumably cause higher yield effects than phytotoxicity.

Table 2. Weather conditions at trial sites, Germany 2013 and 2014

	Air temperature [°C 2 m]*					Precipitation [mm]*					Humidity [%]*				
	Apr	May	Jun	Jul	Aug	Apr	May	Jun	Jul	Aug	Apr	May	Jun	Jul	Aug
2013															
Göttingen	n.a.	13	18	20	18	n.a.	102	193	293	87	n.a.	82	75	76	73
Schwüblingsen	n.a.	12	16	19	18	n.a.	129	21	71	37	n.a.	82	75	78	73
Einbeck	8	12	16	19	18	35	135	21	50	29	74	83	78	78	73
2014															
Göttingen	11	12	15	20	16	24	93	82	105	73	87	89	89	89	92
Schwüblingsen	12	13	16	20	17	45	102	64	100	41	61	61	61	57	60
Einbeck	11	12	15	19	16	39	90	68	117	74	83	84	82	81	81

n.a. not available
*: monthly mean

Herbicides were applied with pneumatic plot sprayers (type *Schachtner PSG,* nozzle type Air Induced (low pressure) flat fan - 110 02 used at Göttingen and Schwüblingsen; type *Agrotop* field-plot sprayer, nozzle type Lundmark F80/015 used at Einbeck). Water volume was 200-300 L ha^{-1}, pressure was 250 kPa and velocity was about 4.5 km h^{-1}.

Local weather data were recorded at all environments (Table 2) and additionally documented during applications.

Herbicide Treatments

Possible weed control strategies with F/T based on the expected approval (single application of 1.00 L ha^{-1} or two applications of 0.50 L ha^{-1}) were compared with the current weed control strategy using classic herbicides (Table 3). F/T contained foramsulfuron (50 g ha^{-1}) and thiencarbazone-methyl (30 g ha^{-1}) (OD, Bayer CropScience Deutschland GmbH). Active ingredients in the classic herbicides were desmedipham (DMP; 47 g ha^{-1}), phenmedipham (PMP; 60 g ha^{-1}), ethofumesate (ETO; 75 g ha^{-1}) and lenacil (LEN; 27 g ha^{-1}) in Betanal® maxxPro® (OD, Bayer CropScience Deutschland GmbH), metamitron (MTM; 700 g ha^{-1}) in Goltix® Gold (SC, Adama) and dimethenamid-P (DIM; 72 g ha^{-1}) in Spectrum® (EC, BASF SE).

To induce phytotoxicity, the single, double and fourfold dosages of the authorized application rates (as anticipated for F/T) were applied. The single and double dosages are relevant for practice e.g. at overlapping spraying areas. The fourfold dosage was applied to prove the anticipated selectivity effects of F/T. Treatments 2-4 and 10-12 follow the post emergence timing of the classic weed control strategy, with three applications to compare F/T and classic herbicides directly. Treatments 5-9 exemplify weed control strategies with F/T for commercial use at later growth stages and with only one or two applications (added by increasing dosages). Treatments 13-16 should reveal possible genotypic effects; they were not tested at Einbeck. Due to the high number of treatments and the intended variation between environments that represent typical sugar beet growing areas in Central Europe, an interaction of environment and treatment was expected.

Table 3. Herbicide treatments in field trials with sugar beet to evaluate selectivity of foramsulfuron (50 g ha^{-1}) + thiencarbazone-methyl (30 g ha^{-1}). Treatments 1-12 at six environments, treatments 13-16 at four environments, Germany 2013 and 2014.

Treatment	Genotype	Herbicide	BBCH						
			10	12	12-14	14	14-16	16	x$^{\#}$-fold
			L ha^{-1}						dosage
1	Non sensitive	Untreated							0
2	Non sensitive	F/T†	0.33		0.33		0.33		1
3	Non sensitive	F/T	0.66		0.66		0.66		2
4	Non sensitive	F/T	1.32		1.32		1.32		4
5	Non sensitive	F/T				1			1
6	Non sensitive	F/T				2			2
7	Non sensitive	F/T		0.5				0.5	1
8	Non sensitive	F/T		1				1	2
9	Non sensitive	F/T		2				2	4
10	Non sensitive	Classic*	1/ 1/ 0.1		1/ 1/ 0.1		1/ 1/ 0.1		1
11	Non sensitive	Classic	2/ 2/ 0.2		2/ 2/ 0.2		2/ 2/ 0.2		2
12	Non sensitive	Classic	4/ 4/ 0.4		4/ 4/ 0.4		4/ 4/ 0.4		4
13	Sensitive	Untreated							0
14	Sensitive	Classic	1/ 1/ 0.1		1/ 1/ 0.1		1/ 1/ 0.1		1
15	Sensitive	Classic	2/ 2/ 0.2		2/ 2/ 0.2		2/ 2/ 0.2		2
16	Sensitive	Classic	4/ 4/ 0.4		4/ 4/ 0.4		4/ 4/ 0.4		4

Classic: 1-fold dosage: desmedipham (47 g ha^{-1}), phenmedipham (60 g ha^{-1}), ethofumesat (75 g ha^{-1}), lenacil (27 g ha^{-1}), metamitron (700 g ha^{-1}), dimethenamid-P (72 g ha^{-1})

† F/T: 1-fold dosage: foramsulfuron (50 g ha^{-1}) + thiencarbazone-methyl (30 g ha^{-1})

\# x-fold: in accordance with commonly used / anticipated authorized (F/T) application rate

Assessments of Phytotoxicity

All weeds in the untreated check and those remaining in the treated plots were removed by hand hoeing or mechanical hoeing to avoid any competitive effects. Phytotoxicity was evaluated according to the EPPO Standard PP 1/135(3). Evaluated symptoms were: modifications in the development cycle (delay in growth), thinning (number of plants), colour modification (e.g. darker green or yellowing), necrosis and deformations (e.g. twisting or crinkling). All symptoms were merged to a mean value for every plot, e.g. 100% of phytotoxicity means no surviving sugar beet plants. Phytotoxicity was assessed one week after each application. To compare phytotoxicity between treatments, the assessment conducted one week after the final application was used as reference date.

Measurements of Leaf Area Index

The leaf area index (LAI) was measured with an LAI-2000 (LI-COR, Lincoln, USA) according to Röver and Koch (1995). Measurements started two to three weeks after the final herbicide application at BBCH stage 31 of sugar beet. Four to five measurements per plot were conducted until visual differences between treatments disappeared.

Determination of yield and quality parameters

Three core rows (10.8 m², 10.0 m² at Einbeck) per plot were mechanically harvested at the end of October (Table 1). Processing was one to three days later. Root yield (RY), sucrose content and concentrations of potassium, sodium and amino-nitrogen were determined using an automatic beet laboratory system (Venema Installations, Eemshaven, NL) at the Institute of Sugar Beet Research following standardised procedures (Hoffmann, 2006). White sugar yield (WSY) was calculated according to standard formulas (Märländer *et al.*, 2003). A direct comparison of absolute yield between genotypes was not made, because the non-sensitive genotype was an experimental hybrid not intended for registration.

Statistical Analysis

Statistical analysis was carried out using the statistic program SAS version 9.4 (SAS Institute Inc., Cary, NC, USA). Genotypes were evaluated separately, as the sensitive genotype was not tested at Einbeck. Evaluation was based on absolute values. After testing for variance homogeneity and normal distribution, phytotoxicity values were altered by angular transformation to fulfil the requirements for carrying out ANOVA. For the other parameters, original data were used. The procedure PROC MIXED was employed for two way ANOVA of all measured data followed by multiple Tukey tests ($p \leq 0.05$). To compare the effect of increased dosage for the ALS-inhibiting herbicide and classic herbicides, treatments with single dosage (treatments 2, 5 and 7), twofold dosage (treatments 3, 6 and 8) and fourfold dosage (treatments 4 and 9) of the ALS-inhibiting herbicide were summarised. This caused an unbalanced design and results were therefore calculated as least squares means.

Results

Environment significantly influenced all tested parameters (Tables 4, 5). Herbicide treatments had a significant effect on phytotoxicity, LAI and RY of both genotypes and on WSY of the non-sensitive genotype, but did not influence quality (sugar content, potassium, sodium and amino-nitrogen concentrations). An interaction of environment and herbicide treatment regarding phytotoxicity and leaf area index also occurred.

Table 4. Analysis of variance for factors influencing selectivity indicators of an ALS-inhibitor herbicide (1-fold dosage: foramsulfuron, 50 g ha^{-1}; thiencarbazone-methyl, 30 g ha^{-1}) and classic herbicides (1-fold dosage: desmedipham, 47 g ha^{-1}; phenmedipham, 60 g ha^{-1}; ethofumesat, 75 g ha^{-1}; lenacil, 27 g ha^{-1}; metamitron, 700 g ha^{-1}; dimethenamid-P, 72 g ha^{-1}) applied to a non-sensitive sugar beet genotype. Field trials at six environments, Germany 2013 and 2014. * and *: significant at p≤0.05 and p≤0.0001; n.s.: not significant. DF: degrees of freedom.**

Non sensitive genotype	Environment		Treatment		Environment x treatment	
	DF: 5		DF: 11		DF: 55	
	F-Value	Pr>F	F-Value	Pr>F	F-Value	Pr>F
Phytotoxicity	12.50	***	176.35	***	7.91	***
Leaf area index	377.15	***	40.92	***	4.32	***
Root yield	279.15	***	7.09	***	1.21	n.s.
Sugar content	142.82	***	0.36	n.s.	0.33	n.s.
White sugar yield	141.94	***	4.31	***	0.92	n.s.
Potassium	600.39	***	1.97	n.s.	1.00	n.s.
Sodium	186.08	***	0.92	n.s.	0.51	n.s.
Amino-N	439.98	***	1.33	n.s.	1.48	n.s.

Table 5. Analysis of variance for factors influencing selectivity indicators of classic herbicides (1-fold dosage: desmedipham, 47 g ha^{-1}; phenmedipham, 60 g ha^{-1}; ethofumesat, 75 g ha^{-1}; lenacil, 27 g ha^{-1}; metamitron, 700 g ha^{-1}; dimethenamid-P, 72 g ha^{-1}) applied to a sugar beet genotype sensitive to acetolactate synthase-inhibitor herbicides. Field trials at four environments, Germany 2013 and 2014. * and *: significant at $p \leq 0.05$ and $p \leq 0.0001$; n.s.: not significant. DF: degrees of freedom.**

Sensitive genotype	Environment		Treatment		Environment x treatment	
	DF: 3		DF: 3		DF: 9	
	F-Value	Pr>F	F-Value	Pr>F	F-Value	Pr>F
Phytotoxicity	97.36.00	***	121.96	***	13.20	***
Leaf area index	28.97	***	23.14	***	5.95	***
Root yield	111.84	***	4.12	*	1.15	n.s.
Sugar content	58.98	***	1.00	n.s.	0.51	n.s.
White sugar yield	87.21	***	2.58	n.s.	1.19	n.s.
Potassium	187.80	***	0.62	n.s.	0.55	n.s.
Sodium	127.19	***	1.34	n.s.	0.69	n.s.
Amino-N	24.67	***	0.30	n.s.	0.24	n.s.

In the F/T treatments, only minimal phytotoxicity symptoms occurred (Fig. 1). No differentiation was found between application of F/T at early growth stages (treatments 2-4), single application (treatments 5+6) or split application (treatments 7-9). In contrast, the classic treatments caused significant effects, even at single dosage, and phytotoxicity significantly increased in both genotypes with increased dosage. It was highest (up to 75%) in treatment 12 (non-sensitive genotype treated with fourfold dosage of classic herbicides). The dominant symptoms were colour modifications and deformations when phytotoxicity was between 2 and 10%, and growth depression and plant losses when it was above 10%. Phytotoxicity symptoms such as deformation and yellowing remained visible until two weeks after the last application, and growth depressions continued longer.

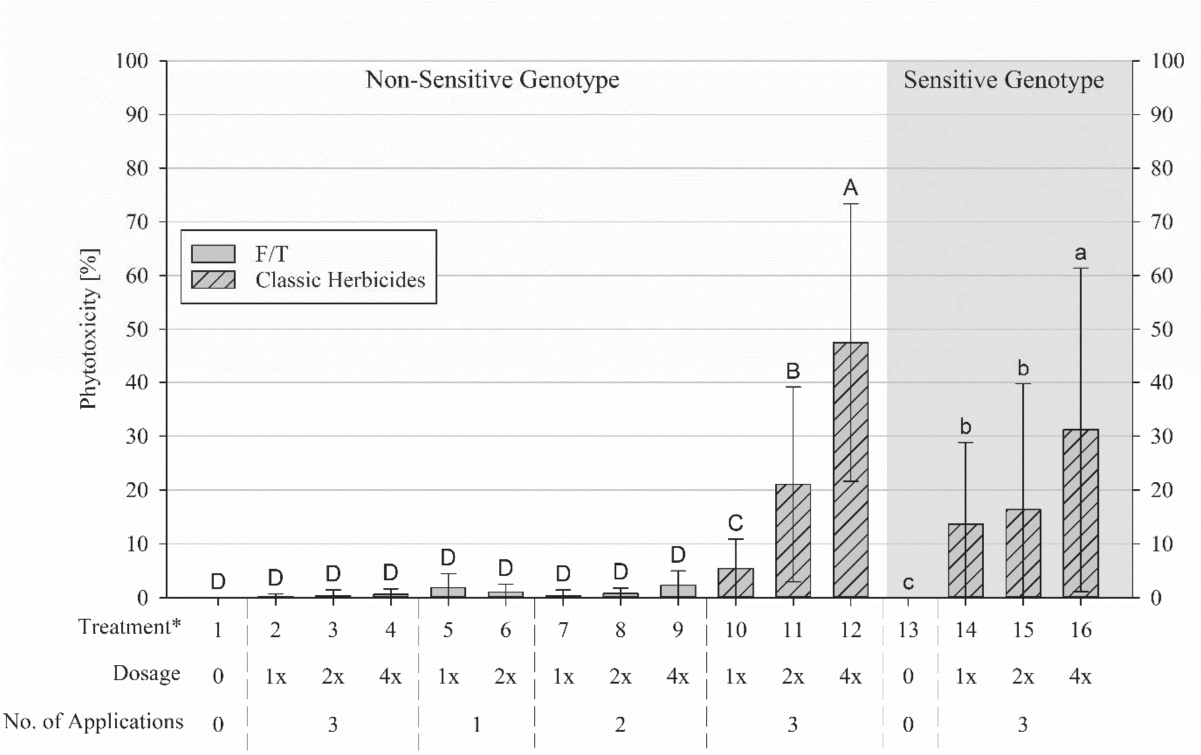

Figure 1. Phytotoxicity values of two sugar beet genotypes treated with F/T (foramsulfuron + thiencarbazone-methyl) or classic herbicides (desmedipham, phenmedipham, ethofumesate, lenacil, metamitron and dimethenamid-P) at different dosages. Treatments 1-12 at six environments, treatments 13-16 at four environments, Germany 2013 and 2014. Different capital letters and different small letters indicate significant differences between treatments 1-12 and 13-16, respectively (Tukey, p≤0.05). *: for details see Table 3.

No effects on LAI occurred in the F/T treatments (Fig. 2). At increased dosage of the classical herbicides, a significant decrease of LAI was proven at the first measurement date for both genotypes (Fig. 2; treatments 10-12 and 14-16). The relative decrease of LAI was greater in the non-sensitive than in the sensitive genotype.

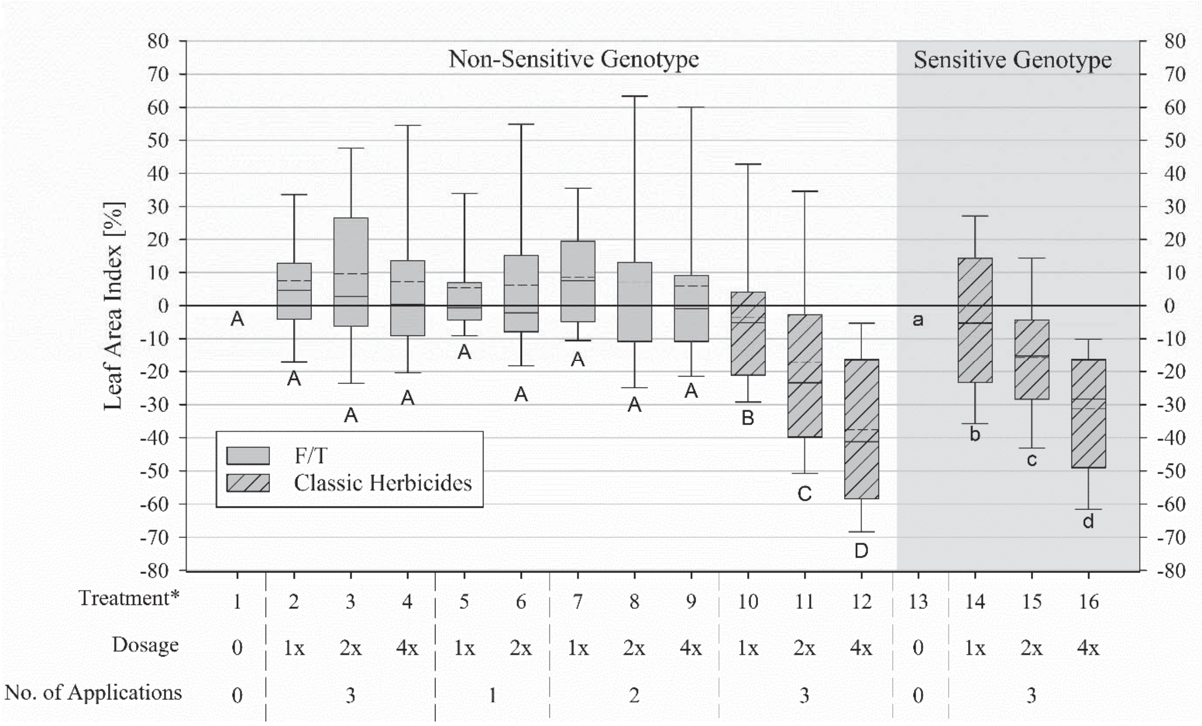

Figure 2. Relative leaf area index of two sugar beet genotypes 2 weeks after the final application of F/T (foramsulfuron + thiencarbazone-methyl) or classic herbicides (desmedipham, phenmedipham, ethofumesate, lenacil, metamitron and dimethenamid-P) at different dosages. Treatments 1-12 at six environments, treatments 13-16 at four environments in Germany 2013 and 2014. 0% = untreated check (treatments 1 or 13, respectively). Solid lines within boxes indicate the median, dashed lines the mean. Different capital letters and different small letters indicate significant differences between treatments 1-12 and 13-16, respectively (Tukey, p≤0.05). *: for details see Table 3.

In the course of the measurements, LAI increased in all four treatments (Fig. 3). At two- and fourfold dosage of F/T (treatments 3, 6, 8 and 4, 9), mean LAI was on the same level as in the untreated check and significantly higher than at two- and fourfold dosage of the classic herbicides (treatments 11 and 12). In the classic herbicide treatments, LAI was significantly lower than in the untreated check. These differences decreased in later measurements.

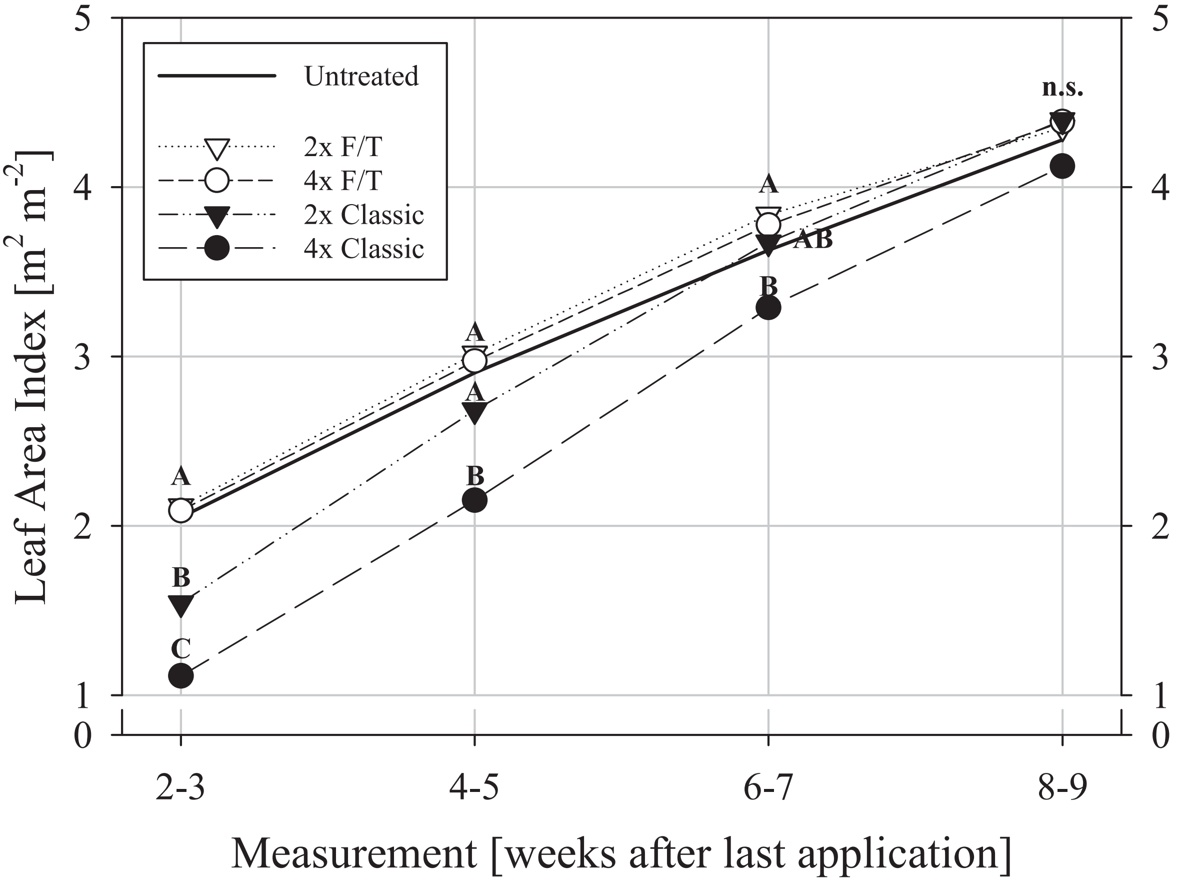

Figure 3. Mean leaf area index of sugar beet at different measurement times after application of F/T (foramsulfuron + thiencarbazone-methyl) or classic herbicides (desmedipham, phenmedipham, ethofumesate, lenacil, metamitron and dimethenamid-P) at different dosages. Six environments in Germany 2013 and 2014. Different letters indicate significant differences between LAI values per measurement (Tukey, p≤0.05).

Relative RY was not affected by F/T (Fig. 4; treatments 2-10). At the fourfold dosage of classic herbicides, it decreased significantly in both genotypes (treatments 12 and 16). This effect was greater in the non-sensitive than in the sensitive genotype. Differences to the untreated check were -1.9% and +0.4% in treatments 11 and 15 and -9.5% and -6.7% in treatments 12 and 16.

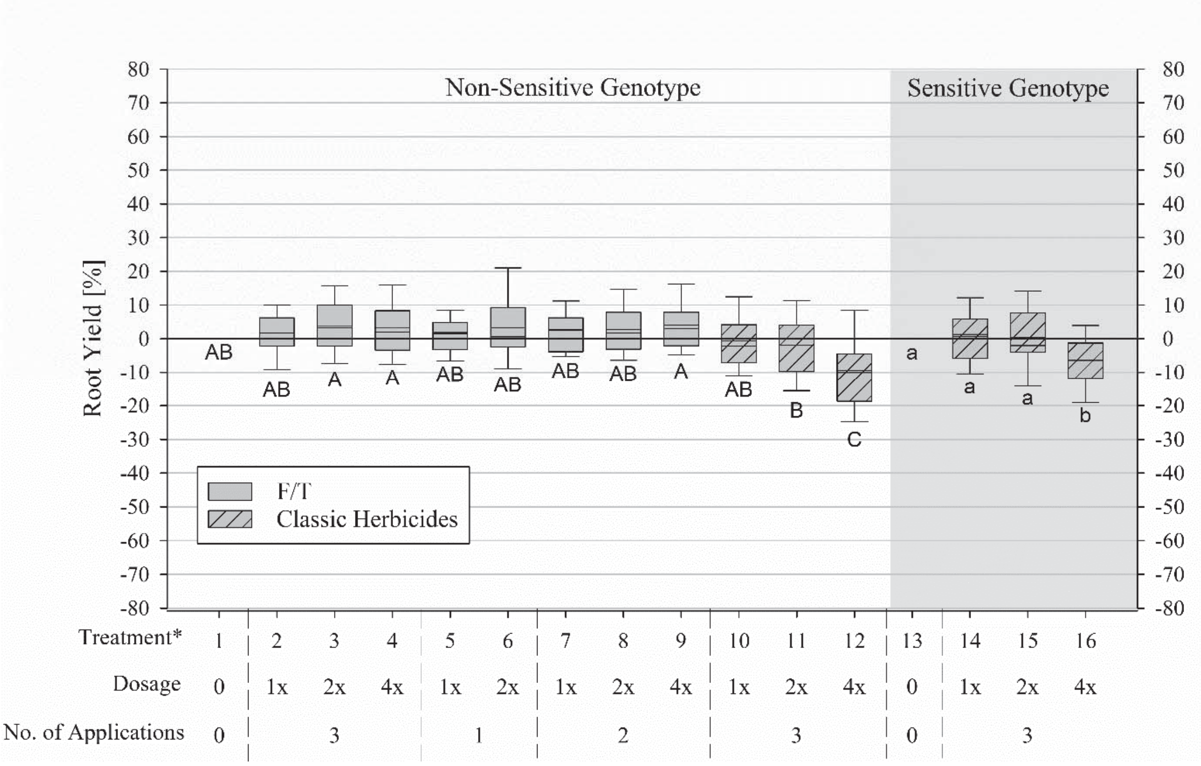

Figure 4. Relative root yield of two sugar beet genotypes treated with F/T (foramsulfuron + thiencarbazone-methyl) or classic herbicides (desmedipham, phenmedipham, ethofumesate, lenacil, metamitron and dimethenamid-P) at different dosages. Treatments 1-12 at six environments, treatments 13-16 at four environments, Germany 2013 and 2014. 0% = untreated check (treatment 1 or 13, respectively). Solid lines within boxes indicate the median, dashed lines the mean. Different capital letters and different small letters indicate significant differences between treatments 1-12 or 13-16, respectively (Tukey, $p \leq 0.05$). *: for details see Table 3.

Across all herbicide treatments, relative LAI was more closely related to phytotoxicity than relative RY (Fig. 5). Variation was high in both parameters and R² was 0.34 for RY and 0.53 for LAI. Nevertheless, the LAI decreased by 60% and RY by 20% at a phytotoxicity level of 80%. Relative LAI had a high variability up to 170% at a phytotoxicity level of 0%.

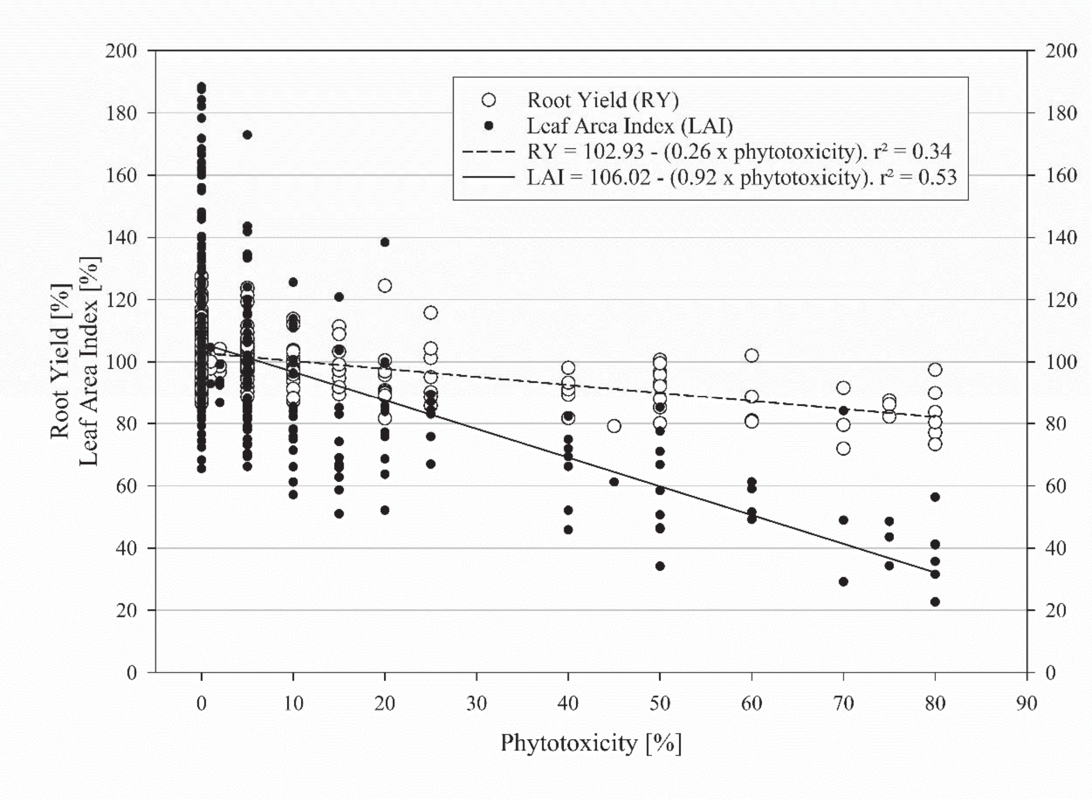

Figure 5. Relation between relative root yield and relative leaf area index of a sugar beet genotype non-sensitive to ALS-inhibitors and phytotoxicity assessed 7 to 14 days after the final application of classic herbicides in May/June. Beets were harvested in late October and LAI was measured 2-3 weeks after final herbicide application. 100% = untreated check; *: significant at p≤0.001, n=309.**

Averaged over all environments, relative white sugar yield of the non-sensitive genotype was not affected by F/T at any dosage, but it decreased significantly at the fourfold dosage of the classic herbicides (Table 6). The dosage effect varied among herbicides and environments. In the sensitive genotype, WSY also decreased at the fourfold dosage of classic herbicides, but this effect was not significant.

Table 6. Relative white sugar yield [%] of sugar beet treated with F/T (foramsulfuron + thiencarbazone-methyl) or classic herbicides (desmedipham, phenmedipham, ethofumesate, lenacil, metamitron and dimethenamid-P) at different dosages (relative to authorized application rate (dosage=1)). Six environments, Germany 2013 and 2014. Genotypes were sensitive or non-sensitive to ALS-inhibitor herbicides. Different capital letters and different small letters indicate significant differences between dosages within each row (Tukey, p≤0.05). *: untreated check; $^{\#}$: sensitive genotype was not grown in Einbeck. Mean white sugar yield in untreated check: non-sensitive genotype 11.41 t ha^{-1}, sensitive genotype 13.02 t ha^{-1}.

	Non-sensitive genotype							Sensitive genotype			
	F/T				Classic herbicides			Classic herbicides			
	dosage										
	0*	1	2	4	1	2	4	0*	1	2	4
2013											
Göttingen	100.0	106.4	106.9	110.4	107.3	108.9	95.1	100.0	105.8	102.9	99.6
	b	a	a	a	a	a	b	B	A	AB	B
Schwüblingsen	100.0	93.9	98.5	91.8	79.3	86.4	83.1	100.0	104.5	108.3	90.3
	ab	abc	a	abc	c	abc	bc	AB	A	A	B
Einbeck $^{\#}$	100.0	98.3	98.4	97.7	89.4	82.0	76.0				
	a	a	a	a	b	c	c				
2014											
Göttingen	100.0	92.5	88.3	90.0	83.4	84.5	76.6	100.0	101.0	101.1	96.4
	a	ab	b	ab	bc	bc	c	A	A	A	A
Schwüblingsen	100.0	105.3	105.9	112.4	101.6	97.1	93.9	100.0	90.1	90.1	88.5
	ab	ab	ab	a	ab	b	b	A	A	A	A
Einbeck$^{\#}$	100.0	98.0	97.7	95.2	90.1	84.0	70.3				
	ab	a	a	ab	bc	c	d				
Mean	100.0	99.3	99.3	99.8	92.7	90.7	82.4	100.0	100.0	100.0	94.2
	ab	ab	a	a	ab	bc	c	A	A	A	A

Discussion

The aim of the present study was to examine the selectivity of F/T in comparison to classic herbicides using phytotoxicity, LAI, RY and WSY as indicators. Although an interaction of treatment and environment occurred in phytotoxicity and LAI, the discussion will focus on treatments rather than on environment, as herbicide and dosage effects were the main objectives of the study.

Phytotoxicity

The high selectivity of F/T was independent of application timing. Similar findings were reported by Wegener *et al*. (2015) for double the F/T dosage expected to be approved. In contrast, dosage dependent phytotoxicity of the classic herbicides was found in both genotypes, as has been demonstrated in several previous experiments (Bethlenfalvay & Norris, 1975 and 1977; Dale *et al*., 2006; Hamouzová *et al*., 2013). In these studies, higher phytotoxicity was associated with unfavourable weather conditions, such as low temperatures before applications, high radiation and high temperatures during applications, and moisture stress after applications, or overall cool and wet conditions during the application period. In our study, phytotoxicity ratings were highest at Einbeck (data not shown). The reason for this effect is unclear, as weather conditions were similar to the other environments in both years and soil conditions were comparable to Göttingen.

The quantification of the genotype effect is limited because the sensitive genotype was not tested at Einbeck. Nevertheless, we assume that phytotoxicity of the classic herbicides is not genotype specific due to its high level in both genotypes.

Leaf Area Index

F/T applications had no effect on LAI, regardless of the strategy or dosage indicating higher flexibility of application timing compared to classic herbicide applications. In the classic herbicide treatments, LAI decreased by up to 67% and thus more severely than in the study by Dale *et al*. (2003), who found a decrease by 30-40% after application of clopyralid (26 g ha^{-1}) and triflusulfuron-methyl (4 g ha^{-1}), but did not increase dosage. Data on LAI response to the a.i. tested in the present study were not available from the current literature. Kadoglidou *et al*. (2008) reported genotypic differences in LAI response (and phytotoxicity symptoms) to herbicide application. In their study, however, they compared absolute LAI values and the absolute differences they found corresponded to equal relative differences.

In general, LAI response to herbicide applications reflected the results of the phytotoxicity assessments. The plants recovered within two weeks after application as reported by Norris (1991) and Pfleiderer *et al*. (2001), but this was only true for symptoms such as bleaching and deformation, while growth depressions remained evident in a reduced LAI.

Root Yield and Quality

Yield response to herbicide applications was expected to reflect the observed effects regarding phytotoxicity and LAI, as LAI at early growth stages is an important factor for yield performance of sugar beet (Jaggard & Qi, 2006). Higher selectivity of F/T compared to classic herbicides was confirmed, because F/T did not affect RY at any dosage tested. Due to the possibility of unintended double dosage applications by spray overlapping in the field, a RY decrease by about 2% can be relevant in practice. Even higher yield losses of up to 5% caused by classic herbicides were reported in previous studies (Deveikyte & Seibutis, 2008; Pfleiderer *et al*., 2001).

Herbicide applications can also affect quality parameters, due to a negative influence on physiological processes and/or light use efficiency. Beißner (2000) and Pfleiderer *et al*. (2001) showed this for root quality parameters as in the case of amino-nitrogen being impaired by high-dosage applications of chloridazon (1600 g ha^{-1}) plus quinmerac (200 g ha^{-1}) and triflusulfuron-methyl (30 g ha^{-1}), respectively. This effect was not found for the a.i. tested in the present study. Deveikyte and Seibutis (2008) applied similar dosages of DMP, PMP, ETO and MTM as tested in the present study and did not measure an effect on either sucrose content or root quality.

White Sugar Yield

WSY is the key indicator to evaluate herbicide selectivity in sugar beet. On average, it was not significantly affected by applying F/T. WSY was even higher in the F/T treatments than in the untreated check in Göttingen 2013 (significant) and Schwüblingsen 2014 (not significant). A similar observation was made for the sensitive genotype up to the double dosage of the classic herbicides in both 2013 trials. The reason for this effect, albeit not significant, might be the setup of the field trials. A certain degree of weed competition could have occurred in the untreated plots in some environments due to the limitations of hand weeding. Furthermore, the necessary human movements within the plots during applications and assessments could have positively influenced beet growth in the treated plots. Beißner (2000) reported similar observations for WSY of a glyphosate tolerant variety being higher in plots treated with glyphosate than in the untreated check, but he, too, was unable to explain the phenomenon. Possible influences of the aforementioned movements within the plots are equal in all herbicide-treated plots. Thus, the relative yield differences in the non-sensitive genotype between F/T and classic herbicides of 8.6 and 17.4 percentage points at the double and fourfold dosages confirm the higher selectivity of F/T compared to the classic herbicides.

The genotypic differences in the mean response to increasing dosage of classic herbicides are partly due to the fact that the sensitive genotype was not tested at Einbeck, but results of an overall evaluation of both genotypes without Einbeck (data not shown) showed only small deviations from the evaluation by genotype. Nevertheless, WSY of both genotypes decreased with increased dosage of the classic herbicides. Pfleiderer *et al*. (2001) found a 5% decrease in WSY caused by similar classic herbicides (710 g ha^{-1} MTM, 102 g ha^{-1} ETO, 50 g ha^{-1} PMP, 13 g ha^{-1} DMP, 30 g ha^{-1} triflusulfuron-methyl) and Beißner (2000) even a 50% decrease after applying the fourfold dosages of MTM, ETO, PMP and DMP plus 1600 g ha^{-1} chloridazon and 200 g ha^{-1} quinmerac. These differences could be partly due to environmental factors such as different soil texture or weather conditions. Furthermore, the a.i. tested by Pfleiderer *et al*. (2001) and Beißner (2000) are only partly in accordance with those tested in the present study and the effects of a.i. and environment are not clearly separable. Factors that lower selectivity of herbicides can accidentally coincide in practical weed control and thus, phytotoxicity may occur even when the authorized dosage is applied (Pfleiderer *et al.*, 2001).

Variety registration

In the breeding process, introduction of new traits, e.g. resistance against pests or diseases, often comes along with a yield penalty (Biancardi *et al*., 2005). A yield penalty can also be expected for new genotypes that are non-sensitive to ALS-inhibitors and thus they might not meet the yield requirements for registration. However, the higher selectivity of the system (F/T plus complementary variety) compared to classic herbicides used on sensitive varieties could counter-balance a possible yield penalty. The aforementioned yield advantage of 8.6 percentage points of WSY in the treatments with double dosage of F/T compared to double dosage of the classic herbicides (a treatment relevant in commercial practice) could represent a substantial compensation for registration which might increase if other classic a.i. (beyond those tested in the present study) are taken into account.

Conclusions

All tested indicators (phytotoxicity, LAI, RY, quality and WSY) demonstrated a higher selectivity of F/T compared to classic herbicides and there is thus no risk of yield loss caused by application of F/T. Higher selectivity also lowers the effect of unfavourable weather conditions or low crop vigour at application time. Moreover, the use of F/T could simplify weed control by a lower number of a.i. than in the classic strategy. All benefits, including control of weedy crops (Wegener *et al*., 2015) or increased flexibility in application timing due to high efficacy (Wendt *et al*., 2016 and 2017), contrast with the risks of weed resistance and/or gene flow (Kudsk & Streibig, 2003). Thus, all agricultural measures have to be coordinated throughout the whole crop rotation in order to minimize potential risks and to reach the full potential of systems with non-sensitive crops and complementary herbicides.

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Kapitel 6

Epilog

Epilog

Der Epilog wird in einer wissenschaftlichen Zeitschrift veröffentlicht werden.

Die Unkrautkontrolle im zentraleuropäischen Zuckerrübenanbau stößt in einigen Punkten auf Probleme, die mit den derzeitigen Herbiziden nicht zu lösen sind. Die Applikationen müssen präzise zum Keimblattstadium der Unkräuter erfolgen und sind deshalb in ihrer Anwendung wenig flexibel. Die Anzahl der Applikationen und die Aufwandmenge der Herbizide lassen sich aufgrund der Dauer der Wirkung im Boden nicht weiter reduzieren. Das Auftreten schwer bekämpfbarer Unkräuter ist ebenfalls gestiegen und phytotoxische Schäden sind aufgrund der geringen Selektivität einiger Herbizide ein stetiges Problem. Ebenso sind Fälle resistenter Unkräuter im Zuckerrübenanbau bekannt. Ein breiterer Einsatz von Acetolactat-Synthase (ALS)-Inhibitoren durch die Einführung der Conviso Smart® Technologie könnte wesentliche Verbesserungen schaffen.

Durch konventionelle Züchtung wurden in den vergangenen Jahren Sorten verschiedener Ackerbaukulturen entwickelt, die eine Verträglichkeit gegenüber bestimmten Herbiziden aufweisen und in Europa sowie Deutschland zugelassen sind (Beckert et al. 2011). Diese Systeme bestehen aus spezifischen Sorten, die gegenüber ihrem Komplementärherbizid nicht-sensitiv sind. Das Herbizid Conviso® befindet sich momentan im Zulassungsprozess und zwei Sorten dieser Technologie wurden 2016 zur Wertprüfung in Deutschland und vielen europäischen Ländern angemeldet. Bei der Zulassung (Sorte und Herbizid) werden zwei Rechtsbereiche separat bewertet. Eine ganzheitliche Betrachtung des gesamten Systems ist insbesondere bezüglich der Interaktionen zwischen Sorte und Herbizid aufgrund der

Zulassung ihrer Einzelkomponenten nicht verfügbar, könnten aber für die Anwendung der Technologie in der Praxis erhebliche Bedeutung haben. Die Technikfolgeabschätzung einer Bund-Länder-Expertengruppe ist Gegenstand einer ganzheitlichen Analyse nicht-sensitiver Ackerbaukulturen (BLE 2014). Es gibt jedoch bisher keine wissenschaftlich belastbaren Erkenntnisse zu dieser Technologie in Zuckerrüben. Im Folgenden sollen deshalb die Teilprojekte Unkrautkontrolle, Selektivität, Behandlungsintensität und Risiko sowie das „Resistenzmanagement“ als Teil einer Systemanalyse näher erläutert werden. Dazu wurden in den Jahren 2013 und 2014 Feldversuche in Norddeutschland auf drei Bodenarten (Sand, Ton und Lehm) durchgeführt.

1 Unkrautkontrolle

Conviso® kann zu einem späteren Zeitpunkt als zum Keimblattstadium der Unkräuter appliziert werden. Damit ist die Anwendung hinsichtlich des Applikationszeitpunktes im Vergleich zu klassischen Herbiziden flexibler. Ebenso ist die Dauer der Wirkung im Boden länger als bei klassischen Herbiziden. Das kann insgesamt zu einer Reduktion von Applikationen bei gleicher oder höherer Wirksamkeit führen. Wirkungslücken bei den klassischen Herbiziden wie gegenüber der Hundspetersilie (*Aethusa cynapium* L.) oder dem Vogelknöterich (*Polygonum aviculare* L.) könnten durch den Einsatz von ALS-Inhibitoren geschlossen werden (Wegener et al. 2015). Eine allgemeine Verunkrautung sowie Einjähriges Bingelkraut (*Mercurialis annua* L.), Auflaufkartoffel (*Solanum tuberosum* L.) und Ausfallraps (*Brassica napus* L.), solange dieser selbst sensitiv gegenüber ALS-Inhibitoren ist, sind mit zwei Applikationen von

Conviso® oder in Kombination mit klassischen Herbiziden hoch effizient regulierbar (Abb.1).

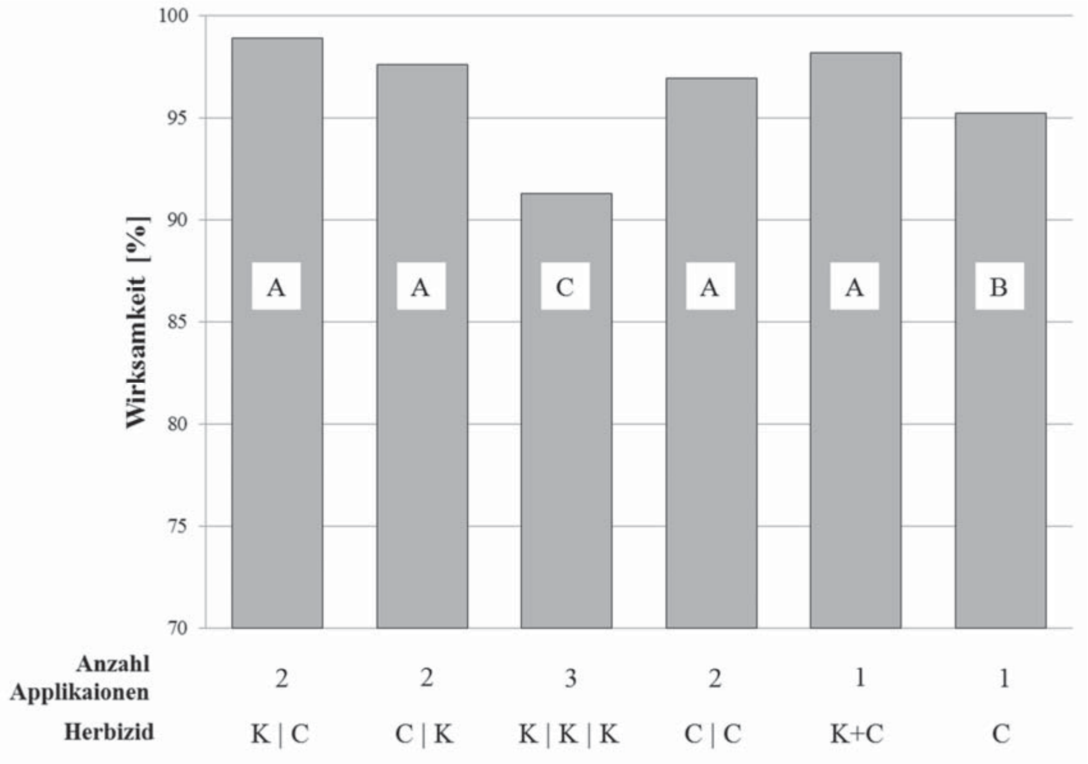

Abbildung 1: Wirksamkeit von Herbizidapplikationen in Zuckerrüben mit Conviso® (C) und klassischen Herbiziden (K) in diversen Kombinationen. Sechs Umwelten, Deutschland 2013 und 2014. Buchstaben markieren signifikante Unterschiede zwischen Varianten (Tukey, $p \leq 0.05$). C: 50 g Foramsulfuron ha^{-1} + 30 g Thiencarbazone-methyl ha^{-1}; K: 94 g Ethofumesat ha^{-1}, 75 g Phenmedipham ha^{-1}, 59 g Desmedipham ha^{-1}, 34 g Lenacil ha^{-1} + 700 g Metamitron ha^{-1}.

Für die praktische Unkrautkontrolle hat die einfache Bekämpfung von Unkrautrüben eine besonders hohe Bedeutung. Denn diese sind in Europa seit den 1970er Jahren zunehmend aufgetreten (Boudry et al. 1993) und in Deutschland auf 10% der Zuckerrübenflächen als schwer bekämpfbar eingestuft (Buhre et al. 2011). Denn momentan sind nur aufwändige Methoden, wie das Hacken von Hand, der Einsatz von Glyphosat mit Streichgeräten oder die Erweiterung der Fruchtfolge möglich. Durch die Conviso Smart® Technologie würde eine einfache Kontrolle möglich sein. Das erneute Auftreten einer Samenbank mit nicht-sensitiven Pflanzen gegenüber Conviso® setzt eine vollständige Beseitigung der Rübenschosser voraus.

Die Zulassung neuer Sorten führt im Zeitverlauf zu einer kontinuierlichen Leistungssteigerung (Märländer 1996). Durch die Selektion eines neuen Merkmals entsteht hinsichtlich des Leistungszuwachses ein Zeitdefizit (Abb.2). Die Zulassung einer Sorte erfolgt in Deutschland durch die Erteilung des landeskulturellen Wertes durch das Bundessortenamt (SaatG 1985), der voraussetzt, dass die neue Sorte in mindestens einer Werteigenschaft besser sein muss, als bereits zugelassene Sorten. Somit könnte zum Zeitpunkt der Registrierung der ersten nicht-sensitiven Sorte der Conviso Smart® Technologie der Ertrag für eine Zulassung nur aufgrund der Leistung nicht ausreichen. Die Definition des Landeskulturellen Wertes ermöglicht es jedoch, ungünstige Eigenschaften, wie z. B. ein Leistungsdefizit durch andere günstigere Eigenschaften, wie höhere Selektivität oder bessere Unkrautkontrolle, auszugleichen.

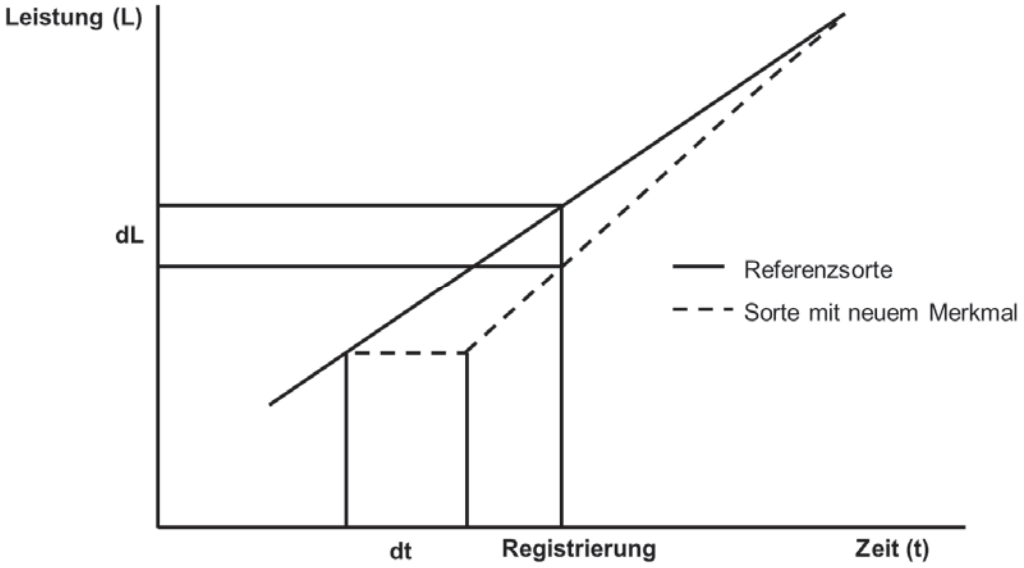

Abbildung 2: Modell zu Züchtungsfortschritt und relativer Vorzüglichkeit (dL) von Referenzsorten und Sorten mit neuem Merkmal. dt: Zeitdauer der Selektion. Verändert nach Märländer (1996).

2 Selektivität

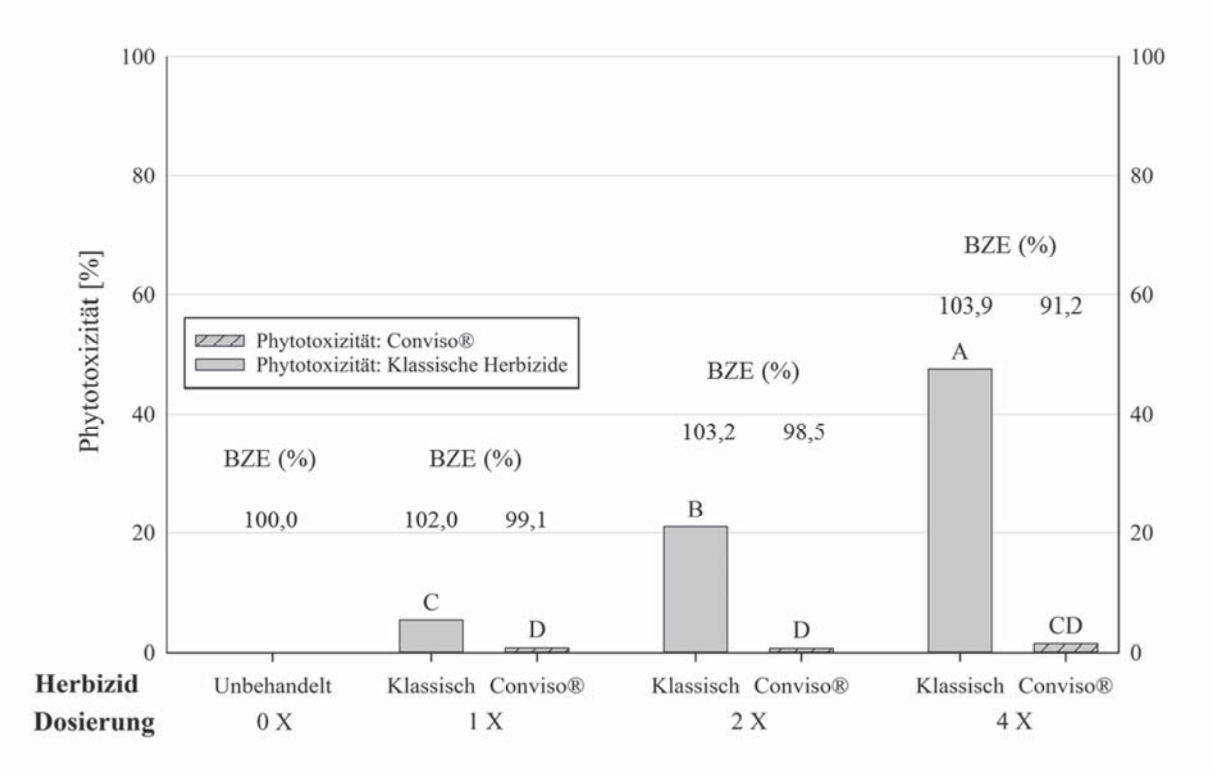

Abbildung 3: Phytotoxizität im Durchschnitt von sechs Umwelten in einem Zuckerrübenversuch in 2013 und 2014. Klassische Herbizide oder Conviso® wurden in verschiedenen Aufwandengen appliziert. Der Zuckerrübengenotyp war gegenüber ALS-Inhibitoren nicht-sensitiv. Aufwandmenge 1 X = zugelassene Aufwandmenge (Schätzung für Conviso®).

Neben einer effizienteren Unkrautkontrolle ist auch die Selektivität von Conviso® höher als die klassischer Herbizide**.** Zwischen Conviso® und den klassischen Herbiziden traten signifikante Unterschiede hinsichtlich der Phytotoxizität (Abb.3) und entsprechend des Bereinigten Zuckerertrages (BZE) (nicht gezeigt) auf. Während sich der BZE in allen Varianten mit Conviso® nicht von der unbehandelten Kontrolle unterschied, resultierte aus höheren Aufwandmengen mit klassischen Herbiziden ein sinkender BZE und eine steigende Differenz zu den Varianten mit Applikation von Conviso®. Diese bessere Verträglichkeit von Conviso® im Vergleich zu klassischen Herbiziden kann ein indirekter Ertragsvorteil in der Praxis sein und zu einer

Steigerung der Flexibilität des Applikationszeitpunktes führen. Beide Effekte könnten für die Zulassung der Sorte von Bedeutung sein.

3 Behandlungsintensität und Risiko

Im Nationalen Aktionsplan Pflanzenschutz (NAP) ist festgeschrieben, das Risiko durch die Anwendung von Pflanzenschutzmitteln zu reduzieren (BMEL 2013). Ein verminderter Herbizideinsatz könnte in Zuckerrüben dazu beitragen.

Der Behandlungsindex (BI) dient als Indikator für die Intensität des Pflanzenschutzmitteleinsatzes (Roßberg et al. 2009). Dieser ist nach Reineke (2014) von 1980 bis 2004 von 6,8 auf 3,1 gesunken und könnte bei einem Anteil nicht-sensitiver Zuckerrübensorten gegenüber ALS-Inhibitoren von 50% der Zuckerrübenflächen in 2020 auf 2,8 sinken. Das tatsächliche Mittel liegt heute bei 2,64 (PAPA 2016), ließe sich aber bei gleicher oder höherer Wirksamkeit zu den heutigen Herbiziden durch Conviso Smart® weiter reduzieren.

Bei einer zweimaligen Applikation von Conviso® mit jeweils 0,5 L ha^{-1} werden insgesamt 80 g Wirkstoff ha^{-1} ausgebracht. Diese Variante zeigte in den Feldversuchen 2013 und 2014 gleiche oder höhere Wirksamkeit als eine dreimalige Applikation mit klassischen Herbiziden (Abb.1), bei denen insgesamt 2886 g Wirkstoff ha^{-1} ausgebracht werden. Die Umweltauswirkungen (Risiko der Anwendung) werden jedoch erst nach entsprechenden Berechnungen mit dem Modell SYNOPS (Gutsche und Strassemeyer 2007) ersichtlich werden können. Die bisher erhobenen Daten bieten eine gute Grundlage für diese weiterführenden Untersuchungen. So könnten unter Anwendung des Modells SYNOPS hinsichtlich des Umweltrisikos der Anwendung Vergleichsrechnungen zwischen dem Einsatz von

Conviso Smart® und klassischen Herbiziden erfolgen und eine mögliche Reduktion abgeschätzt werden.

4 Resistenzmanagement

Momentan sind 158 Unkrautarten, die gegenüber ALS-Inhibitoren resistent sind, weltweit bekannt (Heap 2016). Durch das hohe Resistenzrisiko dieser Wirkstoffklasse und dem schnellen Anstieg resistenter Arten, stehen ALS-Inhibitoren bezüglich des Resistenzmanagements im Fokus. Ein zusätzlicher Einsatz in Zuckerrüben könnte das Resistenzrisiko verstärken, sodass Resistenzvermeidungsstrategien entwickelt und entsprechend die Leitlinien des integrierten Pflanzenschutzes im Zuckerrübenanbau (Gummert et al. 2012) angepasst werden müssen.

Der Einsatz einer weiteren Wirkstoffgruppe kann aber im Hinblick auf die Resistenzvermeidung von Unkräutern durch die Verminderung des Selektionsdrucks (Balgheim 2006) auch einen Vorteil bieten. Der Selektionsdruck auf bereits Metamitron resistenten Weißen Gänsefuß (*Chenopodium album* L.) in Zentraleuropa (Mechant et al. 2008, Varrelmann und Kalfa 2013) könnte durch den verminderten Einsatz dieses Wirkstoffes und Ersatz durch Conviso® reduziert werden. Herbizid-Strategien von Conviso® in Kombination mit Herbiziden anderer Wirkstoffklassen, die eine ebenso hohe Wirksamkeiten bieten, könnten somit zur Resistenzvermeidung beitragen. Eine ausschließliche Anwendung von Conviso Smart® ist hinsichtlich des Resistenzmanagements dagegen keine Option.

5 Fazit

Mit der Conviso Smart® Technologie stehen der Unkrautkontrolle im zentraleuropäischen Zuckerrübenanbau innovative Lösungen einiger bisheriger Probleme zur Verfügung. Dazu zählen höhere zeitliche Flexibilität, reduzierte Anzahl der Applikationen, Verlängerung der Dauer der Wirkung im Boden und eine hohe Wirksamkeit gegenüber schwer bekämpfbarer Unkräuter. Diese sind nur bei Zulassung der Sorten zu realisieren, für die bei geringerer Leistung eine höhere Selektivität bedeutend sein könnte. Neben der Zulassung von Sorte und Herbizid sind weitere Untersuchungen zum praktischen Einsatz in verschiedenen Umwelten erforderlich (Balgheim et al. 2016), wie der Abschätzung des Risikos und der Behandlungsintensität sowie der Anpassung von Resistenzvermeidungsstrategien. Eine offene Diskussion zwischen Industrie, Beratern und Anwendern ist dafür unbedingt erforderlich.

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Zusammenfassung

Die Zulassung von gegenüber Acetolactat-Synthase (ALS) Inhibitoren nicht-sensitiven Zuckerrübensorten und Komplementärherbiziden könnte für die Unkrautregulierung in Zuckerrüben erstmals seit über zwei Jahrzehnten eine Innovation bedeuten. Es waren jedoch bisher keine Ergebnisse öffentlich zugänglich, welche die grundlegenden Anwendungsmerkmale wie Applikationszeitpunkt oder Dauer der Wirkung im Boden und die Kernpunkte der Unkrautregulierung wie Wirksamkeit oder Selektivität dieses Herbizides beschreiben. Dazu wurden in den Jahren 2013 und 2014 jeweils vier Feldversuche auf jeweils einem Sand-, Ton- und Lehmstandort durchgeführt. In diesen Versuchen wurde 1.) der späteste mögliche Applikationszeitpunkt, 2.) die Dauer der Herbizidwirkung im Boden, 3.) die Wirksamkeit gegenüber typischen Unkräutern im Zuckerrübenanbau sowie mögliche Applikationsstrategien und 4.) die Selektivität des Herbizids gegenüber einem nicht-sensitiven Genotyp im Vergleich mit klassischen Zuckerrübenherbiziden bestimmt. Ziel dieser Arbeit war es, eine belastbare Datengrundlage für die Einführung in die Praxis und für weiterführende Untersuchungen bereitzustellen.

Das zur Zulassung beantragte Herbizid Conviso® beinhaltet zwei Wirkstoffe. Foramsulfuron wird über das Blatt aufgenommen und hat eine gute Wirksamkeit gegenüber dikotylen Unkräutern. Im ersten Feldversuch wurde gezeigt, dass der Applikationszeitpunkt im Vergleich zu klassischen Herbiziden flexibler ist. Eine Kontrolle von *Chenopodium album* L. bis zu einem Entwicklungsstadium von BBCH 14 war mit einer Aufwandmenge von 0,5 L ha^{-1} möglich, bis BBCH 16 mit einer Aufwandmenge von 1,0 L ha^{-1} (Manuskript I). Auch andere Unkräuter wie *Matricaria recutita* L. und *Polygonum convolvulus* L. ließen sich bei einer Aufwandmenge von

1,0 L ha^{-1} noch bis zu einem Entwicklungsstadium von BBCH 32, beziehungsweise BBCH 13, kontrollieren.

Das hauptsächlich über die Wurzel aufgenommene Thiencarbazone-methyl ist länger im Boden aktiv als Wirkstoffe klassischer Rübenherbizide. Im zweiten Feldversuch wurde gezeigt, dass die Wirksamkeit von Conviso® im Boden mindestens zehn bis über 20 Tage betrug. Verglichen mit klassischen Herbiziden ist das Intervall zwischen den Applikationen damit um etwa fünf bis zehn Tage länger. Die Dauer der Wirkung im Boden wurde nur schwach von der Aufwandmenge beeinflusst. Neben einer späteren Terminierung der Applikationen ist die Intervalllänge ein entscheidendes Kriterium, das zu einer Reduktion der Anzahl an Applikation beitragen kann. Besonders durch eine längere Wirkung bis zum Reihenschluss kann auf eine etwaige zusätzliche Applikation verzichtet werden.

Die Möglichkeiten eines späteren Applikationszeitpunktes und einer längeren Wirkung im Boden wurden im dritten Feldversuch kombiniert. Hier wurden Strategien nur mit Conviso® oder in Kombination mit klassischen Herbiziden einer klassischen Strategie gegenüber gestellt. In den Strategien mit Conviso® wurde eine erfolgreiche (>97%) Unkrautkontrolle mit nur zwei Applikationen festgestellt. Zusätzlich ist ersichtlich geworden, dass Kombinationen aus Conviso® und klassischen Herbiziden eine hohe Wirksamkeit erreichen und somit weiterhin die Flexibilität der Unkrautkontrolle in Zuckerrüben erhöhen. Besonders gegen *Mercurialis annua* L. und *Solanum tuberosum* L. auf den Sandstandorten bietet Conviso® für diese sonst schwer bekämpfbaren Unkrauter einen Wirkungsvorteil.

Die Kombination aus Sorte und Herbizid soll als Conviso Smart® Technologie eingeführt werden. Das Herbizid Conviso® wies im Vergleich zu klassischen

Herbiziden eine höhere Selektivität auf. Im vierten Feldversuch, in dem Conviso® bis zur vierfachen Menge der zur Zulassung beantragten Aufwandmenge dosiert wurde, zeigte Conviso Smart® nur geringe Phytotoxizität. Es traten jedoch keine signifikanten Effekte hinsichtlich des Blattflächenindexes, Ertrages oder der Qualität auf. Durch klassische Herbizide hingegen, die ebenfalls vierfach dosiert wurden, wurden Blattflächenindex und Ertrag signifikant reduziert und einige Qualitätsparameter signifikant negativ beeinflusst. So war in der Variante der doppelten Dosierungen der relative Bereinigte Zuckerertrag mit Conviso® um 4,7 Prozentpunkte höher als mit klassischen Herbiziden. Dieser Ertragsvorteil könnte ein Entscheidungskriterium bei der Zulassung der Sorte bedeuten.

Für die bisherigen Grenzen der Unkrautkontrolle in Zuckerrüben, wie Flexibilität des Applikationszeitpunktes, Anzahl an Applikationen, Wirksamkeit gegen bestimmte Unkräuter und Selektivität bietet Conviso Smart® einen innovativen Fortschritt. Dennoch sind weiterführende Untersuchungen hinsichtlich der Resistenzentwicklung bei Unkräutern und der Umweltwirkungen notwendig, um die oben genannten Vorteile voll ausschöpfen zu können.

Summary

The first innovative change of weed control in sugar beet since two decades could be realized by the registration of genotypes that are non-sensitive to acetolactate-synthase (ALS) inhibitors and its complementary herbicides. Until now, there were no public results, which describe the basic practice like application timing or duration of soil activity and main issues of weed control like efficacy or selectivity. Therefore, four field trials in 2013 and 2014 have been carried out each year at a sandy, clayey and loamy site. In these trials 1.) the latest application timing, 2.) the duration of soil activity, 3.) the efficacy against typical sugar beet weeds by possible application strategies and 4.) the selectivity of the herbicide to a non-sensitive genotype in comparison to classic sugar beet herbicides were determined. Aim of the study was to provide a reliable data basis for introduction into practice and for further investigations.

The herbicide Conviso®, which is applied for approval, includes two active ingredients. The efficacy of Foramsulfuron against dicotyledonous weeds is high and it is absorbed by foliage. In the first field trial, a more flexible application timing of Conviso® in comparison to classical herbicides could be demonstrated. The control of *Chenopodium album* L. was possible until the development stage of BBCH 14 at a dosage of 0.5 L ha^{-1} and BBCH 16 at a dosage of 1.0 L ha^{-1} (manuscript I). Other weed species like *Matricaria recutita* L. and *Polygonum convolvulus* L. were controlled until development stage of BBCH 32 and BBCH 13, respectively, by a dosage of 1.0 L ha^{-1}.

Thiencarbazone-methyl is mainly absorbed by roots and has a longer duration of soil activity compared to active ingredients of other sugar beet herbicides. Conviso® had

a duration of soil activity of ten to more than 20 days in the second field trial. This is about five to ten days longer in comparison to classical herbicides. The duration of soil activity was only slightly affected by dosage. Next to a later application timing, the extent of an interval between the applications is a decisive factor which could lead to a reduced number of applications in weed control. Especially, a further application would not be necessary if soil activity of the herbicide would last until canopy closure.

In the third field trial, the combination of later application timing and longer durability of soil activity was examined. Strategies only with Conviso® as well as in combination with classical herbicides have been compared to a classic herbicide strategy. A strategy with two applications of Conviso® lead to a successful (>97%) weed control. Furthermore, combinations of Conviso® and classical herbicides became obvious to reach high efficacy. Flexibility of weed control is also increased by these combinations. Especially at the sandy sites, Conviso® had an advantage of efficacy against *Mercurialis annua* L. and *Solanum tuberosum* L.. These weeds are usually difficult to control.

The combination of variety and herbicide is supposed to be introduced as Conviso Smart® Technology. The herbicide Conviso® showed higher selectivity compared to classical herbicides. In the fourth field trial, Conviso® was applied with the fourfold dosage of the authorized application rate for approval. Only a very low level of phytotoxicity was observed. No significant effects regarding leaf area index, yield or quality occurred. In contrast, classical herbicides that were also applied with the fourfold dosage of its authorized application rate reduced leaf area index and yield significantly. Some quality parameters were also significantly influenced negative. The relative white sugar yield was 4.7 percentage points higher with Conviso® than with classical herbicide in the treatment with double dosage. The higher yield is an advantage which could influence the registration process of the non-sensitive variety.

Conviso Smart® is a real innovation for the present limits of weed control. Flexibility of application timing, the number of applications, efficacy against certain weed species and selectivity are improved. Nevertheless, further investigations regarding the development of resistance of weeds and the environmental impact are necessary to maximize the above mentioned advantages.

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