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# Untersuchung alternativer Unkrautmanagementsysteme für Kulturraps unter Einbeziehung von Möglichkeiten zur Reduzierung des Auftretens von Raps als Durchwuchs

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# Inhaltsverzeichnis

# 1 Einleitung

Raps ist, gemessen am Weltmarktanteil, nach Soja weltweit die zweitbedeutendste Ölpflanze. In Deutschland stellt Raps die wichtigste Ölpflanze dar (LfL, 2020). Zukünftig ist davon auszugehen, dass die Bedeutung von Raps für die Europäische Union und Deutschland weiter zunimmt; denn durch den European Green Deal, einem klimapolitischen Konzept der Europäischen Kommission von 2019, hat sich die Europäische Union zum Ziel gesetzt, ihre Nettotreibhausgasemissionen bis 2050 auf null zu reduzieren und damit zum ersten klimaneutralen Kontinent zu werden. Dabei sollte der Bedarf an erneuerbaren Biokraftstoffen und damit auch der Ölsaatenbedarf steigen, wobei gleichzeitig der zukünftige Import von Erzeugnissen anderer international bedeutender Ölpflanzen wie Soja oder Ölpalme diesem Ziel entgegenstehen würde (Europäische Kommission, 2019; Götze, 2019; Tamma *et al.*, 2019; Europäische Union, 2021). Zum Einem geht deren Anbau teilweise mit kontroversen Bedingungen einher, wie beispielsweise Regenwaldabholzung und Biodiversitätsverlusten, zum Anderen sind die langen Transportwege mit zusätzlichen Treibhausgasemissionen verbunden (Fearnside, 2001; Obidzinski *et al.*, 2012; Savilaakso *et al.*, 2014; Ferdous Alam *et al.*, 2015; Qaim *et al.*, 2020).

In Deutschland wurde Raps 2019 auf circa 857 500 ha produziert. Dabei schwankten die durchschnittlichen Erträge in Abhängigkeit des Erntejahres. Im Mittel des Zeitraumes von 2013 bis 2018 wurden in Deutschland ca. 3,7 t $ha^{-1}$ geerntet (BMEL, 2019). Das bedeutendste Erzeugnis aus Rapssamen ist Rapsöl. Es ist als erneuerbarer Energieträger Ausgangsstoff für die Biokraftstoff- bzw. -schmierstoffherstellung. Zudem wird Rapsöl als Futtermittel oder Speiseöl verwendet. Rapsexpeller und Rapsextraktionsschrot sind Koppelprodukte der Rapsölherstellung. Sie kommen in der Tierernährung zum Einsatz. Durch ihre relativ hohen Eiweißgehalte können sie zu einem niedrigeren (Import-) Sojaanteil in der Futterration beitragen. Rapsstroh verbleibt zumeist auf dem Acker, kann aber auch einer energetischen Nutzung in Form von Wärmegewinnung unterzogen werden (FNR, 2005; BASF, 2006; LfL, 2008, 2020).

Die Preise für Erzeugnisse der konventionellen pflanzlichen landwirtschaftlichen Urproduktion sind für viele Kulturen niedrig. Getreidearten und Raps werden vom Markt bevorzugt. Aufgrund dieser Marksituation kommt es häufig zu engen Fruchtfolgen mit hohen Getreideanteil, oftmals ohne Sommerung und mit Raps als einziger Blattfrucht (BMEL, 2019; LfL, 2020). Aufgrund des Preisdrucks sahen sich viele landwirtschaftliche Betriebe gezwungen ihr Produktionsverfahren anzupassen. Einer der Hauptkosten stellt die Bodenbearbeitung dar. Aus diesem Grund wurde die wendende Bodenbearbeitung häufig durch kostengünstigere Verfahren der konservierenden Bodenbearbeitung ersetzt (Statistisches Bundesamt, 2011, 2017). Die konservierende Bodenbearbeitung ist für eine nachhaltige Unkrautkontrolle im Vergleich zur wendenden Bodenbearbeitung das weniger wirksame Verfahren. Während bei der wendenden Bodenbearbeitung Unkrautsamen tiefer vergraben werden, kommt es bei der bei der konservierenden Bodenbearbeitung zu einer Konzentration von Unkrautsamen in dem oberen Bereich des Bearbeitungshorizonts. Durch die niedrigere Vergrabungstiefe von Unkrautsamen erfolgt weniger fatale Keimung, weniger Unkrautsamen sterben durch Alterung oder Predation und ein höherer Anteil an Unkräutern kann auflaufen. Zudem befinden sich nach der wendenden Bodenbearbeitung weniger Erntereste auf der Bodenoberfläche und der Boden ist ganzflächig, tief gelockert. Das sorgt für bessere Auflaufbedingungen, eine schnellere Entwicklung der Kultur und damit für eine höhere Konkurrenzkraft gegenüber Unkräutern. Bei der Anwendung des konservierenden Bodenbearbeitungsverfahren erhöht sich in der Folge der

Unkrautdruck, an die kurze Fruchtfolge angepasste Unkräuter werden selektiert und gefördert (Hoogmoed & Derpsch, 1985; Vencill & Banks, 1994; Roger-Estrade *et al.*, 2001; Chauhan *et al.*, 2006; Torabi *et al.*, 2008; Holman *et al.*, 2011; Scherner *et al.*, 2016). Dabei handelt es sich zumeist um bestimmte Ungräser, wie Ackerfuchsschwanz, Weidelgräser und Windhalm, aber auch zweikeimblättrige Unkräuter, wie Raukearten, Durchwuchsraps, Ackerhellerkraut, Gänsefußarten, Klettenlabkraut, Taubnesselarten, Kamillearten, Gewöhnliche Vogelmiere, Ehrenpreisarten, Ackerstiefmütterchen und Hirtentäschelkraut (Bullied *et al.*, 2003; Niknam *et al.*, 2003; Chauvel *et al.*, 2009; Bushong *et al.*, 2011; Roberts, 2011; Hanzlik & Gerowitt, 2012; Lemerle *et al.*, 2014a; Aboutalebian *et al.*, 2017; Landau *et al.*, 2017; Salisbury *et al.*, 2018). Die Kontrolle der auftretenden Unkräuter wird zunehmend schwieriger, zudem steht nur eine begrenzte Auswahl von herbiziden Wirkstoffen zur Verfügung. Deren häufige Anwendung zu einer zunehmenden Resistenzentwicklung bei Unkräutern führt, wodurch die Möglichkeiten der wirksamen Unkrautbekämpfung weiter minimiert werden (Beckie, 2006; Asaduzzaman *et al.*, 2020; Krähmer *et al.*, 2020).

Die Zulassung neuer herbizider Wirkstoffe ist in nächster Zeit unwahrscheinlich, weil deren Entwicklung sehr kostenintensiv, risikobehaftet und Teil einer kontroversen öffentlichen Wahrnehmung ist: die während des Zulassungsprozesses gestellten Anforderungen an die ökologische Sicherheit des Herbizids sind gestiegen, der Prozess ist langwierig und mit hohen Kosten verbunden, zusätzlich besteht ein zunehmendes Interesse der Gesellschaft und der Öffentlichkeit an einer ökologischeren Landwirtschaft verbunden mit der Reduktion des Pflanzenschutzmitteleinsatzes (Duke, 2012).

Da Raps vermutlich zukünftig weiter an Bedeutung als wichtiger erneuerbarer Energieträger gewinnt, werden in den folgenden Herausforderungen und Möglichkeiten der Unkrautkontrolle in dieser Kultur näher beleuchtet. Einerseits steht die Unkrautkontrolle im Kulturraps im Fokus, andererseits wird auf die Problematik des Durchwuchsraps näher eingegangen.

Unkrautkontrolle im Kulturraps

Unkräuter im Rapsbestand stehen mit diesen in Konkurrenz um Nährstoffe, Raum, Wasser und Licht; außerdem können sie zu einer Ertragsdepression um bis zu 70% führen und die Samenqualität des Raps negativ beeinflussen (Melander, 1993; Lutman *et al.*, 1994; Holman *et al.*, 2004; Borger *et al.*, 2010; Baux *et al.*, 2011; Llewellyn *et al.*, 2016; Salisbury *et al.*, 2018; Sharma *et al.*, 2021). Wenn der Raps trocken und erntereif ist, sind Unkräuter im Rapsbestand zumeist noch lebend, grün und weisen einen höheren Feuchtegehalt auf. Dadurch wird der Ernteprozess erschwert und die Feuchtigkeit des Ernteguts erhöht, wodurch dessen Lagerfähigkeit verringert wird (Beckie *et al.*, 2008; Llewellyn *et al.*, 2016).

Bei einer engen Fruchtfolge treten in Rapsbeständen vermehrt kreuzblütige Unkräuter auf (vor allem Raukearten, Hirtentäschelkraut, Ackerhellerkraut und Durchwuchsraps), die sich aufgrund der nahen Verwandtschaft zum Kulturraps (Raukearten, Hirtentäschelkraut, Ackerhellerkraut: gleiche Familie wie Kulturraps; Durchwuchsraps: gleiche Spezies wie Kulturraps) mit gebräuchlichen Herbiziden nur schwer kontrollieren lassen. Eine sehr wirksame Kontrollmöglichkeit stellt das Clearfield® -System dar. Dabei handelt es sich um eine Kombination aus breitwirksamem Clearfield®-Herbizid und einer Clearfield®-Rapssorte, die eine Toleranz gegenüber dem Herbizid aufweist. Das Herbizid wird im Nachauflauf angewendet, enthält einen Wirkstoff aus der Gruppe der Imidazolinone und gehört zu der Klasse der Acetolactase-

Synthase (ALS)-Hemmer (Tan *et al.*, 2005). In Deutschland findet der Wirkstoff Imazamox unter anderem im Clearfield®-Herbizid Clearfield®-Vantiga® D Anwendung. Die Imidazolinone-Toleranz des Raps basiert auf Mutationen der Raps ALS und wurde über Mutagenese-Züchtung und anschließender Rückkreuzung in kommerzielle Rapssorten implementiert. Es handelt sich dabei um ein gentechnikfreies Verfahren (Swanson *et al.*, 1989). Gewöhnliche Rapspflanzen bzw. -sorten, ohne Imidazolinone-Toleranz, zeigen bereits bei niedrigen Imidazolinone-Dosen letale Symptome (Krato *et al.*, 2012). Durch die Anwendung des Clearfield®-Systems in Raps können kreuzblütige Unkräuter und Durchwuchsraps ohne Imidazolinone Toleranz sicher bekämpft werden (Swanson *et al.*, 1989; Krato *et al.*, 2012; Shaw, 2014). Eine im Vergleich zum Clearfield®-System stärker etablierte Methode der Unkrautbekämpfung ist in der landwirtschaftlichen Praxis die Durchführung einer Herbizid-Maßnahme im Vorauflaufstadium des Raps. Je nach Jahresbedingungen findet unter Umständen zur gleichen Zeit die Getreideernte und die Rapsaussaat statt, aus diesen Umständen können sich Personalengpässe ergeben. Mit der Nutzung des Clearfield®-Systems verlagert sich die Herbizidanwendung in den Nachauflauf und Arbeitsspitzen können entzerrt werden. Daneben besteht für Landwirte seit der Zulassung des Wirkstoffes Halauxifen-methyl im Raps 2019 die Möglichkeit unabhängig vom Clearfield®-System breitwirksame Herbizidpräparate im Nachauflauf einzusetzen (Raiffeisen, 2019a,b; Gehring & Thyssen, 2020, 2021). Halauxifen-methyl enthaltende Produkte tragen ebenfalls zur Entzerrung von Arbeitsspitzen bei. Allerdings sind sie für eine sichere Wirkung im Herbst im Splitting-Verfahren zu nutzen und benötigen daher zwei Feldüberfahrten, die Verträglichkeit ist insbesondere in frühen Entwicklungsstadien des Raps niedrig, daher lässt sich der Anwendungszeitpunkt bei heterogen entwickelten Rapsbeständen schwer bestimmen. Die Anwendung ist in solchen Fällen entweder mit Herbizidschäden am Raps verbunden oder mit einer zu späten Unkrautbekämpfung. Weiterhin schränkt die Anwendung von Halauxifen-methyl haltigen Produkten im Herbst die zur Auswahl stehenden Fungizide bzw. Wachstumsregulatoren ein, Präparate mit dem Wirkstoff Metconazol sollten dann aus Verträglichkeitsgründen nicht angewendet werden. Zudem ist die Wirkung gegen Wegrauke im Verlgeich zum Clearfield®-System niedriger (Schackmann, 2019; Gehring & Thyssen, 2021).

Erhöhte Aufmerksamkeit bei der Anwendung des Clearfield®-Systems erfordert die Vererbbarkeit der Herbizidtoleranz und eine mit der Imidazolinone-Toleranz einhergehende Kreuztoleranz gegenüber der herbiziden Gruppe der Sulfonyharnstoffen (Swanson *et al.*, 1989; Krato *et al.*, 2012). Aus Clearfield®-Sorten stammender Durchwuchsraps besitzt je nach genetischer Aufspaltung mindestens eine partielle Herbizidtoleranz, wodurch dessen Kontrolle in den Folgefrüchten erschwert wird (Krato *et al.*, 2012; Huang *et al.*, 2016a; Jursík *et al.*, 2019b; Jhala *et al.*, 2021). Weiterhin besteht für landwirtschaftliche Betriebe das Risiko eines Totalschadens, wenn sie Clearfield®- und nicht- Clearfield®-Sorten in der gleichen Vegetationsperiode anbauen und auf einem nicht- Clearfield®-Feld versehentlich ein Clearfield®-Herbizid angewendet wird (Krato *et al.*, 2012). Zusätzlich sind ALS-Hemmer anfällig gegenüber Resistenzbildungen seitens der Unkräuter. Ohne das Clearfield®-System findet keine ALS-Hemmer Anwendung im Raps statt. Durch die bei der Verwendung des Clearfield®-Systems zusätzliche Anwendung eines ALS-Hemmers in der Fruchtfolge, steigt der Selektionsdruck auf die Unkrautpopulation und neue Unkrautresistenzentwicklungen werden wahrscheinlicher (Powles & Yu, 2010; Löbmann *et al.*, 2021).

Neben der Anwendung von Herbiziden sind ebenfalls mechanische Verfahren zur Unkrautbekämpfung möglich. Sie können in die Unkraut-Management-Strategie integriert werden und stellen im Vergleich zur reinen chemischen Unkrautbekämpfung einen ganzheitlicheren, nachhaltigeren Ansatz dar (Parish, 1990; Blackshaw *et al.*, 2005; Pannacci *et al.*, 2017; Asaduzzaman *et al.*, 2020). In der ökologischen Landwirtschaft und in vielen Anbausystemen der Entwicklungsländern ist die mechanische Unkrautkontrolle bis in die Gegenwart die bedeutendste Möglichkeit zur Unkrautbekämpfung (Wei *et al.*, 2010; Pannacci *et al.*, 2017). Die wesentlichen Vorteile mechanischer Unkrautkontrolle liegen in den je nach Verfahren mitunter sehr niedrigen Investitionskosten und dem Ausbleiben von Unkrautresistenzentwicklungen (Wei *et al.*, 2010; Green & Owen, 2011). Nachteilig wirken sich die mangelnde Selektivität aus, wodurch es zu Schäden an der Kulturpflanze kommen kann. Zudem lassen sich Unkräuter häufig nur in frühen Entwicklungsstadien wirksam kontrollieren. Des Weiteren ist der Bekämpfungserfolg maßgeblich abhängig von Wetter- und Bodenbedingungen und die Flächenleistung kann je nach Verfahren sehr niedrig sein (Parish, 1990; Wei *et al.*, 2010; Green & Owen, 2011; Kunz *et al.*, 2015).

Als mechanische Unkrautbekämpfungsvariante bei Raps ist Hacken ein vielversprechender Ansatz. Die Wirkung dieses Unkrautbekämpfungsverfahren wird durch flaches Schneiden, Entwurzeln und Verschütten der Unkräuter erreicht (Pullen & Cowell, 1997; Bond & Grundy, 2001; Rasmussen, 2004; Fogliatto *et al.*, 2017). Raps ist weitsaatverträglich, die Reihenweite bei der Saat kann auf bis zu 50 cm erhöht werden, ohne dass mit einem Ertragseinbruch gerechnet werden muss und somit Raum für die Hackschare generiert werden kann (Melander *et al.*, 2013; Schwabe *et al.*, 2021, 2022). Systembedingt findet durch das Hacken auf der Fläche nur eine partielle Unkrautbekämpfung statt. Unkräuter die sehr nahe an der Saatreihe auflaufen, können durch das Hackschar nicht erfasst werden. Dieser Nachteil kann durch die Konkurrenzkraft moderner Raps-Hybridsorten kompensiert werden (Lemerle *et al.*, 2016). Insbesondere beim Auftreten von herbizidresistenten Unkräutern und im Hinblick auf strengere Regulierungen bei der Anwendung von chemischen Pflanzenschutzmitteln kann Hacken als mechanische Unkrautbekämpfungsmaßnahme die bestehenden chemischen Unkrautkontrollmöglichkeiten erweitern und einen Beitrag zum integrierten Pflanzenschutz leisten (Schwabe *et al.*, 2022).

## Durchwuchsraps als Unkraut

Werden Samen von Raps ungünstigen Keimbedingungen ausgesetzt, wie Sauerstoffmangel, Dunkelheit und Wassermangel, so können diese eine sekundäre Dormanz entwickeln und in diesem Stadium im Boden überdauern (Momoh *et al.*, 2002). In der landwirtschaftlichen Praxis ist mit der Entwicklung sekundärer Dormanz bei Ausfallrapssamen zu rechnen, wenn eine Bodenbearbeitung kurz nach der Ernte von Raps unter trockenen Bedingungen stattfindet (Gruber *et al.*, 2004; Huang *et al.*, 2016a). Sekundär dormante Rapssamen formen einen Bodensamenvorrat aus diesem der Durchwuchsraps über einen Zeitraum von bis zu 11 Jahren in den Folgefrüchten auflaufen kann (Gruber & Claupein, 2006; Andersen *et al.*, 2010; Huang *et al.*, 2018). Tritt Durchwuchsraps in anderen Kulturen als Unkraut auf, gestaltet sich die Bekämpfung besonders schwer, wenn es sich um Samen einer herbizidtoleranten Rapssorte handelt (wie beispielsweise beim Clearfield®-System). Die Herbizidtoleranz wird folglich an die Nachkommen vererbt. Weiterhin dient Durchwuchsraps als „Grüne Brücke“ zur Übertragung von Pathogenen auf den in der Fruchtfolge folgenden Kulturraps (Hwang *et al.*, 2012; Krato *et al.*, 2012; Jursík *et al.*, 2019b; Jhala *et al.*, 2021). Läuft Durchwuchsraps in Hybrid-Kulturraps auf, reduziert er den möglichen Flächenertrag durch ein genetisch bedingtes niedrigeres

Ertragspotential. Außerdem führt die höhere Pflanzendichte zu einem stärkeren Streckungswachstum im Herbst und reduziert dadurch Winterhärte des Bestands. Wenn sich das Fettsäuremuster von Kulturraps und Durchwuchsraps unterscheidet, kann das Auftreten von Durchwuchsraps zusätzlich zu einer negativen Beeinflussung der Ölqualität führen. Dies geschieht sowohl durch Auskreuzungen zwischen Durchwuchs- und Kulturraps und als auch durch die Samenproduktion des Durchwuchsraps (Grosse *et al.*, 1992; Smith *et al.*, 2010; Baux *et al.*, 2011).

Die Überdauerungsfähigkeit der Rapssamen im Boden lässt sich reduzieren durch den Anbau von Rapssorten mit einem niedrigeren Potential für sekundäre Dormanz und durch eine verzögerte Stoppelbearbeitung mit anschließender tiefen Grundbodenbearbeitung. Durch eine niedrigere Samenüberdauerung im Boden, wird gleichzeitig ein verringertes Auftreten von Durchwuchsraps in den Folgekulturen erreicht (Gruber *et al.*, 2005, 2009, 2010; Huang *et al.*, 2016a,b). Für verschiedene Pflanzenarten konnte weiterhin festgestellt werden, dass eine Behandlung von Samen mit Nährstoffen und Gibberellinsäure die Entwicklung sekundärer Dormanz verringert und damit auch ihre potentielle Überdauerungsfähigkeit im Boden (Finch-Savage & Leubner-Metzger, 2006; Bojovic, 2010; Farooq *et al.*, 2011, 2012; Arefi *et al.*, 2012; Dresch *et al.*, 2014). Wenn sich diese Wirkung für Rapssamen bestätigen lassen, könnte eine Behandlung von Ausfallrapssamen nach der Ernte die Entwicklung sekundärer Dormanz minimieren. Weniger Rapssamen überdauerten im Boden, der Bodensamenvorrat würde kleiner sein und es würde weniger Durchwuchsraps in den Folgekulturen auflaufen. Die mit dem Durchwuchsraps einhergehenden agronomischen Nachteile könnten auf direkten Weg reduziert werden.

Ziele dieser Dissertation sind die Untersuchung (i) des Clearfield®-Systems und (ii) der Anwendung des Hackens als alternative Unkrautmanagementsysteme für Kulturraps, inklusive (iii) der Evaluierung von potentiellen Möglichkeiten zur Reduzierung der Durchwuchsrapsproblematik durch Rapssamenbehandlungen mit Nährstoffen und Gibberellinsäure.

Die Basis der Dissertation bilden drei wissenschaftliche Publikationen. Innerhalb dieser wurde die Gültigkeit der im Folgenden aufgestellten Hypothesen überprüft.

In Publikation I aufgestellte Hypothesen:

1. Das Clearfield®-Herbizid und die Herbizide einer praxisüblichen Vorauflaufstrategie zeigen eine ähnliche Effizienz.

2. Die Bewirtschaftungsintensität hat einen Effekt auf die Unkrautdichte, beeinflusst aber nicht den Ertrag.

3. Die Herbizidstrategie hat keinen Einfluss auf den Ertrag.

In Publikation II aufgestellte Hypothesen:

1. Alle getesteten Substanzen (Nährstofflösungen und Gibberellinsäure) reduzieren die Induktion von sekundärer Dormanz bei Rapssamen.

2. Die getesteten Substanzen reduzieren die Induktion sekundärer Dormanz unterschiedlich stark.

3. Die getesteten Substanzen haben einen Effekt auf die Induktion sekundärer Dormanz unabhängig davon, ob die getesteten Rapssamen von Sorten mit einer hohen oder niedrigen Neigung zur sekundären Dormanzentwicklung stammen.

4. Wenn eine Sorte zur Ausbildung von einer hohen sekundären Dormanz neigt, wird deren Induktion stärker durch die getesteten Substanzen reduziert, als bei Samen von einer Sorte mit einer niedrigen Neigung zur Ausbildung sekundärer Dormanz.

In Publikation III aufgestellte Hypothesen:

1. Durch Hacken wird die gleiche Effizienz in der Unkrautkontrolle erreicht wie durch Herbizide.

2. Unabhängig davon ob Herbizide oder Hacken als Unkrautkontrolle eingesetzt werden, lässt sich der gleiche Rapsertrag realisieren.

Zusammengefasst wurden in dieser Dissertation die Eignung des Clearfield®-Systems und die des Hackens als alternative Unkrautmanagementsysteme für Kulturraps im Vergleich zu praxisüblichen Herbizidstrategien evaluiert. Da beim Anbau von Clearfield®-Rapssorten chemisch schwer kontrollierbarer Clearfield®-Durchwuchsraps als Unkraut in den folgenden Früchten auftreten kann, wurde weiterhin untersucht, inwieweit Rapssamenbehandlungen mit Nährstoffen und Gibberellinsäure zu einer Verringerung der Durchwuchsrapsproblematik beitragen können. Die Methodik reichte dabei von der Grundlagenforschung dienenden Laborversuchen mit kontrollierten Verhältnissen bis hin zu mehrjährigen Untersuchungen im Feld unter komplexen Umweltbedingungen.

# 2 Übersicht über die Publikation

Diese Dissertation besteht aus drei, in internationalen Fachjournalen veröffentlichten Publikationen, die in den folgenden Kapiteln dargestellt werden. Die Reihenfolge der Publikationen ergibt sich aus deren Beitrag zur Gesamtthematik der Dissertation:

In Publikation I stehen Untersuchungen zur Anwendung des Clearfield®-System in Kulturraps als alternatives chemisches Unkrautmanagementsystem im Vordergrund. Aus Clearfield®-Raps resultierender Durchwuchsraps lässt sich als Unkraut in den in der Fruchtfolge folgenden Kulturen schwieriger bekämpfen. Deshalb wurde in Publikation II untersucht, inwieweit Rapssamenbehandlungen mit Nährstoffen und Gibberellinsäure zu einer niedrigeren Dormanzentwicklung und Überdauerungsfähigkeit der Samen führen und damit auch zu einer Verminderung des Auftretens von Durchwuchsraps. In Publikation III wurde die Eignung des Hacken als alternatives mechanisches Unkrautmanagementsystem in Kulturraps im Vergleich zu einer gewöhnlichen, nicht-Clearfield® Herbizidstrategie im Hinblick auf Ertragsparameter und Unkrautaufkommen untersucht.

**Publikation I in Kapitel 3**

Sebastian Schwabe, Sabine Gruber, Wilhelm Claupein (2021): Oilseed Rape Yield Performance in the Clearfield® System under Varying Management Intensities.
Agronomy, 11, 2551. DOI: 10.3390/agronomy11122551

**Publikation II in Kapitel 4**

Sebastian Schwabe, Ernst Albrecht Weber, Samuel Gesell, Sabine Gruber, Wilhelm Claupein (2019): Overcoming seed dormancy in oilseed rape (*Brassica napus* L.) with exogenous compounds.
Weed Research, 59, 119–129. DOI: 10.1111/wre.12346

**Publikation III in Kapitel 5**

Sebastian Schwabe, Sabine Gruber, Wilhelm Claupein (2021): Hoeing as a possibility for mechanical weed control in winter oilseed rape (*Brassica napus* L.).
Crops, 2, 1-13. DOI: 10.3390/crops2010001

Die kursiven Beschreibungen zu Beginn des jeweiligen Kapitels dienen der Abstraktion der Fragestellung der Publikation und der Darstellung der verwendeten Methodik.

# 3 Publikation I

Sebastian Schwabe, Sabine Gruber, Wilhelm Claupein (2021):

**Oilseed Rape Yield Performance in the Clearfield® System under Varying Management Intensities**

Agronomy

*Das Clearfield®-System ist ein alternatives Unkrautmanagementsystem für Kulturraps. Dabei handelt es sich um eine Kombination aus einem breitwirksamen Nachauflauf-Herbizid und einer Clearfield®-Rapssorte, die eine Toleranz gegenüber dem Herbizid aufweist. Die Toleranz gegenüber dem Herbizid wurde durch konventionelle, gentechnikfreie Züchtungsverfahren in Clearfield®-Rapssorten implementiert. Auf Nicht-Clearfield®-Rapssorten besitzen Clearfield®-Herbizide eine letale Wirkung. Das Clearfield®- System erweitert im Raps die Möglichkeiten der Unkrautkontrolle und kann einen Beitrag zur Entzerrung von Arbeitsspitzen leisten. In einem zweijährigen Feldversuch wurde die Leistungsfähigkeit des Clearfield®-Systems im Raps unter verschiedenen Bewirtschaftungsintensitäten im Vergleich zu einem praxisüblicheren Vorauflaufherbizids*ystem evaluiert.

agronomy

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Article

# Oilseed Rape Yield Performance in the Clearfield® System under Varying Management Intensities

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**Abstract:** Oilseed rape production is under pressure due to a limited availability of herbicides. Therefore, the performance in terms of management intensity (MI) and herbicide strategy (HS) and the involved yield formation was evaluated in a two-year Clearfield® oilseed rape field experiment. Furthermore, weed density and weed composition were also investigated. The variants of MI were standard sowing density (StS; seed rate: 50 seeds $m^{-2}$, primary tillage: plow, row width: 12 cm), reduced sowing density (RD; seed rate: 25 seeds $m^{-2}$, primary tillage: plow, row width: 50 cm), and strip-till (ST; seed rate: 25 seeds $m^{-2}$, primary tillage: strip tillage, row width: 50 cm). The variants of HS were preemergence strategy (PES; application of dimethachlor, napropamide, clomazone in preemergence and application of prapaquizafop in postemergence) and Clearfield® strategy (CLS; application of imazamox, quinmerac in preemergence, no postemergence herbicide application). In the first year of the trial, there were no interactions between the factors in terms of grain yield. Grain yield in StS was 3.85 t and 5.2% significantly lower than in ST, and the value of RD was not significantly different from StS and ST. Grain yield in CLS was 3.7 t and 2.7% lower than in PES. In the second year of the trial, the grain yield in ST CLS was significantly lower, and there were no significant differences between the other variants. Higher weed emergence was observed in CLS RD (2.7 to 4 times higher weed density compared to PES RD) and CLS ST (2.8 to 4.5 times higher weed density compared to PES ST). No significant differences existed between StS PES and StS CLS in both trial years. The Clearfield® system offers significant advantages in the control of cruciferous weeds. Although these did not occur on the trial fields, the Clearfield® system in this study showed to be an alternative to the more common pre-emergence system, especially with regard to the parameter grain yield.

**Keywords:** canola; imidazolinone; imazamox; herbicide tolerant; weed emergence/control; grain yield



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## 1. Introduction

Oilseed rape (OSR) plays an important role worldwide as a break and oilseed cash crop [1]. Weed competition is one of the main yield-limiting factors in modern OSR cultivation and can cause yield reduction up to 70 percent depending on weed pressure and weed composition [1–6]. In recent decades, herbicide strategies have been developed to secure the yield potential. This is normally done by applying herbicides in different growth stages throughout the season, which can lead to up to three applications for certain crops. In addition, these herbicides are often less effective or cannot be controlled if the crop and weed belong to the same family. To overcome these issues, cropping systems that use herbicide-tolerant crops, for example, with crops resistant to glyphosate, glufosinate, or triazine, extend the available agronomic tools considering weed control but are also discussed controversially [7,8]. An additional tool represents the Clearfield® (CL)-system in OSR which consists of a broad-spectrum herbicide in combination with a tolerant OSR variety. The herbicide contains an active agent of the chemical group Imidazolinones [9] and belongs to the herbicide class of acetolactate synthase inhibitors (ALS; HRAC class: B). It is applied as imazamox in the herbicide Clearfield® Vantiga® D in Germany (company: BASF, Germany). Imidazolinone tolerance was implemented in the OSR genome by conventional breeding methods due to mutagenesis [10]. Non-CL OSR varieties would perish after an imidazolinone treatment [11].

This offers several agronomic advantages. CL herbicides have high efficacy against cruciferous weeds, which are hard to control with common agents in OSR. Common OSR volunteers can be controlled in CL OSR crops, and thus, the CL-System can contribute to a reduction of an OSR soil seed bank as long as its prevention strategies are working after the establishment of CL OSR in a crop rotation [7,10,11]. Greenhouse trials have shown that when = CL varieties are grown, similar yields are achieved as when non-CL varieties are used. A yield depression in the field due to the variety is therefore not to be expected [12]. The development of new herbicides with new modes of action is not expected in the near future. Approval procedures are time-consuming and cost-intensive. There is a desire in society for environmentally friendly agriculture, and widely used cultivation systems consisting in the use of a total herbicide with a crop that is tolerant to it are cost-effective. Newly developed, expensive herbicides would therefore be at a competitive disadvantage [13]. The application of the CL system enables the more effective use of existing herbicidal active substances. In addition, farmers' workload peaks are reduced due to the application time of CL Vantiga® D in a post-emergence stage. The possible application period of the CL herbicide is relatively long without damaging the OSR crop [14]. In locations with high occurrences of non-CL volunteer OSR, the CL system can lead to their reduction. Non-CL volunteer OSR is effectively controlled by CL herbicides in a CL oilseed rape crop [11]. The agronomic disadvantages associated with volunteer OSR can thus be reduced. Volunteer OSR competes with the cultivated crop [15], and in grown hybrid oilseed rape, it reduces the yield per unit area, as it has a lower genetic yield potential [16,17]. Volunteer OSR is a vector of pathogens in the crop rotation [18], frost tolerance of grown OSR is reduced, as a higher plant density in autumn leads to a critical stimulation of length growth, and oil quality of the grown OSR can be influenced negatively [19].

Critically must be considered, that the herbicide tolerance will be inherited to progenies of the CL OSR crop. Moreover, there is a cross tolerance to some sulfonyl ureas [11]. Under unfavourable conditions regarding to tillage timing and weather conditions seeds from harvest losses or natural pod shatter can enter the soil seed bank which will appear later as volunteers [20–22]. These seeds emerge in subsequent crops where chemical control is more challenging [23,24]. Other risks in confusing herbicides exist, especially if CL and non-CL varieties are grown on the same farm. Applying CL-herbicides on non-CL varieties could lead to a total loss. In addition, there is an increased likelihood of weed resistance developing in ALS inhibitors when CL-herbicides are applied, as ALS inhibitors are commonly used in crop rotation, but they are not applied in non-CL OSR. The additional application in CL OSR provides higher selection pressure on weeds [25,26].

Previous studies have shown that modern, hybrid oilseed rape varieties can achieve similar yields under different management intensities (MI) due to their competitive ability. In particular, with respect to different seed densities, row widths, and types of tillage. Weed emergence and weed composition may differ among these variants [1,2,27–31].

The performance of the CL-System in OSR under different MI in terms of grain yield criteria and weed emergence compared to a more common practice pre-emergence herbicide strategy (HS) has not yet been scientifically evaluated under Central European conditions. The aim of the study is to conduct such an assessment. We hypothesised that (i) the applied CL-herbicides and these of the common agricultural practice show comparable efficacies, (ii) MI has an effect on weed emergence but does not affect yield, and (iii) the HS does not affect the yield.

## 2. Materials and Methods

A two-year field experiment (2014/2015 and 2015/2016) with three management intensities (MI; main factor) and two herbicide strategies (HS; sub factor) of Clearfield® oilseed rape (*Brassica napus*; winter variety 'PT228CL'; CL OSR) was conducted. The trial was set up in a split-plot design with a plot size of 10 m × 6 m and four replicates at the agricultural experiment station, 'Ihinger Hof,' of the University of Hohenheim, Renningen, South-West Germany. The predominant soil type is classified as Luvisol on both fields, with loam as the soil type. The long-term mean annual temperature of the site was 8.3 °C, and the average annual precipitation of the location was about 690 mm.

MI was defined as a combination of primary tillage, sowing density, and row spacing. It consisted of three treatments: (i) standard sowing density (StS), (ii) reduced sowing density (RD), and strip-till (ST). In NS, sowing was performed by a drill with a sowing density of 50 seeds $m^{-2}$ and a 12 cm row spacing after primary tillage by mouldboard ploughing at 25 cm depth. In RD, precision seeding was performed with 50 cm row spacing and a sowing density of 25 seeds $m^{-2}$, also after mouldboard ploughing at 25 cm. For ST, sowing density and row spacing were the same as in RD, but strip tillage was conducted instead of ploughing. In the trial year 2015, the previous crop was winter barley (*Hordeum vulgare*), and in the trial year 2016, it was winter wheat (*Triticum aestivum*).

There were two HS treatments: (i) pre-emergence strategy (PES) and (ii) Clearfield® strategy (CLS). In PES, Colzor® Trio was applied at pre-emergence of the crop, for a broad-spectrum weed control, and Agil®-S was applied post-emergence to control grass weeds, especially volunteer cereals (Table 1). In CLS, Clearfield®-Vantiga® D was applied at post-emergence at the same time as Agil®-S in PES. In CLS, no graminicide was applied because Clearfield®-Vantiga® D has a partial control effect on grass weeds, according to the company.

For all treatments, the CL OSR variety PT228CL was sown (Table 1). In 2016, Fusilade Max® was applied as a graminicide to all plots due to a high density of emerged volunteer wheat, especially in ST CLS. All agronomic operations during the experiment are presented in Table 1. Weed density and composition was recorded by using a 1 $m^2$ estimation frame on 18 April 2015 and 12 April 2016 at OSR BBCH 57.

In the centre of each plot, a 2 × 10 m strip was harvested with a plot combine. The grain yield in t dry weight (DW) per ha was calculated from the strip harvested after cleaning and drying each sample (24 h at 95 °C until constant weight).

*Statistical Analysis*

The statistical analysis was accomplished using the procedure MIXED of the software package SAS 9.3 (SAS Institute, Cary, NC, USA). To ensure variance homogeneity, the weed density data of 2016 were square root transformed. For all other data sets, a transformation was not necessary. If a factor was identified to be significant at $\alpha = 0.05$, the means were compared using the Student's *t*-test. For presentation purposes, means and standard errors of means were back-transformed after statistical analysis.

**Table 1.** Agronomic treatments during the Clearfield® OSR management intensities experiment.

| Date (dd.mm.yy) | Treatment | Active Agent | Trade Name/Company | Herbicide Strategy |
|---|---|---|---|---|
| | | 2015 | | |
| 22.08.14 | Sowing | - | PT228CL/Pioneer | PES, CLS |
| 23.08.14 | Herbicide | 750 g $ha^{-1}$ dimethachlor<br>750 g $ha^{-1}$ napropamide<br>120 g $ha^{-1}$ clomazone | Colzor® Trio/Syngenta | PES |
| 16.09.14 | Herbicide | 70 g $ha^{-1}$ prapaquizafop | Agil®-S/Adama | PES |
| 16.09.14 | Herbicide | 750 g $ha^{-1}$ metazachlor<br>12.5 g $ha^{-1}$ imazamox<br>250 g $ha^{-1}$ quinmerac | Clearfield®-Vantiga® D /BASF | CLS |
| 09.09.14 | Insecticide | 7.5 g $ha^{-1}$ deltamethrin | Decis® flüssig/Bayer CropScience | PES, CLS |
| 26.09.14 | Insecticide | 7.5 g $ha^{-1}$ deltamethrin | Decis® flüssig/Bayer CropScience | PES, CLS |
| 15.04.15 | Insecticide | 57.5 g $ha^{-1}$ etofenprox | Trebon® 30 EC/BASF | PES, CLS |
| 23.04.15 | Insecticide | 72 g $ha^{-1}$ thiacloprid | Biscaya®/Bayer CropScience | PES, CLS |
| 06.05.15 | Insecticide | 48 g $ha^{-1}$ tau-fluvalinate | Mavrik® Citro Pack/Adama | PES, CLS |
| 06.05.15 | Fungicide | 250 g $ha^{-1}$ azoxystrobin | Ortiva®/Syngenta | PES, CLS |
| 01.10.14 | Fertiliser | calcium ammonium nitrate (40 kg N $ha^{-1}$) | YaraBela® EXTRAN 27®/Yara International | PES, CLS |
| 10.03.15 | Fertiliser | ammonium sulphate nitrate (90 kg N $ha^{-1}$) | Domogran® 45/Domo Chemicals | PES, CLS |
| 08.04.15 | Fertiliser | ammonium sulphate nitrate (90 kg N $ha^{-1}$) | Domogran® 45/Domo Chemicals | PES, CLS |
| 22.07.15 | Harvest | | | PES, CLS |
| | | 2016 | | |
| 26.08.15 | Sowing | - | PT228CL/Pioneer | PES, CLS |
| 26.08.15 | Herbicide | 750 g $ha^{-1}$ dimethachlor<br>750 g $ha^{-1}$ napropamide<br>120 g $ha^{-1}$ clomazone | Colzor® Trio/Syngenta | PES |
| 30.09.15 | Herbicide | 70 g $ha^{-1}$ prapaquizafop | Agil®-S/Adama | PES |
| 30.09.15 | Herbicide | 750 g $ha^{-1}$ metazachlor<br>12.5 g $ha^{-1}$ imazamox<br>250 g $ha^{-1}$ quinmerac | Clearfield®-Vantiga® D /BASF | CLS |
| 05.04.16 | Insecticide | 57.5 g $ha^{-1}$ etofenprox | Trebon® 30 EC/BASF | PES, CLS |
| 05.04.16 | Fungicide | 56 g $ha^{-1}$ prothioconazole<br>112 g $ha^{-1}$ tebuconazole | Tilmor®/Bayer CropScience | PES, CLS |
| 11.04.16 | Insecticide | 72 g $ha^{-1}$ thiacloprid | Biscaya®/Bayer CropScience | PES, CLS |
| 12.04.16 | Herbicide | 125 g $ha^{-1}$ fluazifop-p-butyl | Fusilade Max®/Syngenta | PES, CLS |
| 22.04.16 | Insecticide | 40 g $ha^{-1}$ acetamiprid | Mospilan® SG/Cheminova | PES, CLS |
| 10.03.16 | Fertilizer | ammonium sulphate nitrate (78 kg N $ha^{-1}$) | Domogran® 45/Domo Chemicals | PES, CLS |
| 07.04.16 | Fertilizer | ammonium sulphate nitrate (100 kg N $ha^{-1}$) | Domogran® 45/Domo Chemicals | PES, CLS |
| 22.07.15 | Harvest | | | PES, CLS |

## 3. Results

### 3.1. Grain Yield

In 2015, the OSR grain yield ranged between 3.6 t $ha^{-1}$ (ST CL) and 3.9 t $ha^{-1}$ (StS PES; Figure 1, 2015). The effects of the main factors, MI and HS, were significant, but their interactions had no significant effect. The herbicide strategy PES (3.8 t $ha^{-1}$) yielded 2.7%, significantly higher than CLS (3.7 t $ha^{-1}$; not shown graphically). The statistical analysis for MI revealed significant differences between StS (3.9 t ha$^{-1}$) and ST (3.6 t ha$^{-1}$). Neither treatments differed significantly from RD (3.8 t ha$^{-1}$; not shown graphically).

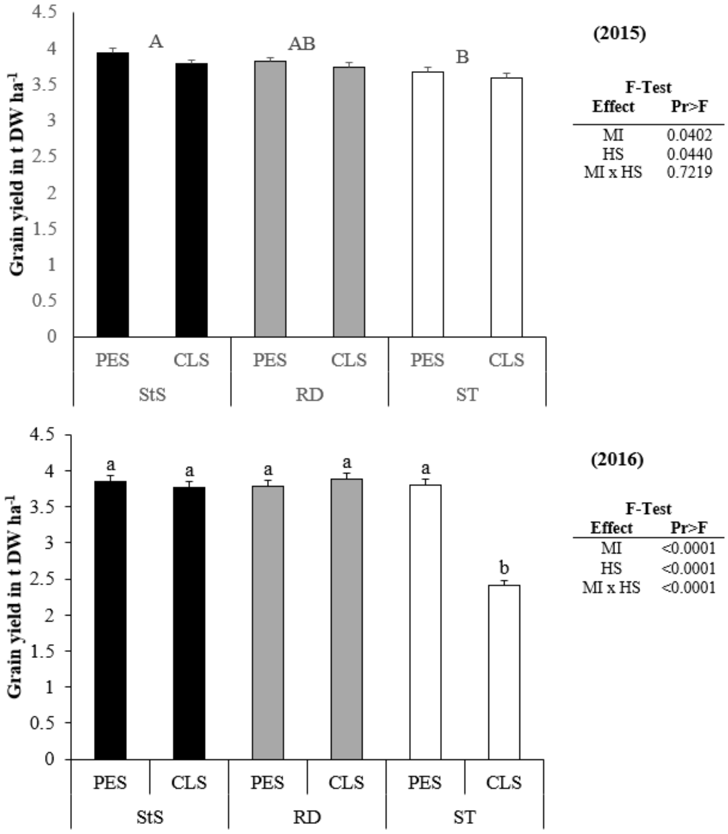


**Figure 1.** Grain yield of Clearfield®-oilseed rape (t DW ha$^{-1}$) as effect of different management intensities and herbicide strategies in the years 2015 and 2016, experimental station Ihinger Hof. StS: standard sowing (mouldboard ploughing, 50 seeds m$^{-2}$, 12 cm row spacing); RD: reduced sowing density (mouldboard ploughing, 25 sown seeds m$^{-2}$, 50 cm row spacing); ST: strip-till (strip tillage, 25 seeds m$^{-2}$, 50 cm row spacing); PES: pre-emergence application of Colzor® Trio and post-emergence application of Agil®-S. CLS: post-emergence application of Clearfield®-Vantiga®-D. Values labelled by the same letter are not significantly different. 2015: letters refer to the main effects of StS, RD and ST, for 2016: letters refer to the interactions ($p \leq 0.05$; Student's *t*-test). Error bars: standard error of mean.

In 2016, the OSR grain yield ranged from 2.4 t ha$^{-1}$ (ST CLS) to 3.9 t ha$^{-1}$ (RD CLS; Figure 1, 2016). The interactions between MI and HS were significant. The variant ST CLS yielded between 36% and 38%, significantly lower than the others, which did not differ among themselves.

### 3.2. Grain Yield Structure

The grain yield structure elements PD, PpP, SpP, and TKW were mainly influenced by the factor MI (Table 2). The effects of HS occurred exceptionally in 2016 for PpP and TKW. PD was highest in StS (2015: 36.0, 2016: 35.1; main effects of MI and HS not shown in the table). PD of RD (2015: 15.6, 2016: 19.7) and ST (2015: 15.5, 2016: 17.3) did not significantly differ within one year. In 2015, PpP in StS (334.2) was significantly lower compared to RD (552.9) and ST (482.7), which did not significantly differ among themselves. In 2016, PpP of StS (567.1) and RD (635.3) were higher than in ST (361.1), and CLS resulted in higher values (566.7) than PES (475.6). In 2015, SpP of StS (11.6) differed from ST (22,1), whilst both showed no differences with RD (16.6). In 2016, SpP of StS (7.4) and RD (11.8) were significantly lower than in ST (19.7). TKW of RD (3.373 g) and ST (3.488 g) were significantly lower than StS (3.644 g) in 2015. In 2016, TKW ranged from 3.4463 g (ST CLS) to 3.6355 g (RD PES). HS variants of StS and ST did not differ significantly. The highest TKWs were observed in RD, in which PES reached a significantly higher value than CLS (3.5365 g).

**Table 2.** Grain yield structure of Clearfield®-oilseed rape as effect of different management intensities (MI) and herbicide strategies (HS) in the years 2015 and 2016, experimental station Ihinger Hof. StS: standard sowing (mouldboard ploughing, 50 seeds $m^{-2}$, 12 cm row spacing); RD: reduced sowing density (mouldboard ploughing, 25 sown seeds $m^{-2}$, 50 cm row spacing); ST: strip-till (strip tillage, 25 seeds $m^{-2}$, 50 cm row spacing); PES: pre-emergence application of Colzor® Trio and post-emergence application of Agil®-S. CLS: post-emergence application of Clearfield®-Vantiga®-D. Grain yield structure elements: plant density (PD) in plants $m^{-2}$, pods per plant (PpP), seeds per pod (SpP) and thousand-kernel weight (TKW) in g. Values labelled by the same letter are not significantly different. Capital letters refer to effects of MI; lowercase letters refer to interactions of MI × HS ($p \leq 0.05$; Student's *t*-test).

| Factor | | Grain Yield Structure | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 2015 | | | | | | | | 2016 | | | | | | | |
| MI | HS | PD | | PpP | | SpP | | TKW | | PD | | PpP | | SpP | | TKW | |
| StS | PES | 35.4 | A | 384.8 | B | 10.4 | B | 3.587 | A | 35.4 | A | 605.2 | A | 6.8 | B | 3.4465 | c |
| | CLS | 36.5 | | 283.5 | | 12.8 | | 3.700 | | 34.7 | | 529.0 | | 8.0 | | 3.5135 | bc |
| RD | PES | 15.8 | B | 529.9 | A | 15.7 | AB | 3.338 | B | 19.5 | B | 681.5 | A | 11.2 | B | 3.6355 | a |
| | CLS | 15.3 | | 575.9 | | 17.4 | | 3.407 | | 19.8 | | 589.0 | | 12.3 | | 3.5365 | b |
| ST | PES | 15.8 | B | 425.1 | A | 20.8 | A | 3.501 | B | 20.5 | B | 413.4 | B | 19.4 | A | 3.4673 | bc |
| | CLS | 15.1 | | 540.2 | | 23.4 | | 3.475 | | 14.0 | | 308.8 | | 19.9 | | 3.4463 | c |

### 3.3. Weed Density and Composition

While the weed flora was composed by barley volunteers and a variety of wild plants such as *Viola arvensis* and *Stellaria media* in 2015, wheat volunteers dominated in 2016 (Figure 2). In both years, significant interactions occurred in weed density between management intensity and herbicide strategy. The highest weed numbers were observed in 2015 under the herbicide strategy CLS in strip-till (ST) and in reduced sowing density. In ST, barley volunteers were the major group of weeds. In 2016, weed density (mainly wheat volunteers) was clearly highest in ST with CLS.

CLS and PES resulted in similar weed densities when plants were managed in StS (2015 and 2016) or in RD (2016).

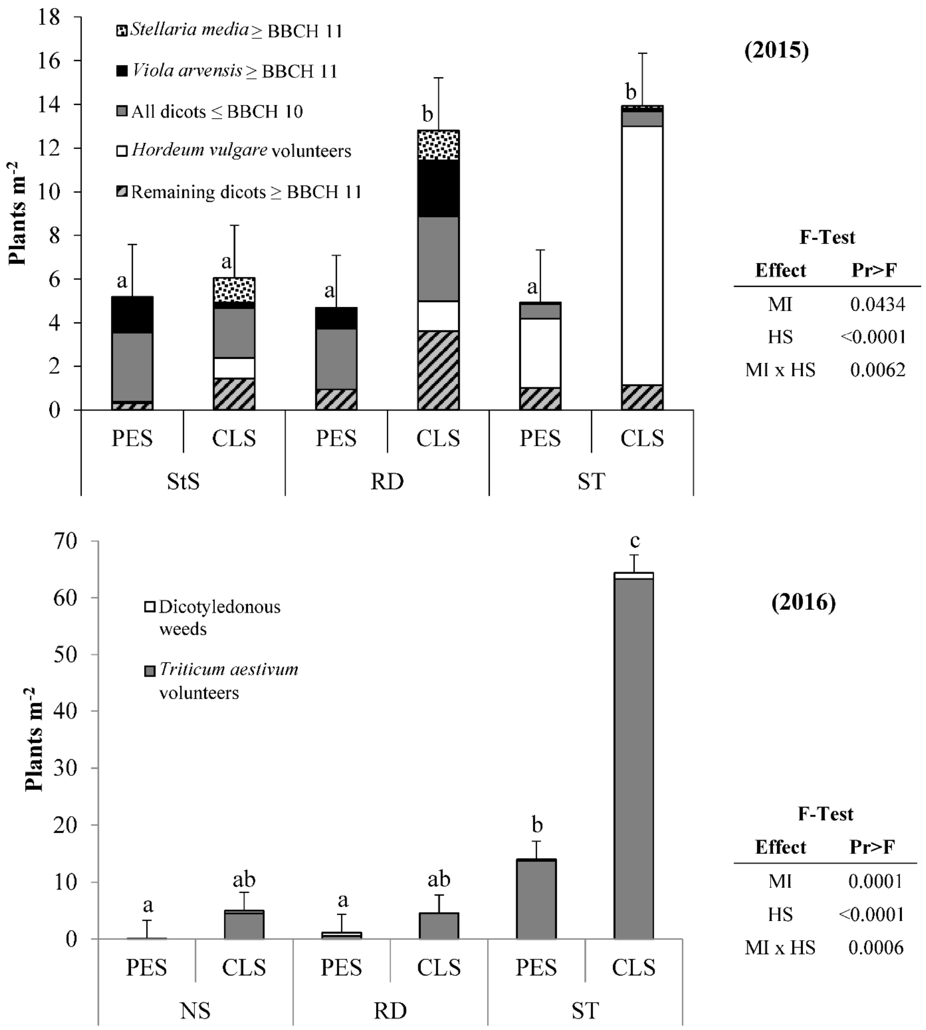


**Figure 2.** Weed density and weed composition in plants $m^{-2}$ in Clearfield®-oilseed rape as effect of different management intensities and herbicide strategies in the years 2015 and 2016, experimental station Ihinger Hof. StS: standard sowing (mouldboard ploughing, 50 seeds $m^{-2}$, 12 cm row spacing); RD: reduced sowing density (mouldboard ploughing, 25 sown seeds $m^{-2}$, 50 cm row spacing); ST: strip-till (strip tillage, 25 seeds $m^{-2}$, 50 cm row spacing); PES: pre-emergence application of Colzor® Trio and post-emergence application of Agil®-S. CLS: post-emergence application of Clearfield®-Vantiga®-D. Values labelled by the same letter are not significantly different; letters refer to the total number of weeds per variant ($\alpha$ = 0.05; Student's *t*-test). Error bars: standard error of mean. Experimental station: Ihinger Hof.

## 4. Discussion

The application of the Clearfield® system in OSR resulted in similar grain yields as the usual, pre-emergence system independent of MI, although weed emergence was higher in the RD and ST variants in particular than in the StS variant. The OSR hybrid variety, PT228CL, showed a high competitive strength, which is very common for modern OSR hybrid varieties, and showed no yield depression [29–32]. The only exception was the ST CLS variant in 2016, where a lower grain yield was recorded. Yield differences in terms of management intensities in 2015 can likely be attributed to better emergence conditions due to differences in tillage. The use of the plough in StS and RD showed advantages that which were mainly due to a clean and reconsolidated seedbed, faster soil warming, and better weed control. The often-described advantage of the strip-till system's lower water requirements and better seed placement did not show an effect. This can be traced back to the favourable weather and growing conditions at the trial site [27,28].

The yield structure was mainly influenced by MI and is dependent on OSR plant density and the spatial distribution of OSR plants. Differences in the yield structure resulted from the effects of intraspecific competition. The higher the plant density and the smaller the distance between the plants, the higher the intraspecific competition and the lower the yield per individual plant. The OSR plants react, in particular, with changes in the number of pods and the number of grains per pod [33]. A high plant density (StS) leads to higher intraspecific competition due to the smaller distance between the plants and thus, a lower number of pods per plant and a lower number of seeds per pod. The opposite could be observed with low OSR plant density (RD, ST). In particular, the pods per plant ranged from 283.5 in StS CLS 2015 to 681.5 in RD PES 2016, and the seeds per pod ranged from 6.8 in StS PES 2016 to 23.4 in ST CLS, which shows a strong adaptability of OSR using different sowing rates and the associated cropping system. This was also reported in previous studies [29,33–35]. This exhibits a high degree of flexibility for farmers to choose the right sowing density without expecting yield losses.

Both trial years differed in weed density and weed composition. In 2015, winter barley (*Hordeum vulgare* L.) was the preceding crop; in 2016, it was winter wheat (*Triticum aestivum* L.). While various dicot weeds and volunteer barley occurred in 2015, volunteer wheat was predominant in 2016. Within MI, smaller differences occurred between PES and CLS in weed density in 2015 compared to 2016, especially for the ST variants. The differences in weed composition in both years resulted from the rotation of the experimental field and from different previous crops. It can be assumed that different soil seed banks were present on both trial fields, which resulted in the emergence of different weeds. The higher density of volunteer wheat in 2016, especially in the ST CLS variant, may be due to higher seed potential or lower efficacy of Clearfield® Vantiga®-D against volunteer wheat compared to volunteer barley. The cause of an increased seed potential could be due to suboptimal combine settings or harvest conditions which resulted in a higher loss during the wheat harvest.

In both trial years, weed density was lowest in the StS PES and RD PES variants. This was due to the broad efficacy of the PES herbicide system and the weed-reducing effect of plowing. It ensures deep burial of emerged weed plants and weed seeds, which results in fewer emerging weeds during the vegetation period and can be considered as a sustainable weed control effect. This is especially true for the StS variant, as 50 seeds were sown instead of 25 compared to RD. This ensures faster shading of the soil and thus a lower weed emergence in StS [1,36]. As a result, no significant differences in weed density were found in the StS variant between PES and CLS in either trial year. However, in the CLS variant using the other two management intensity variants (RD, ST), partly higher weed densities were found. It can therefore be assumed that the Clearfield® herbicide Vantiga®-D shows a lower effectiveness in weed control, but this could be compensated by a higher seed rate in the StS variant.

In the strip-till method, higher rates of volunteer emergence from the previous crop can generally be expected resulting from the method of soil tillage and could be observed in both years. Volunteers from seed losses are less controlled or buried due to a lack of tillage between rows before sowing the next crop. On the other hand, other weeds hardly emerged, as they are not stimulated to germinate by a lack of tillage. As a result, there is a strong weed pressure due to volunteers. Consequently, this led to a drop in grain yield in ST CLS 2016, while the other variants did not differ significantly in 2016. Fewer volunteer cereals occurred overall in the PES variants. An additional herbicide treatment with the foliar active ingredient, prapaquizafop, in postemergence provided a reliable control.

The Clearfield® system in OSR was developed primarily for sites where cruciferous weeds are difficult or impossible to control with existing herbicides in oilseed rape, or where an increased emergence of non-Clearfield® OSR volunteers is to be expected. There were no difficult-to-control cruciferous weeds on the trial fields, nor was there an increased incidence of volunteer oilseed rape on these fields. Nevertheless, the Clearfield® system in this study was shown be an alternative to the more common pre-emergence system, especially with regard to the parameter grain yield. However, one application of the foliar-active grass herbicide could be saved compared to the pre-emergence system. As a result, depending on MI, the partly increased emergence of volunteer cereals (especially in the trial year 2016) can be prevented in agricultural practice by the additional application of such a grass herbicide (such as propaquizafop in this study). It can be assumed that the Clearfield® system performs better than the pre-emergence system in terms of both yield and weed control effectiveness, particularly in areas where cruciferous weeds pose a challenge to oilseed rape cultivation.

## 5. Conclusions

The Clearfield® herbicide system in oilseed rape can achieve similar grain yields as a more common, pre-emergence herbicide system. With larger row spacing or lower tillage intensity, higher weed pressure may be expected when using the Clearfield® system. However, this does not necessarily have a negative effect on grain yield. Reduced effects of the Clearfield® system on grasses or volunteer cereals can be countered in agricultural practice with the additional application of a graminicide. The Clearfield® system expands farmers' options for chemical weed control in oilseed rape.

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# 4 Publikation II

Sebastian Schwabe, Ernst Albrecht Weber, Samuel Gesell, Sabine Gruber, Wilhelm Claupein (2019):

**Overcoming seed dormancy in oilseed rape (*Brassica napus* L.) with exogenous compounds**

Weed Research

*Ausfallrapssamen können eine sekundäre Dormanz entwickeln, im Boden überdauern und als Durchwuchsraps in den Folgefrüchten auflaufen. Wenn Durchwuchsraps von herbizidtoleranten Kulturraps, wie beispielsweise Clearfield®-Raps abstammt, ist er durch die Vererbbarkeit der Herbizidtoleranz in den Folgekulturen schwerer chemisch zu bekämpfen. Weiterhin steht Durchwuchsraps als Unkraut in Konkurrenz zur jeweiligen Kultur, dient als grüne Brücke für Pathogene und kann in Kulturraps Wachstum und Qualität negativ beeinflussen. Zur Ermöglichung einer aktiven, prophylaktischen Verhinderung der Durchwuchsrapsproblematik wurde in Labor- und Feldversuchen untersucht, inwieweit eine Samenbehandlung mit Nährstoffen und Gibberellinsäure einen Einfluss auf die Verminderung von Dormanzbildung und Überdauerungsfähigkeit von Rapssamen besitzt.*

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# Overcoming seed dormancy in oilseed rape (*Brassica napus L.*) with exogenous compounds

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## Summary

Dormant seeds of oilseed rape (OSR) can persist in the soil and cause OSR volunteers in subsequent crops. Several approaches were tested in the laboratory and in the field to determine whether dormancy induction and seed persistence can be reduced by using dormancy-breaking exogenous compounds. In a laboratory experiment, OSR seeds were coated with $KNO_3$, micronutrients, or gibberellic acid (GA) prior to a secondary dormancy test. In a field experiment, seeds were coated in a manner analogous to the laboratory experiment, and then buried 10 cm deep in the soil for 2.5 months. In a practical demonstration, OSR plants were sprayed with either urea ammonium nitrate (UAN) or a commercial product containing GA prior to seed maturity. Seed coating (laboratory and field experiments) reduced secondary dormancy and seed persistence in the field by up to 99%. The efficiency of the treatments for mitigating secondary dormancy (laboratory and field experiments) in decreasing order was GA > micronutrients > $KNO_3$ > control. With pre-maturity spraying (practical demonstration), UAN reduced primary dormancy by up to 77% and the development of secondary dormancy by up to 38%; GA had no effect. Dormancy and seed persistence of OSR seeds may be reduced by a pre-maturity UAN treatment of OSR mother plants, or by applying appropriate exogenous compounds to OSR seeds.

**Keywords:** soil seedbank, phytohormones, dormancy breaking, micronutrients, $KNO_3$, canola.

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## Introduction

Oilseed rape (OSR; *Brassica napus* L.) seeds from harvest losses can develop secondary dormancy when exposed to unfavourable germination conditions, such as osmotic stress or oxygen deficiency in darkness (Momoh *et al*., 2002). This would be the case when OSR seeds are buried by tillage under dry conditions (Gruber *et al*., 2004a; Huang *et al*., 2015). Secondarily dormant OSR seeds form a soil seedbank and are able to emerge as volunteers in following crops for up to 11 years (Andersen *et al*., 2010). *Brassica napus* volunteers can affect crop yield (Krato & Petersen, 2012), and they are of particular concern if they become weeds in the sown OSR, because selective chemical control can then become difficult, especially when OSR varieties without herbicide-resistant traits are grown. Moreover, volunteers can reduce OSR oil quality and potentially spread herbicide-resistant genes. Apart from secondary (induced) dormancy, OSR seeds can show primary (innate) dormancy to a small extent at harvesting (Momoh *et al*., 2002; Huang *et al*., 2016), which rapidly decreases to zero after <6 months of storage (Gruber *et al*., 2004a).

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Strategies to reduce OSR seed persistence in the soil already exist. By growing OSR varieties that tend to have lower secondary dormancy levels, the likelihood of seed survival in the soil is reduced (Gruber *et al.*, 2009; Huang *et al.*, 2016). In areas with harsh winter conditions, the soil seedbank is decreased by winterkill because emerging OSR volunteers perish as a result of very low temperatures in winter (Geddes & Gulden, 2017). Also, the amount of OSR seeds that enter the soil seedbank can be reduced by delayed stubble tillage in combination with a deep primary tillage (Gruber *et al.*, 2004b, 2010; Huang *et al.*, *2015*).

Seed dormancy is reduced, and germination promoted by nitrate, gibberellic acid ($C_{19}H_{22}O_6$; GA) and micronutrients (Finch-Savage & Leubner-Metzger, 2006; Bojovic, 2010; Farooq *et al.*, 2011; Arefi *et al.*, 2012; ISTA, 2013; Dresch *et al.*, 2014). Therefore, these chemicals seem worthy of further study for the development of additional strategies to avoid a persistent soil seedbank. If seeds from harvest losses drop onto the soil, seeds could theoretically be treated by the application of dormancy reduction agents to avoid secondary dormancy. Also, a reduction in the potential of dormancy development of OSR seeds during seed development on the mother plant would minimise the establishment of a soil seedbank.

The aim of this study was to test: GA, Gibb$_3$® (a GA-containing commercial plant protection product), micronutrient suspensions Wuxal® Terios (WT) and Wuxal® Semilion (WS), urea ammonium nitrate solution (UAN) and potassium nitrate ($KNO_3$), for their ability to prevent or reduce the ability of OSR seeds to become dormant. Three consecutive trials (one laboratory, one field experiment and one practical demonstration) were set up. First, the efficacies of proposed dormancy reduction agents were determined on mature seeds. Second, as a demonstration of practical applicability, OSR plants were sprayed with dormancy reduction agents during seed development to show their effect on primary and secondary dormancy development. We hypothesised (i) that all tested exogenous compounds would reduce the induction of secondary dormancy, (ii) that different exogenous compounds differ in their efficacy to reduce secondary dormancy induction, (iii) that both low- and high-dormancy varieties would respond to the application of the exogenous compounds, and (iv) that secondary dormancy induction of high-dormancy varieties is more reduced compared with that of low-dormancy varieties.

## Material and methods

### *Plant materials*

In all experiments, OSR varieties with different dormancy levels were chosen. Because of time lags between experiments and interest in using contemporary varieties, varieties differed among the three experiments. After harvesting, the seeds were stored in darkness at 5°C with a moisture content of 8% until the start of the experiments. Prior to the experiments, the seeds were inspected visually; only intact seeds were used.

### *Dormancy tests*

To investigate seed persistence as well as primary and secondary dormancy, different testing procedures were used. For the laboratory experiment, secondary dormancy of seeds was tested following the Rapid Dormancy test (Weber *et al.*, 2010). For the practical demonstration, primary dormancy and secondary dormancy of the seeds were tested in accordance with the Hohenheim Standard Dormancy test (Weber *et al.*, 2010). The persistence rate of seeds in the field experiment was determined by a germination test, which is also a subprocedure. It is also a subprocedure of the Rapid Dormancy test and the Hohenheim Standard Dormancy test to examine seeds' viability.

The Rapid Dormancy test was performed by first subjecting seeds to conditions known to induce secondary dormancy in OSR seeds. Specifically, seeds were placed in Petri dishes (diameter: 8.5 cm; 50 seeds per Petri dish) that contained a polyethylene glycol ($HO(C_2H_4O)_nH$; PEG; average molecular weight 5000 g mol$^{-1}$) solution that generated an osmotic potential of $-15$ bar (354.4 g PEG in 1 L deionised water). Petri dishes with seeds and PEG solutions were kept in darkness at 20°C for 7 days. Seeds were then subjected to conditions conducive to germination by transferring them in darkness to Petri dishes with a double layer of filter paper and 8 mL of deionised water. Petri dishes with seeds and water were kept in darkness at 20°C for 7 days. Non-dormant seeds germinated during this period. Afterwards, ungerminated seeds were tested for viability for 7 days (12 h darkness and 3°C, 12 h light and 30°C: this environment terminates dormancy and stimulates germination). Viable seeds, which did not germinate prior to the viability test, were defined as secondary dormant seeds. The dormancy potential was then calculated as a percentage; the number of dormant seeds was divided by the total number of viable seeds used in the test.

 

To investigate secondary dormancy in accordance with the Hohenheim Standard Dormancy test, 100 seeds per laboratory replicate were put in darkness into Petri dishes (diameter: 8.5 cm) fitted with filter paper and filled with 8 mL PEG solution (354.4 g in 1 L $H_2O$). Afterwards, the seeds were moved in darkness to a germination cabinet for 14 days at 20°C. During this time, germinated seeds and seed losses (mouldy and soft seeds) were counted and removed, according to ISTA (2013). Ungerminated, firm and viable-looking seeds were classified as potentially dormant. For testing actual viability, seeds were exposed to conditions that stimulate germination (7 days under 12 h darkness at 3°C, 12 h light at 30°C). Germinated seeds were counted, and the dormancy potential was then calculated in the same way, as in the Rapid Dormancy test. Primary seed dormancy was assessed with the Hohenheim Standard Dormancy test without the first step that induces secondary dormancy.

### *Dormancy induction in PEG with pre-treated seeds (Laboratory Experiment)*

Seeds of the OSR varieties Lilian and Nemax harvested in 2009 were coated with different agents during May–June 2012. Seeds were stored from harvest until use in darkness at 5°C. Agents evaluated were solutions of $KNO_3$, gibberellic acid (GA), Gibb$_3$®, WS and WT at different concentrations (Table 1). Gibb$_3$® is a GA-containing growth regulator used in viniculture to improve air circulation within fruit clusters of grape (*Vitis* sp.). Concentration is provided in Table 1. WS and WT are highly concentrated nutrient suspensions for seed treatment of cereals, cotton and rice, which were developed to promote germination and seedling vigour under adverse growing conditions.

To increase the adhesion of agents to seeds, 2 g talcum ($Mg_3Si_4O_{10}(OH)_2$) was added per 100 mL for the $KNO_3$, GA and Gibb$_3$® solutions. The coating procedure was done as follows: 20 µL (GA-, $KNO_3$-, Gibb$_3$®, deionised water, deionised water + talcum) or 40 µL (WT, WS) of the solutions was added to Petri dishes containing 50 seeds each. Using forceps, the seeds were then carefully rolled to spread the agents uniformly over the seed surfaces. Coated seeds were dried at room temperature for 24 h. Seeds were then subjected to the Rapid Dormancy test (for method, see description under Dormancy test). Petri dishes (diameter: 8.5 cm) containing the treatments (variety × coating) were arranged in an germination cabinet with four replicates during the dormancy test procedure.

### *Seed burial in the soil with pre-treated seeds (field experiment)*

The field experiment was performed from June to September 2012 at an experimental field (Luvisol, soil type: clay loam) of the University of Hohenheim, Stuttgart, South-West Germany. Seeds from the harvest 2009 (four replicates of 100 seeds per treatment) of the winter OSR varieties Lilian and Nemax from seed coating treatments 2, 3, 4, 6, 7 and 9 (Table 1) were enclosed in 10 × 10 cm fabric mesh bags and buried at 10 cm soil depth on 27 June 2012. The experiment was arranged in a randomised complete block design with four replicates. The mesh size of the bags was 0.5 mm. Prior to and immediately after seed burial, the experimental area (3 × 2 m) was covered by a foil tunnel for 14 and 7 days respectively, permitting the soil to dry, and to provide beneficial conditions for secondary dormancy induction. Precipitation and temperature data for the duration of the field experiment after removal of the foil tunnel are displayed in Fig. 1.

After 2.5 months, the mesh bags were unearthed and intact non-germinated seeds were counted. The obviously intact persisted seeds then underwent a germination test (7 days under 12 h darkness at 3°C, 12 h light at 30°C) to determine whether the seeds are still viable. The persistence rate was calculated as a percentage of intact viable seeds after burial from the initial number of buried seeds.

### *Dormancy prevention by pre-maturity treatments in the field (practical demonstration)*

In the practical demonstration, two varieties of OSR were treated with agents that potentially inhibit dormancy induction. The OSR varieties used were NX2220 (NX) and NT132178H (NT). Applied agents were Gibb$_3$® and urea ammonium nitrate solution (UAN) in two different concentrations per agent (Table 2). The demonstration was a field study conducted in 2015 and repeated in 2016 in an experimental field (Luvisol, soil type: loam) at the agricultural experiment station 'Ihinger Hof' of the University of Hohenheim, Renningen, South-West Germany. OSR was sown on 27 August 2015 and 25 August 2016. For each year, the row spacing was 12 cm and the sowing density was 45 seeds $m^{-2}$. The agronomic practices during the growing season are listed in Table 3 for each trial year.

The practical demonstration was arranged in a split-plot design with four field replicates. Each main plot (variety) had dimensions of 6 m × 4 m in which the subplots (treatment) of 0.5 $m^2$ size were distributed randomly. On 22 June 2016 and on 19 June 2017 at

**Table 1** Exogenous compound treatments for oilseed rape seeds and their concentrations for a dormancy test (laboratory experiment) and a burial experiment (field experiment)

| | Treatment | Concentration | Inclusion of talcum | Comment | Source |
|---|---|---|---|---|---|
| 1 | Distilled water (control) | – | No | – | – |
| 2 | Control + talcum | 2% talcum | Yes | Talcum ($Mg_3Si_4O_{10}(OH)_2$) dissolved in deionised water | Rema AG, Poing, Germany |
| 3 | $KNO_3$ | 0.4% $KNO_3$ + 2% talcum | Yes | Dissolved in deionised water | Merck, Düsseldorf, Germany |
| 4 | Gibberellic acid (GA) 0.04 | 0.04% GA + 2% talcum | Yes | Dissolved in deionised water | Merck Schuchardt OHG, Hohenbrunn, Germany |
| 5 | GA 0.08 | 0.08% GA + 2% talcum | Yes | Dissolved in deionised water | |
| 6 | $Gibb_3$® | 1.0% $Gibb_3$ (=0.1% gibberellic acid) + 2.0% talcum | Yes | Commercial product, contains 10% Gibberellic acid dissolved in deionised water | Globachem Sint-Truiden, Belgium |
| 7 | Wuxal® Terios (WT 100) | Pure (100%) | No | Pure suspension, commercial product, contains 25 g Cu, 15 g Mn, 5 g Mo, 25 g Zn, 106 g $NH_4$-N, 150 g $P_2O_5$, 21 g S per litre | Wilhelm Haug GmbH & Co. KG, Düsseldorf, Germany |
| 8 | Wuxal® Terios (WT 50) | 50.0% | No | Dissolved in deionised water | |
| 9 | Wuxal® Semillion (WS 100) | Pure (100%) | No | Pure suspension, commercial product, contains 22.5 g N, 39 g S, 15 g B, 7.5 g Cu, 15 g Mn, 22.5 g Mo, 22.5 g Zn per litre | Wilhelm Haug GmbH & Co. KG, Düsseldorf, Germany |
| 10 | Wuxal® Semillion (WS 50) | 50.0% | No | Dissolved in deionised water | |

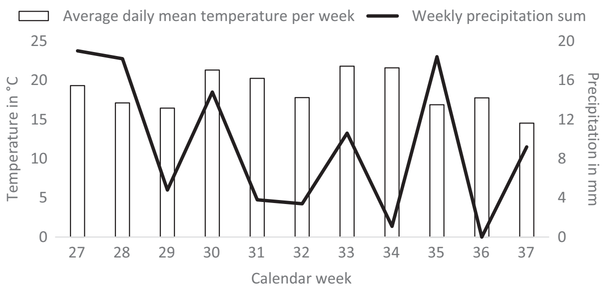


**Fig. 1** Average daily mean temperature in °C and weekly precipitation sum in mm for the duration of the field experiment at the University of Hohenheim after foil tunnel removal (calendar weeks in 2012).

OSR stage BBCH 77 (seed development), agents were applied by spraying with a mechanical hand-held sprayer in accordance with the application rates in Table 2. After OSR reached maturity, the upper parts of OSR plants with pods were collected manually on 19 July 2016 and on 17 July 2017. OSR plant materials were dried separately for each plot in cotton sacks at room temperature for 1 day. Afterwards, the harvested material was threshed and winnowed to isolate intact seeds without impurities. From July to August, the seeds underwent a laboratory experiment for testing primary and secondary dormancy in accordance with the Hohenheim Standard Dormancy test. From the harvested seed sample of one field replicate, four laboratory replicates of the Standard Dormancy test were sub-sampled.

### *Statistical analysis*

Statistical analyses for all experiments were conducted in accordance with the respective experimental designs using the procedure MIXED of the software package

**Table 2** Exogenous compound treatments at seed development stage of oilseed rape plants and their application rates to test their impact on primary and secondary dormancy

| Treatment | | Application rate | Comment | Source |
|---|---|---|---|---|
| 1 | Control | – | Without treatment | – |
| 2 | Urea ammonium nitrate solution low concentration (UANl) | 80 mL 2.78% UAN solution $m^{-2}$ | Equals 8 kg N $ha^{-1}$ | SKW Stickstoffwerke Piesteritz GmbH, Lutherstadt Wittenberg, Germany |
| 3 | Urea ammonium nitrate solution high concentration (UANh) | 80 mL 27.78% UAN solution $m^{-2}$ | Equals 80 kg N $ha^{-1}$ | |
| 4 | $Gibb_3$® low concentration ($Gibb_3$ l) | 80 mL 0.002% $Gibb_3$® solution $m^{-2}$ | Equals 1.6 g Gibberellic acid $ha^{-1}$ | Globachem Sint-Truiden, Belgium |
| 5 | $Gibb_3$® high concentration ($Gibb_3$ h) | 80 mL 0.02% $Gibb_3$® solution $m^{-2}$ | Equals 16 g Gibberellic acid $ha^{-1}$ | |

**Table 3** Agronomic treatments during the growing season of the practical demonstration

| Date | Treatment | Active agent | Trade name/manufacturer |
|---|---|---|---|
| Trial year 2016 | | | |
| 31 August 2015 | Herbicide | 500 g $ha^{-1}$ metazachlor<br>500 g $ha^{-1}$ dimethenamid<br>250 g $ha^{-1}$ quinmerac | Butisan® Gold/BASF |
| 08 October 2015 | Herbicide | 80 g $ha^{-1}$ prapaquizafop | Agil®-S/Adama |
| 26 October 2015 | Fungicide | 96 g $ha^{-1}$ prothioconazole<br>192 g $ha^{-1}$ tebuconazole | Tilmor®/Bayer CropScience |
| 15 March 2016 | Nitrogen fertiliser | Ammonium sulphate nitrate (90 kg N $ha^{-1}$) | Domogran® 45/Domo Chemicals |
| 05 April 2016 | Fungicide | 56 g $ha^{-1}$ prothioconazole<br>112 g $ha^{-1}$ tebuconazole | Tilmor®/Bayer CropScience |
| 05 April 2016 | Insecticide | 57.5 g $ha^{-1}$ etofenprox | Trebon® 30 EC/BASF |
| 07 April 2016 | Nitrogen fertiliser | Ammonium sulphate nitrate (90 kg N $ha^{-1}$) | Domogran® 45/Domo Chemicals |
| 11 April 2016 | Insecticide | 72 g $ha^{-1}$ thiacloprid | Biscaya®/Bayer CropScience |
| 22 April 2016 | Insecticide | 40 g $ha^{-1}$ acetamiprid | Mospilan® SG/Cheminova |
| Trial year 2017 | | | |
| 01 September 2016 | Herbicide | 500 g $ha^{-1}$ metazachlor<br>500 g $ha^{-1}$ dimethenamid<br>250 g $ha^{-1}$ quinmerac | Butisan® Gold/BASF |
| 05 October 2016 | Insecticide | 0.075 g $ha^{-1}$ Beta-Cyfluthrin | Bulldock®/Adama |
| 05 October 2016 | Herbicide | 80 g $ha^{-1}$ prapaquizafop | Agil®-S/Adama |
| 05 October 2016 | Herbicide | 93.5 g $ha^{-1}$ clopyralid<br>23.5 g $ha^{-1}$ picloram | Effigo™/Dow AgroSciences |
| 21 October 2016 | Nitrogen fertiliser | Calcium ammonium nitrate (30 kgN $ha^{-1}$) | YaraBela® EXTRAN 27®/Yara International |
| 15 March 2017 | Nitrogen fertiliser | Ammonium sulphate nitrate (80 kg N $ha^{-1}$) | Domogran® 45/Domo Chemicals |
| 03 April 2017 | Fungicide | 48 g $ha^{-1}$ prothioconazole<br>96 g $ha^{-1}$ tebuconazole | Tilmor®/Bayer CropScience |
| 03 April 2017 | Insecticide | 57.5 g $ha^{-1}$ etofenprox | Trebon® 30 EC/BASF |
| 06 April 2017 | Nitrogen fertiliser | Ammonium sulphate nitrate (90 kg N $ha^{-1}$) | Domogran® 45/Domo Chemicals |

SAS 9.3 (SAS Institute, Cary, NC). In the four experiments, different fixed effects, random effects and experimental designs were set up (Table 4).

In the laboratory and the field experiments, a transformation of data was necessary to normalise variances. The following arcsine-transformation, according to Chatterjee and Hadi (2012), was used:

$$y = \arcsin\left(\sqrt{\frac{d+\frac{3}{8}}{v+\frac{3}{4}}}\right), \quad (1)$$

where $y$ = transformed value, $d$ = number of dormant seeds and $v$ = number of viable seeds for the laboratory experiment and $y$ = transformed value,

**Table 4** Assumption for model parameters and experimental design of the experiments

| Experiment | Fixed effects | Random effects | Design |
|---|---|---|---|
| Laboratory | Seed coating treatment, replicate (separate analysis per variety) | Error | Randomised complete block design |
| Field | Seed coating treatment, replicate (separate analysis per variety) | Error | Randomised complete block design |
| Practical demonstration | Maternal plant treatment, field replicate (separate analysis per variety) | Field replicate * laboratory replicate error | Randomised complete block design |

$d$ = number of persisted seeds and $v$ = number of buried seeds for the field experiment.

In the practical demonstration, a data transformation was not necessary. For the laboratory experiment, the response variable was the secondary dormancy level of OSR seeds. In case of the field experiment, the response variable was the persistence level of OSR seeds. For the practical demonstration, the response variables were primary and secondary dormancy levels of the OSR seeds. The comparison of means was done within variety to highlight the efficacy of exogenous compounds within single varieties. Residuals were checked graphically for homogeneity and normal distribution. If the factor seed coating treatment within 1 year and one variety was identified to be significant at $\alpha = 0.05$, means were compared using the Student's *t*-test. For presentation purposes, means and standard errors of means were back-transformed after statistical analysis.

## Results

### Laboratory experiment

Coating of OSR seeds with potential dormancy-breaking or germination-promoting agents significantly reduced the induction of secondary dormancy (Fig. 2). The high-dormancy variety Lilian tended to show higher secondary dormancy than the variety Nemax in all treatments except those with GA. In both varieties, talcum had no effect on secondary dormancy induction compared with the control. While $KNO_3$ and WS 50 led to a significant reduction in the induction of secondary dormancy in Nemax, the secondary dormancy level of Lilian was not affected by $KNO_3$ or WS 50. WS 100 followed by both concentrations of WT resulted in a significant reduction in secondary dormancy in both varieties. Treatments containing gibberellic acid (Gibb$_3$® and GA) lowered secondary dormancy induction of both varieties even further to below 5%. The secondary dormancy induction of Nemax was 43% in the control and was reduced, depending on treatment, by between 54% and 97%.

### Field experiment

After the burial period, 97% of seeds were intact and non-germinated (data not shown). The rates of seed viability after burial did not differ between varieties (data not shown). Coating the seeds with any of the agents reduced the seed persistence of both OSR varieties over 3 months compared with untreated seeds (Fig. 3). While *c.* 40% of the seeds of Lilian and 14% of Nemax survived without germinating in the non-treated control, <17% (Lilian) or 2% (Nemax) of the seeds persisted when treated with $KNO_3$, and seed persistence was generally below 3% for both varieties when seeds were coated with WS 100, WT 100, Gibb$_3$® and GA 0.04 before burial (Fig. 3).

### Practical demonstration

In the trial year 2016, the levels of primary dormancy across varieties and treatments ranged between 3.3% [treatment with urea ammonium nitrate solution high concentration (UANh) of variety NT] and 14.5% (control, NT; Fig. 4A). Pre-harvest treatment had a significant effect on the level of primary dormancy. Only the treatment UANh resulted in primary dormancy significantly lower than the control (48.8% lower for NX and 77.2% lower for NT; Fig. 4A). No significant differences occurred across the pre-harvest treatments in the trial year 2017 (Fig. 4B). The level of primary dormancy ranged between 2.9% [treatment with urea ammonium nitrate solution low concentration (UANl) of variety NX] and 0.1% (UANl, NT; Fig. 4B).

In both trial years, all pre-harvest treatments in NX had no significant impact on the development of secondary dormancy (Fig. 5A and B). All treatments in NT resulted in lower dormancy values than all treatments in NX. In NT, only the pre-harvest treatment UANh (42.1% in trial year 2016; 28.8% in trial year 2017) showed a significant lower value than the

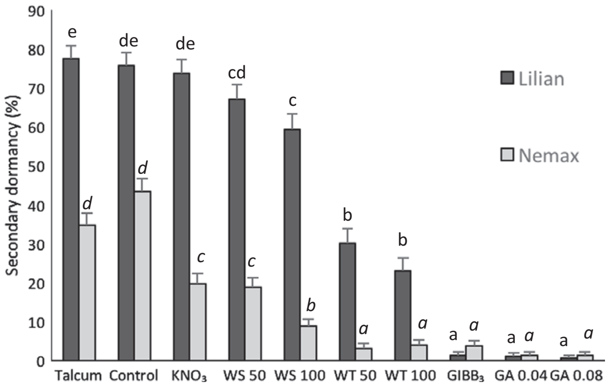


**Fig. 2** Effect of seed coating on secondary dormancy induction of two oilseed rape varieties (Lilian and Nemax) with different agents. Values within one variety labelled by the same letter are not significantly different ($\alpha = 0.05$; Student's *t*-test on transformed values; letters for Nemax in italics). Error bars: standard error of mean. $KNO_3$: 0.4% solution; WS: Wuxal® Semillion pure (100) and diluted to 50% (50); WT: Wuxal® Terios pure (100) or diluted to 50% (50); $Gibb_3$®: 0.1% solution of a gibberellic acid containing (10%) growth regulator; GA: gibberellic acid in 0.04% (0.04) and 0.08% (0.08) concentration (Table 1).

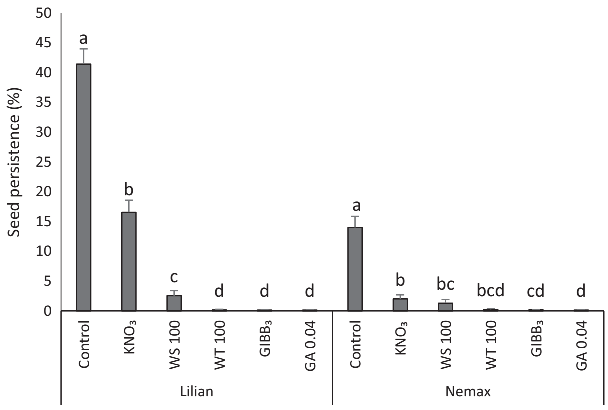


**Fig. 3** Seed persistence of buried seeds of two oilseed rape varieties (Lilian and Nemax), coated with different agents prior to burial, after a period of 3 months buried at 10 cm soil depth in a field at University of Hohenheim, 2012. Values within one variety labelled by the same letter are not significantly different ($\alpha = 0.05$; Student's *t*-test on transformed values). Error bars: standard error of mean. $KNO_3$: 0.4% solution; WS 100: Wuxal® Semillion pure; WT 100: Wuxal® Terios pure; $Gibb_3$®- 0.1% solution of a gibberellic acid containing (10%) growth regulator; GA 0.04: gibberellic acid in 0.04% concentration (Table 1).

untreated control (67.7% in trial year 2016; 46.8% in trial year 2017) which also was lower than the other treatments.

## Discussion

Secondary dormancy was reduced when OSR seeds were treated with exogenous gibberellic acid (GA), potassium nitrate ($KNO_3$) and micronutrients. GA plays an important role in releasing seeds from dormancy and promoting germination of imbibed seeds (Arefi *et al.*, 2012; ISTA, 2013; Shu *et al.*, 2015). $KNO_3$ is also known to be capable of breaking dormancy (Baskin & Baskin, 2001). The dormancy-breaking effect can be linked to nitrate (Baskin & Baskin, 2001; Finch-Savage & Leubner-Metzger, 2006) and is presumably caused, in part, by the reduction in abscisic acid levels along with an increase in GA levels in the seeds of several crop species (Matakiadis *et al.*, 2009; Shu *et al.*, 2015). In addition, it should be noted that extended storage time might have reduced potential for secondary dormancy reduction in OSR seeds (Gulden *et al.*, 2004).

In the laboratory experiment, the high-dormancy variety Lilian and the low-dormancy variety Nemax responded differently to the $KNO_3$ treatment, although seed persistence of both varieties was reduced by $KNO_3$ in the field experiment. In the laboratory, variety-specific responses to $KNO_3$ might have been caused by the relatively short duration of $KNO_3$ exposure (2 weeks). In the field experiment, seeds potentially interacted with $KNO_3$ for 2.5 months. The relatively long period of $KNO_3$ exposure under field conditions might have facilitated $KNO_3$ effects on seeds for both high- and low-dormancy varieties.

Coating seeds with micronutrient solutions reduced secondary dormancy induction somewhat, depending on the variety, especially if the solutions were highly

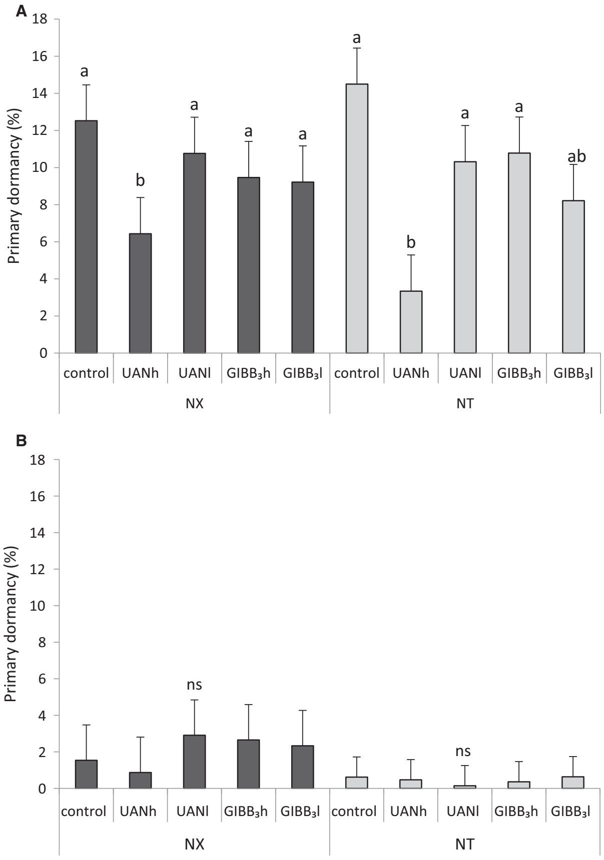


**Fig. 4** Primary dormancy of oilseed rape seeds of two varieties (NX and NT) after pre-harvest treatment of plants with different agents of the trial years 2016 (A) and 2017 (B). Values within one variety labelled by the same letter are not significantly different ($\alpha$ = 0.05; Student's *t*-test). Error bars: standard error of mean. Control: no treatment; UANh: treatment with 80 mL 27.78% UAN solution $m^{-2}$; UANl: treatment with 80 mL 2.78% UAN solution $m^{-2}$; $GIBB_3$ h: treatment with 80 mL 0.02% solution of $Gibb_3^{®}$ a gibberellic acid containing (10%) growth regulator $m^{-2}$; $GIBB_3$l: treatment with 80 mL 0.002% solution of $Gibb_3^{®}$ $m^{-2}$ (Table 2).

concentrated. The mode of action, however, is not yet clear. Some micronutrients are known to promote germination, for example boron, copper, zinc and manganese (Cresswell & Nelson, 1972; Delatorre & Barros, 1996; Farooq *et al*., 2012; Imran *et al*., 2015). The tested solutions WS and WT contained nitrogen and other macronutrients, so solution components other than the micronutrients could also have altered dormancy responses. Seeds coated with micronutrients responded more strongly to the treatment when tested in the field than when tested in the laboratory. It is possible that temperature fluctuations and other external factors unique to field conditions prevented secondary dormancy induction more in the field than under artificial, controlled conditions in the laboratory.

Spraying agents before ripening on the standing crop could be an approach to reduce primary dormancy, and also the capacity of seeds to become secondarily dormant. It was tested in a first approach, in the field with selected agents and selected concentrations (practical demonstration), so as to show whether there is any response in dormancy at all. Both primary (in the first trial year) and secondary dormancy (in both trial years) could be reduced. In the second trial year, the general primary dormancy level was relatively low, thus a significant decreasing effect of the agents could not be observed. Primary dormancy development is mainly regulated by abscisic acid (Nambara *et al*., 2010). Its synthesis is determined genetically and by environmental conditions (Chono *et al*., 2006), which could have caused different primary dormancy levels in both trial years.

Treating plants with dormancy reduction agents could be adopted in farming practice by usage of existing spraying technologies. Ecological harm due to

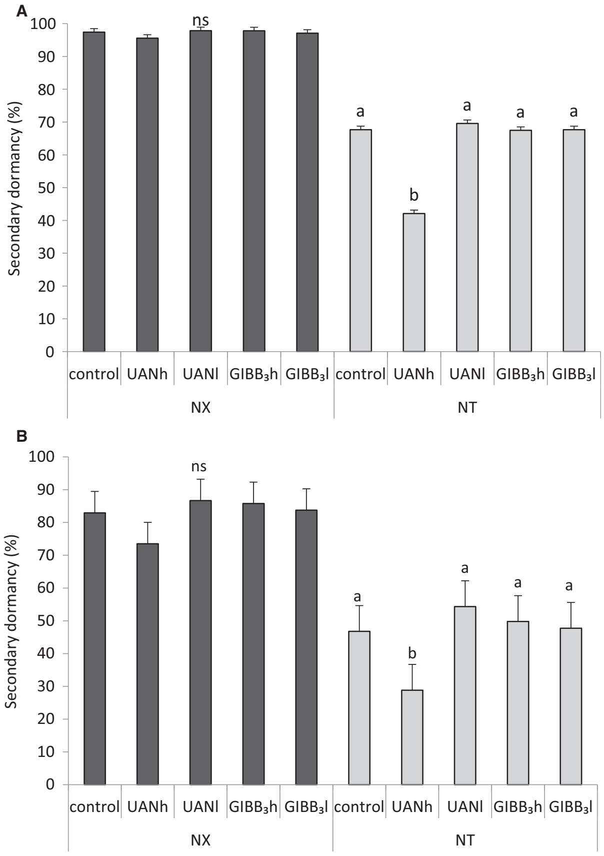


**Fig. 5** Secondary dormancy of oilseed rape seeds of the varieties NX and NT after pre-harvest treatment of plants with different agents of the trial years 2016 (A) and 2017 (B). Values within one variety labelled by the same letter are not significantly different ($\alpha = 0.05$; Student's *t*-test). Error bars: standard error of mean. Control: no treatment; UANh: treatment with 80 mL 27.78% UAN solution $m^{-2}$; UANl: treatment with 80 mL 2.78% UAN solution $m^{-2}$; $GIBB_3$ h: treatment with 80 mL 0.02% solution of $Gibb_3$® a gibberellic acid containing (10%) growth regulator $m^{-2}$; $GIBB_3$ l: treatment with 80 mL 0.002% solution of $Gibb_3$® $m^{-2}$ (Table 2).

applications of dormancy reduction agents is unlikely because, in Germany, $Gibb_3$® is a state-approved plant protection product, UAN and $KNO_3$ are common nitrogen fertilisers, and WS and WT contain micro- and macronutrients that are part of usual fertilisation strategies. However, this study was conducted to examine general effects of exogenous compounds on seed dormancy of OSR. Further investigations are recommended for evaluations of ecological risk and for determining the influence of dormancy reduction agents on seed quality parameters including oil quality.

Primary dormancy can occur in pre-mature seeds during seed development on the mother plant of OSR (Huang *et al.*, 2016). A reduction in primary seed dormancy would be beneficial for managing volunteer OSR, in case of natural pod shatter or pod damage caused by heavy rainfall or hailstorms before harvesting. Studies with *Arabidopsis thaliana* L. indicated that an increase in nitrate availability during seed development may reduce abscisic acid levels in the seed and, therefore, also reduce the dormancy potential (Alboresi *et al.*, 2005; Matakiadis *et al.*, 2009). We do not yet know at which stage the application of UAN, and which concentrations of UAN, would provide the greatest efficacy. $Gibb_3$® did not affect primary and secondary dormancy in the practical demonstration. Exogenous applications of $Gibb_3$® might not affect OSR seed dormancy or the chosen spraying scheme could have prevented its efficacy. Specifically, the spraying scheme might not have facilitated GA uptake by the plants, or the concentration, or the timing, was not yet appropriate.

Although the experiments showed that seed dormancy in OSR can be manipulated readily through the application of effective exogenous compounds, procedures have to be developed and specified to show how these compounds should be applied in the field, in terms of timing, concentration, frequency and techniques. This study, however, provided basic information about the effects of the tested substances and gave deeper insights into strategies showing how the development of dormancy may be prevented in OSR seeds. The study points out several options for practical farming, which may serve in the future as further strategies to overcome the unwanted effects of OSR volunteers.

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# 5 Publikation III

Sebastian Schwabe, Sabine Gruber, Wilhelm Claupein (2021):

**Hoeing as a possibility for mechanical weed control in winter oilseed rape (*Brassica napus* L.)**

Crops

*Vor dem Hintergrund zunehmender Herbizidresistenzen bei Unkräutern und der damit einhergehenden erschwerten Kontrolle von diesen, wurde die Effizienz des Hackens als alternatives mechanische Unkrautmanagementsystem im Kulturraps untersucht und in einem dreijährigen Feldversuch mit einer chemischen Unkrautkontrollstrategie verglichen.*

*crops* MDPI

*Article*

# Hoeing as a Possibility for Mechanical Weed Control in Winter Oilseed Rape (*Brassica napus* L.)

**Sebastian Schwabe *, Sabine Gruber and Wilhelm Claupein**

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**Abstract:** The framework conditions for chemical weed control in oilseed rape (OSR) are becoming increasingly unfavorable in Central Europe. On the one hand, weed resistance is spreading and, on the other, there is a growing social desire to reduce or eliminate the use of chemical crop protection products. In a field experiment, hoeing, as a weed control measure performed two times per growing season (one time in autumn and one time in spring) in oilseed rape (*Brassica napus*; two varieties), was compared to chemical control by herbicides and a combination of hoeing and herbicide application (five treatments altogether). The chemical control by herbicides consisted of a broad-spectrum pre-emergence treatment and a post-emergence graminicide application. The trial was set up in each of three periods (years 2014/2015, 2015/2016, and 2016/2017) at the experimental station Ihinger Hof, University of Hohenheim, Stuttgart, Germany. The effect of the treatments on weed plant density, weed biomass at the time of harvesting, and on OSR grain yield was investigated. Weed plant density was measured four times per trial year, each time before and after hoeing. In 2015/2016 after spring hoeing, and in 2016/2017 at all data collection times, weed plant density was significantly higher in hoeing without herbicide application than in the other variants. No significant differences occurred at the other data collection times. The weed plant density ranged from 0.5 to 57.8 plants $m^{-2}$. Regardless of the trial year, pure hoeing always resulted in a significantly higher weed biomass at the time of harvesting than the herbicide applications or the combinations. The weed biomass at the time of harvesting ranged between 0.1 and 54.7 g $m^{-2}$. No significant differences in grain yield between hoeing and herbicide application occurred in all three trial years. According to the results, hoeing is a suitable extension of existing integrated weed control strategies in OSR.

**Keywords:** canola; herbicides; inter row



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## 1. Introduction

Weeds can cause several agronomic problems in oilseed rape (OSR), for example, by competition for nutrients, water, light, and space, and thus lead to a reduction in yield and seed quality [1–3]. Weeds can also cause harvest complications due to their moisture content, and slow the mechanical harvest process. In addition, OSR grains are often soggier after harvest if they had close contact to weed biomass during the threshing process, whereby storability decreases [2,4].

Weed control in OSR is usually performed by herbicides. However, herbicide strategies have to be reconsidered in light of herbicide tolerant crops, a continuing trend to reduced tillage and occurrence of herbicide resistant weeds, and increasing safety concerns about the use of some herbicides [5–12].

A direct way of weed control without herbicides is mechanical control. It could have a more holistic and sustainable effect on weed reduction than herbicide-only measures when implemented in the weed management strategy [8,13–15]. Before herbicides were developed, mechanical weed control was the standard tool for reducing weeds [13]. In organic agriculture, and in low-input agricultural systems, especially in less developed countries, mechanical weed control is still the main tool to actively control weeds [14,16]. The main advantage of mechanical weed control is primarily consistent efficacy; weeds cannot develop resistance. In addition, it can be realized with only a modest investment [16,17]. On the other hand, mechanical weed control can also have disadvantages, especially in comparison with the use of herbicides. It is not selective, the crop can also be damaged, mostly high effectiveness is achieved only in early stages of development of the weed, its effectiveness depends on weather and soil conditions., and the implementation can be very time-consuming, depending on the method [13,16–18].

OSR plants are very sensitive and are thus not suitable for full-surface harrowing. Therefore, the most promising option is inter-row cultivation, for example, by hoeing. In order to create space for the hoeing tines, the row spacing for OSR can be increased to up to 50 cm without yield reduction [19]. During hoeing, weeds are destroyed by flat cutting, uprooting, and burying [19–23]. The efficiency of the hoe is higher when weeds are in an early stage of development, the general weed pressure is low, and when its performed under dry soil conditions [19–22]. OSR should have emerged earlier than the weeds and thereby be more resistant to possible damage by hoeing. In addition, crop damage can be prevented by a larger row spacing, the use of camera-guided hoeing systems, and active implement steering especially when hoeing is performed in large scale [19–21,24,25]. In addition, camera-guided hoeing systems make the weed control process more efficient, as higher driving speeds can be applied [18]. Between 65% and 90% of the weeds between the rows can be controlled by hoeing [25,26]. In maize, hoeing significantly reduced the number of weeds, but did not achieve herbicide efficacy, and yield was lower [21]. For beans (*Vigna sinensis* L.), mechanical and chemical weed control were found to show no significant differences in weed occurrence and yield [27]. A study with lentils (*Lens culinaris*) concluded that an integrated approach consisting of increased sowing density, mechanical weed control, and reduced herbicide application rate had the same effect on yield and weed suppression as the standard approach of standard sowing density, full herbicide application and no mechanical weed control [28]. In a study with organically cultivated OSR hoeing significantly reduced the number of weeds [29]. Weed control between the rows may be sufficient to prevent crop depression, as OSR is highly competitive and can effectively shade the soil and other weeds through its branches [19].

The aim of this study is to evaluate hoeing as mechanical inter-row weed control compared with a common herbicide strategy with regard to weed appearance, weed biomass, and OSR grain yield. We hypothesize that hoeing has similar efficacy on weed control such as herbicides; mechanical and chemical weed control result in similar OSR grain yield.

## 2. Materials and Methods

A three-year field trial with oilseed rape (OSR, *Brassica napus* L.) was conducted in the years 2014/2015, 2015/2016, and 2016/2017 at the experimental station 'Ihinger Hof' of the University of Hohenheim, Stuttgart, South-West Germany (Luvisol, soil type: loam). The average annual precipitation of the location is 690 mm and the average annual temperature is 7.9 °C. The monthly average temperature and the monthly precipitation for the entire trial period are provided in Figure 1.

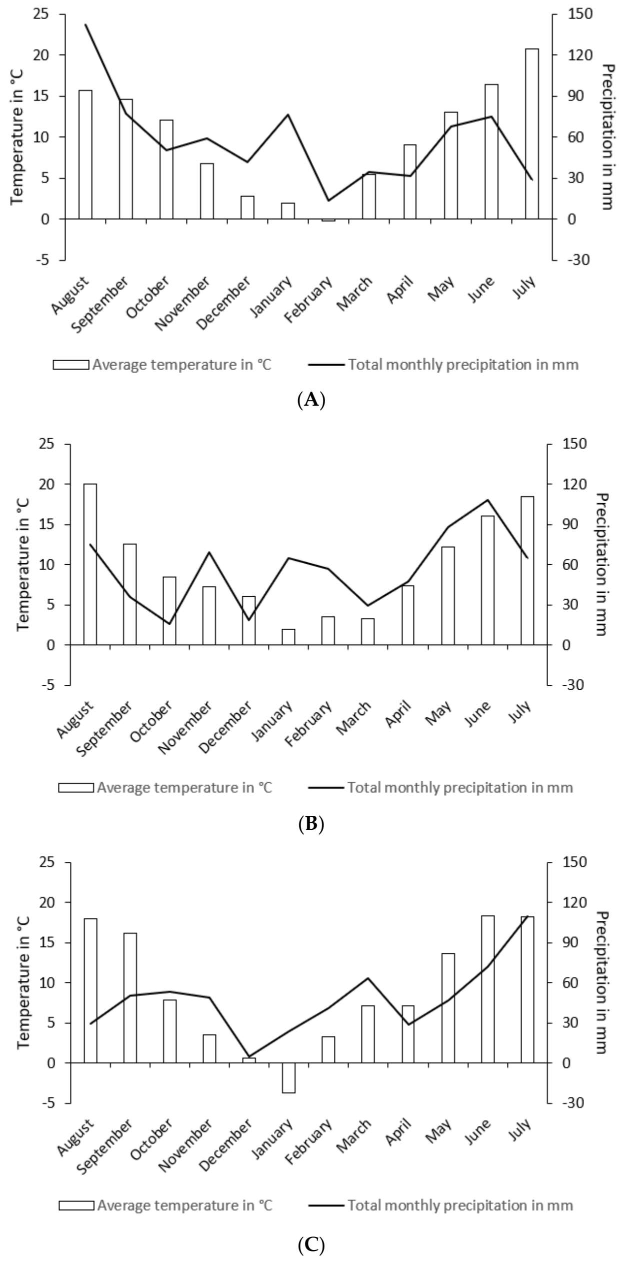


**Figure 1.** Monthly average temperature and total monthly precipitation for the trial years 2014/2015 (**A**), 2015/2016 (**B**), 2016/2017 (**C**); experimental station Ihinger Hof, Germany.

The trial was set up with two factors in a split-plot design with four replicates. The main factor (factor 1) was weed control, consisting of the treatments hoeing combined with usage of a common herbicide strategy (HO + HE), hoeing without herbicide application (HO) and the usage of a common herbicide strategy without hoeing (HE). In the treatments HO and HO + HE hoeing was performed twice per trial year. The first hoeing in autumn was performed as soon as the OSR had reached the 6-leaf growth stage and soil and weather conditions were suitable for the operation. The second hoeing was performed in spring as soon as the soil was trafficable. To enable hoeing the row spacing was 24 cm in all treatments. The tines of the hoe had a width of 16 cm and a cutting distance of 24 cm. Working depth was 4 cm. Factor 2 was the variety of winter OSR in two levels (varieties), variety 1 and variety 2. The sowing density was 45 seeds $m^{-2}$. The experiment was blocked by replicate and weed control. The experiment was conducted on a different field of the experimental station in each growing season. The preceding crop was winter barley in each case. Before sowing, conventional tillage was carried out with the plough and subsequent cultivation with the rotary harrow.

The sowing, harvest, and hoeing dates of all trial years are displayed in Table 1. During the growing season the weed plant density (WPD) was counted. Data were collected shortly before mechanical weed control and three weeks after weed control to describe the efficacy of hoeing (Table 1). WPD was counted ten times per plot with a 0.1 $m^2$ frame and calculated to plants $m^{-2}$.

**Table 1.** Sowing, hoeing, weed count, and harvest dates of a three-year weed control experiment in oilseed rape at the research station Ihinger Hof, SW Germany.

| Process | 2014/2015 | 2015/2016 | 2016/2017 |
|---|---|---|---|
| Sowing | 3 September | 27 August | 25 August |
| Weed count | 24 October | 30 September | 30 November |
| Hoeing autumn | 28 October | 1 October | 2 December |
| Weed count | 17 November | 19 October | 20 December |
| Weed count | 16 March | 22 March | 20 March |
| Hoeing spring | 18 March | 24 March | 21 March |
| Weed count | 10 April | 18 April | 12 April |
| Harvest | 28 July | 30 July | 29 July |

The plant protection program, consisting of insecticides, herbicides and fungicides, and the fertilizer strategy of the experiment is provided in Table 2.

The above-ground weed biomass (WBM) was sampled at four spots of 0.5 $m^2$ each in the plot within one week before harvest, dried for 24 h at 95 °C, and then weighed. The OSR harvest was carried out with a plot combine. A strip of 2 m × 6 m was harvested in the middle of each plot. Based on the amount harvested per strip, the grain yield was calculated in t dry matter per ha. To calculate dry matter, grain samples from each plot were dried at 95 °C for 24 h, and then weighed.

*Statistical Analysis*

The statistical analysis as Student's *t*-test was performed using the Glimmix and Mixed procedures of the SAS 9.3 software. Data of weed biomass and grain yield were statistically analyzed by using the procedure mixed. Data of weed plant density were analyzed by using the procedure Glimmix. In the statistical model, the following factors were defined as fixed effects: weed control; variety; interactions of weed control, and variety. The following factors were defined as random effects: replicate; interactions of replicate, and weed control. Transformations were partly necessary to reach normal distribution of data. In the statistical analysis of weed plant density, the data were logarithmically transformed. In terms of weed biomass, the data from 2014/2015 and 2016/2017 were square-root transformed, the year two was logarithmically transformed. A transformation was not required for the grain yield data. For presentation purposes, the following figures show only back-transformed data.

**Table 2.** Application date of insecticide, fungicide, herbicide, and fertilizer treatments, including agent, trade name and manufacturer, during a three-year weed control experiment in oilseed rape.

| | 2014/2015 | | 2015/2016 | | 2016/2017 | |
|---|---|---|---|---|---|---|
| **Treatment** | **Date** | **Agent** | **Date** | **Agent** | **Date** | **Agent** |
| Insecticides | 9 September | 7.5 g $ha^{-1}$ deltamethrin | 5 April | 57.5 g $ha^{-1}$ etofenprox | 5 October | 7.5 g $ha^{-1}$ beta-cyfluthrin |
| | 26 September | 7.5 g $ha^{-1}$ deltamethrin | 11 April | 72 g $ha^{-1}$ thiacloprid | 3 April | 57.5 g $ha^{-1}$ etofenprox |
| | 15 April | 57.5 g $ha^{-1}$ etofenprox | 22 April | 40 g $ha^{-1}$ acetamiprid | | |
| | 20 April | 25.5 g $ha^{-1}$ indoxacarb | | | | |
| | 6 May | 48 g $ha^{-1}$ tau-fluvinate<br>300 g $ha^{-1}$ citric acid | | | | |
| Herbicides | 10 September | 500 g $ha^{-1}$ metazachlor<br>500 g $ha^{-1}$ dimethenamid-P<br>250 g $ha^{-1}$ quinmerac | 31 August | 500 g $ha^{-1}$ metazachlor<br>500 g $ha^{-1}$ dimethenamid-P<br>250 g $ha^{-1}$ quinmerac | 1 September | 500 g $ha^{-1}$ metazachlor<br>500 g $ha^{-1}$ dimethenamid-P<br>250 g $ha^{-1}$ quinmerac |
| | 20 October | 80 g $ha^{-1}$ propaquizafop | 8 October | 80 g $ha^{-1}$ propaquizafop | 5 October | 80 g $ha^{-1}$ propaquizafop |
| Fungicides | 6 May | 250 g $ha^{-1}$ azoxystrobin | 26 October | 96 g $ha^{-1}$ prothioconazole<br>192 g $ha^{-1}$ tebuconazole | 3 April | 96 g $ha^{-1}$ prothioconazole<br>192 g $ha^{-1}$ tebuconazole |
| | | | 5 April | 96 g $ha^{-1}$ prothioconazole<br>192 g $ha^{-1}$ tebuconazole | | |
| Nitrogen fertiliser | 1 October | 40 kg N $ha^{-1}$ calcium ammonium nitrate | 15 March | 90 kg N $ha^{-1}$ ammonium sulphate nitrate | 21 October | 30 kg N $ha^{-1}$ calcium ammonium nitrate |
| | 10 March | 90 kg N $ha^{-1}$ ammonium sulphate nitrate | 7 April | 90 kg N $ha^{-1}$ ammonium sulphate nitrate | 15 March | 80 kg N $ha^{-1}$ ammonium sulphate nitrate |
| | 8 April | 90 kg N $ha^{-1}$ ammonium sulphate nitrate | | | 6 April | 90 kg N $ha^{-1}$ ammonium sulphate nitrate |

## 3. Results

### 3.1. Weeds

The following weeds occurred during the trial period: *Thlaspi arvense* L., *Stellaria media* L., *Hordeum vulgare* L., *Sonchus arvensis* L., *Veronica agrestis* L., *Lamium purpureum* L., *Galium aparine* L., *Capsella bursa-pastoris* L., *Geranium rotundifolium* L., *Matricaria chamomilla* L., *Cirsium arvense* L., *Falopia convolvulus* L., *Fumaria officinalis* L., and *Alopecurus myosuroides* Huds. The dominant weeds in the trial year 2014/2015 were *Thlaspi arvense* L. and *Stellaria media* L. In the trial years 2015/2016 and 2016/2017 the dominant weeds were *Fumaria officinalis* L., *Thlaspi arvense* L., and *Stellaria media* L.

The WPD in trial year 2015/2016 decreased in all treatments during the season, as mean over both OSR varieties. The WPD ranged from 2.2 plants $m^{-2}$ (HO + HE/counting 4; Figure 2) to 34.4 (HO/counting 1). Across all countings, HO resulted in the highest number of weeds.

The level of weed infestation in trial year 2015/2016 was lower compared to 2014/2015 (Figure 2), and ranged between 0.6 plants $m^{-2}$ (HO + HE/counting 3) and 7.5 plants $m^{-2}$ (HO/counting 4). From counting 1 to 3, weed number stayed within a narrow range from 0.6 (HO + HE/counting 3) to 4.5 plants $m^{-2}$ (HO/counting 1) At counting 4, weed numbers in HO (7.5 plants $m^{-2}$) were significantly higher than in HE (0.7 plants $m^{-2}$) and HO + HE (1.0 plants $m^{-2}$).

The highest number of weeds of all trial years was observed in trial year 2016/2017 (Figure 2) and ranged between 0.5 plants $m^{-2}$ (HO + HE/counting 3) and 57.8 (HO/counting 1). There were significantly more weeds in all countings in treatment HO compared to HO + HE and HE. Weed numbers in HO + HE and HE were quite similar, except in counting 4, where significantly more weeds were observed in HE.

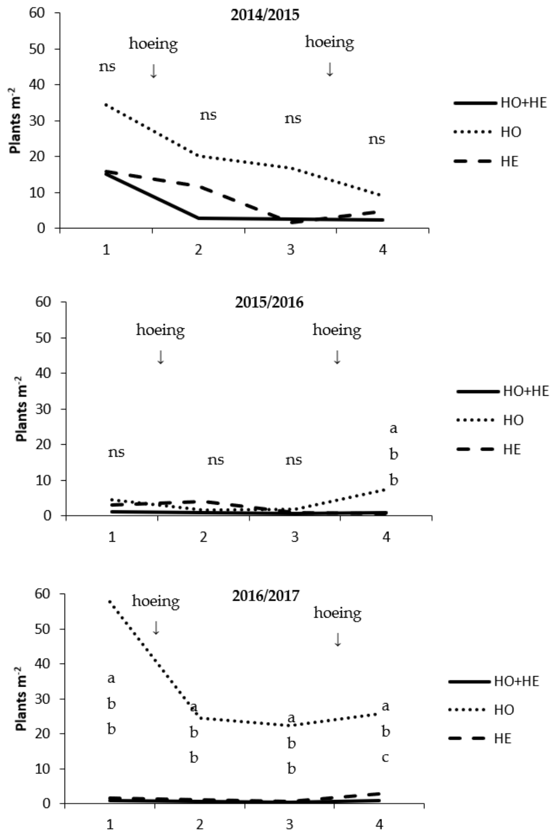


**Figure 2.** Weed plant density in number of weed plants m$^{-2}$ in winter oilseed rape (mean of two varieties) before (1) and after (2) hoeing in autumn, and before (3) and after (4) hoeing in spring as effect of the weed control strategies: hoeing + herbicide application (HO + HE); hoeing without herbicide application (HO); herbicide application without hoeing (HE); herbicides as depicted in Table 2; values within the same time of survey with different letters within are significantly different; non-significant differences are indicated by the abbreviation 'ns'. (Student's *t*-test on transformed values; $\alpha = 0.05$); experimental station Ihinger Hof, Germany.

The fixed effects of the statistical analyses of WPD for the four annual weed counts in the three trial years are shown in Table 3. If significant effects occurred, then only in the weed control factor. The factor variety and interactions from the factors variety and weed control had no significant influence.

WBM was highest in HO in all years, and ranged from 0.1 (HE, 2015/2016) to 107.6 g m$^{-2}$ (HO, 2014/2015; Figure 3). Independent of trial year WBM in HO + HE and HE was by 76 to 99% lower compared to HO. The years differed in weed with WDM of HO as reference: 2015/2016 (HO: 18.1 g m$^{-2}$); 2016/2017 (HO: 54.7 g m$^{-2}$); and 2014/2015 (HO: 107.6 g m$^{-2}$).

**Table 3.** Degrees of freedom (DF), F value and probability level (Pr > F) of the fixed effects weed control (WC), variety (V), and their interactions (WC × V) of the statistical analyses of the weed plant density of four annual weed counts in a three-year weed control experiment in oilseed rape at the research station Ihinger Hof, SW Germany.

| | | DF | F Value | Pr > F |
|---|---|---|---|---|
| **Weed count** | | | **1** | |
| 2014/2015 | WC | 2 | 0.77 | 0.5050 |
| | V | 1 | 0.02 | 0.8879 |
| | WC × V | 2 | 2.29 | 0.1567 |
| 2015/2016 | WC | 2 | 3.07 | 0.1205 |
| | V | 1 | 0.05 | 0.8275 |
| | WC × V | 2 | 0.50 | 0.6229 |
| 2016/2017 | WC | 2 | 42.84 | 0.0003 |
| | V | 1 | 0.59 | 0.4631 |
| | WC × V | 2 | 0.67 | 0.5337 |
| **Weed count** | | | **2** | |
| 2014/2015 | WC | 2 | 2.90 | 0.1316 |
| | V | 1 | 1.68 | 0.2269 |
| | WC × V | 2 | 0.81 | 0.4732 |
| 2015/2016 | WC | 2 | 2.94 | 0.1288 |
| | V | 1 | 0.64 | 0.4432 |
| | WC × V | 2 | 3.81 | 0.2634 |
| 2016/2017 | WC | 2 | 49.18 | 0.0002 |
| | V | 1 | 0.70 | 0.4237 |
| | WC × V | 2 | 0.53 | 0.6043 |
| **Weed count** | | | **3** | |
| 2014/2015 | WC | 2 | 3.16 | 0.1155 |
| | V | 1 | 0.39 | 0.5461 |
| | WC × V | 2 | 0.20 | 0.8221 |
| 2015/2016 | WC | 2 | 3.03 | 0.1230 |
| | V | 1 | 2.97 | 0.1188 |
| | WC × V | 2 | 0.38 | 0.6919 |
| 2016/2017 | WC | 2 | 114.78 | <0.0001 |
| | V | 1 | 1.36 | 0.2730 |
| | WC × V | 2 | 0.36 | 0.7050 |
| **Weed count** | | | **4** | |
| 2014/2015 | WC | 2 | 1.15 | 0.3783 |
| | V | 1 | 0.29 | 0.6018 |
| | WC × V | 2 | 0.15 | 0.8668 |
| 2015/2016 | WC | 2 | 16.41 | 0.0037 |
| | V | 1 | 18.08 | 0.1521 |
| | WC × V | 2 | 5.47 | 0.4279 |
| 2016/2017 | WC | 2 | 23.80 | 0.0014 |
| | V | 1 | 1.24 | 0.2941 |
| | WC × V | 2 | 0.44 | 0.6556 |

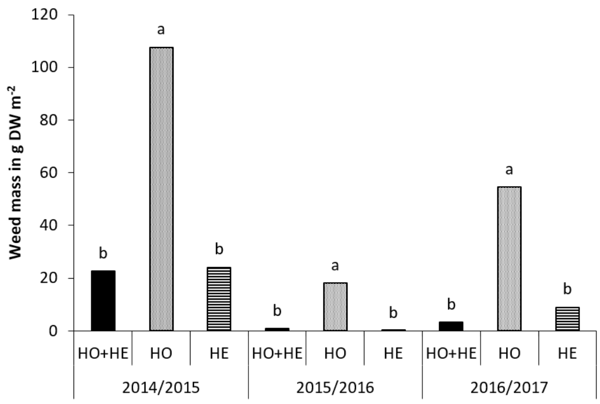


**Figure 3.** Weed biomass (g $m^{-2}$) in winter oilseed rape (mean of two varieties) in the trial years 2014/2015, 2015/2016, and 2016/2017 depending on weed control: hoeing + common herbicide strategy (HO + HE); hoeing without any herbicides (HO); common herbicide strategy without hoeing (HE). Different letters within one trial year indicate significant differences (Student's *t*-test on transformed values; α = 0.05); experimental station Ihinger Hof, Germany.

The fixed effects of the statistical analyses of WPD in the three trial years are shown in Table 4. If significant effects occurred, then only in the weed control factor. The factor variety and interactions from the factors variety and weed control had no significant influence.

**Table 4.** Degrees of freedom (DF), F value and probability level (Pr > F) of the fixed effects weed control (WC), variety (V), and their interactions (WC × V) of the statistical analyses of the weed biomass in a three-year weed control experiment in oilseed rape at the research station Ihinger Hof, SW Germany.

| Trial Year | Effect | DF | F Value | Pr > F |
|---|---|---|---|---|
| 2014/2015 | WC | 2 | 6.32 | 0.0333 |
| | V | 1 | 3.32 | 0.1015 |
| | WC × V | 2 | 0.44 | 0.6601 |
| 2015/2016 | WC | 2 | 9.29 | 0.0145 |
| | V | 1 | 5.24 | 0.0578 |
| | WC × V | 2 | 0.29 | 0.7553 |
| 2016/2017 | WC | 2 | 5.61 | 0.0422 |
| | V | 1 | 10.24 | 0.0708 |
| | WC × V | 2 | 9.45 | 0.1062 |

*3.2. Oilseed Rape Grain Yield*

The grain yield ranged from 2.9 t DM (HO, 2015/2016) to 3.9 t DM $ha^{-1}$ (HO + HE, 2016/2017; Figure 4). Significant differences between the treatments occurred only in 2016/2017; lowest grain yield however, was always obtained in treatment HO. The significant yield gap between HO and HO + HE in 206/2017 was 0.6 t $ha^{-1}$.

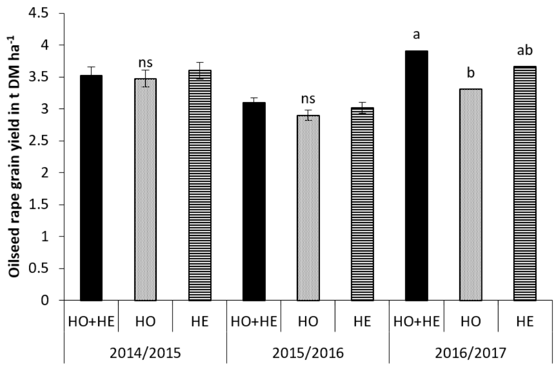


**Figure 4.** Grain yield of two oilseed rape varieties (t dry matter (DM) ha$^{-1}$) in the trial years 2014/2015, 2015/2016, and 2016/2017 dependent of the weed control strategy: hoeing + common herbicide strategy (HO + HE); hoeing without any herbicides (HO); common herbicide strategy without hoeing (HE). Different letters within one trial year indicate significant differences; if no significant differences (ns) occurred, the standard error of mean (SE) was displayed as error bar in the figure (Student's *t*-test; $\alpha$ = 0.05); experimental station Ihinger Hof.

The fixed effects of the statistical analyses of the grain yield in the three trial years are shown in Table 5. If significant effects occurred, then only in the weed control factor. The factor variety and interactions from the factors variety and weed control had no significant influence.

**Table 5.** Degrees of freedom (DF), F value and probability level (Pr > F) of the fixed effects weed control (WC), variety (V), and their interactions (WC × V) of the statistical analyses of the grain yield in a three-year weed control experiment in oilseed rape at the research station Ihinger Hof, SW Germany.

| Trial Year | Effect | DF | F Value | Pr > F |
|---|---|---|---|---|
| 2014/2015 | WC | 2 | 0.49 | 0.6332 |
| | V | 1 | 0.48 | 0.5069 |
| | WC × V | 2 | 0.63 | 0.5536 |
| 2015/2016 | WC | 2 | 2.74 | 0.1429 |
| | V | 1 | 0.22 | 0.6528 |
| | WC × V | 2 | 1.53 | 0.2685 |
| 2016/2017 | WC | 2 | 6.93 | 0.0276 |
| | V | 1 | 1.90 | 0.2014 |
| | WC × V | 2 | 0.06 | 0.9408 |

## 4. Discussion

The success of hoeing in controlling weeds and promoting high OSR grain yield depends on the general weed pressure, and on the weather conditions, dry soils allow a higher efficiency of the hoeing [23]. The general weed pressure differed over the three trial years. When comparing WPD and WDM (Figures 2 and 3), the general weed pressure in the test years 2014/2015 and 2016/2017 appears to be higher than in the test year 2015/2016. This may be due to soil seed banks of different sizes and species composition on the respective trial fields. In addition, the annual weather conditions can have an influence on the emergence of weeds. In particular, it is noticeable that there were hardly any sunshine hours in the trial year 2015/2016 (Figure 1B), which meant that less light reached the soil and fewer weeds were stimulated to germinate. In addition, September and October of the year were relatively dry and counteracted strong weed emergencies

(Figure 1). Nevertheless, the higher number of weeds was mostly found in the HO variant. Even though these differences were only partially significant, a clear tendency can still be seen with higher weed pressures (trial years 2014/2015 and 2016/2017). The differences in efficiency in HO can be explained by the fact that hoeing does not take place over the entire surface, and therefore parts of the surface cannot be cultivated [26]. With a row spacing of 24 cm between the OSR plants, only 16 cm were cultivated by the hoeing coulter per row, while weeds on the remaining 8 cm could not be controlled. The effect of hoeing on weeds is based on uprooting, flat cutting, and burying [19–23]. It cannot be excluded that cut-off weeds can sprout again or re-grow especially if they are in an advanced growth stage [19–22]. The number of weeds in the HE and HO + HE variants was similar, and in the years 2014/2015 and 2016/2017, was either tending or significantly lower than the number of weeds in the HO variant. The lower number of weeds in the HE and HO + HE variants, compared to the HO variant, especially in the trial years 2014/2015 and 2016/2017, is due to the fact that weed control by the herbicides took place over the entire area and their efficacy is higher. For better mechanical weed control within the rows by hoeing, specialised hoes can also be equipped with intra-row elements. This could control up to 78% of the weeds within the rows and could lead to smaller differences between the chemical and mechanical variants of weed control [25]. Surprisingly, the number of weeds in HO + HE was less than in HE. As hoeing is an intervention in the soil, it would be likely that the active agent layer formed above the soil by the herbicides would be damaged and that as a result more weeds would emerge. In some cases, however, the opposite was true. Especially in counting 2 in the trial year 2014/2015 and counting 4 in the trial years 2014/2015 and 2016/2017 (Figure 2). In counting 2 of the trial year 2014/2015, the effect of the herbicide had probably not yet fully taken impact due to the weather conditions. Compared to the other two trial years, the months September to November (time between sowing and counting 2) were relatively warm, with high precipitation and hours of sunshine (Figure 1). These vigorous conditions could lead to an increased weed emergence, so that new weeds may have emerged between the counting 1 and counting 2; and the weeds could be more vital, which may cause them to react later to herbicide application. Weeds that did not yet show lethal symptoms and died later in the year may have been counted. As the year progressed, the effectiveness of the soil herbicide probably decreased and new weeds could accumulate in the HO variant during the fourth counting period [30,31]. This loss of efficacy was compensated by hoeing in the HO + HE variant. Such a trend cannot be detected for the 2015/2016 trial year because the general weed pressure was probably too low.

As the number of weeds in the counting 4 at least tended to indicate, the weed mass at harvesting in the HO variant is significantly higher in all trial years than in the other two variants. The reason for the different weed masses in the three experimental years is the difference in the weight of the individual weed plants, which occur due to different weather conditions and a specific weed composition.

With regard to grain yield, no significant differences were found in all three trial years between the herbicide application method used in conventional agricultural practice in the HE variant and the hoeing method without the use of herbicides in the HO variant. The competitive capacity of OSR, based mainly on the formation of branches, seemed to be greater than the effect of weeds on yield [4,19]. The combination of hoeing and herbicide use in HO + HE resulted in a significantly higher yield in the trial year 2016/2017 than in HO, and can probably be explained by a significantly lower weed amount in combination with a tendency to lower weed mass at harvest.

According to the results, hoeing as a mechanical weed control option can be regarded as an alternative to the herbicide use previously practiced in conventional agriculture. However, if the hoe is used over a large area at higher speeds, care must be taken not to damage the OSR plants, which could also have a negative effect on grain yield [18]. It would be advisable to use camera-guided systems for this purpose and to choose a row spacing between 24 and 50 cm, then the occurrence of damage would be unlikely [18–21]. However, the renunciation of herbicides resulted in an increased number of weeds. It can be assumed that weeds that have not been controlled before the threshing stage of the OSR will reach seed maturity, and that weed seeds will accumulate increasingly in the soil seed bank and that the general weed pressure could increase in the following years. The comparison of WPD (Figure 2) shows that the effectiveness of hoeing is lower at higher weed pressure (comparison of the test years 2014/2015 and 2017/2018 with higher weed pressure with the test year 2016/2017 with lower weed pressure). If herbicides are consistently avoided for several years during mechanical weed control by hoeing, it is likely that the effectiveness of hoeing will decline further due to the increasing weed pressure. In order to successfully control weeds without herbicides over several years, holistic approaches are needed in addition to direct mechanical weed control, including long crop rotations, mulching, adapted tillage, optimized sowing operation, and the use of selected intercrops [3,32–36]. However, hoeing is particularly suitable in an environment of social desire for more ecological agriculture, where there are increasing bans or restrictions on the use of herbicides and a lack of approval of new herbicidal active agents as a supplement to chemical crop protection, therefore providing an additional way of controlling weeds that became difficult to control chemically [18,25,37].

## 5. Conclusions

Hoeing is a suitable option for weed control in OSR. Compared to chemical herbicide application, weeds can be controlled less efficiently by hoeing. However, this is not necessarily related to yield losses. This is especially true when highly competitive hybrid oilseed rape varieties are used [38]. Moreover, hoeing can be combined with a chemical weed control strategy, which can be expected to improve the control of resistant weeds.

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# 6 Gesamtdiskussion

Die wichtigsten Ergebnisse der vorgestellten Publikationen sollen in diesem Kapitel in einem gemeinsamen Kontext näher beleuchtet und diskutiert werden. Im Mittelpunkt der Dissertation stehen alternative Unkrautkontrollmöglichkeiten im Raps. Einerseits wurde die Wirkung des Hackens als mechanische Unkrautkontrollvariante untersucht, andererseits kam das Clearfield®-System zur Anwendung und wurde hinsichtlich seiner Leistungsfähigkeit unter verschiedenen Bewirtschaftungsintensitäten im Vergleich zu einer praxisüblicheren Vorauflauf-Herbizidstrategie evaluiert. Die Herbizidtoleranz von Clearfield®-Rapssorten wird mindestens teilweise an die Nachkommen vererbt. Aus Clearfield®-Raps resultierender Durchwuchsraps lässt sich folglich schwieriger chemisch in den folgenden Früchten kontrollieren (Krato *et al.*, 2012). Zur Verminderung der Durchwuchsrapsproblematik wurde deshalb untersucht, inwieweit eine Raps-Samenbehandlung mit Nährstoffen und Gibberellinsäure zur Verhinderung der Ausbildung von Dormanz sorgen kann, wodurch sich gleichzeitig die Überdauerungsfähigkeit der Samen und das Auftreten von Durchwuchsraps reduzieren ließen.

Die Unkrautkontrolle im konventionellen Ackerbau ist zunehmend erschwert, da aufgrund ökonomischer Gesichtspunkte und des auf Landwirten wirkenden Preisdrucks, agronomische Entscheidungen des Öfteren zum Nachteil einer nachhaltigen Unkrautbekämpfungsstrategie getroffen werden. Durch häufig angewendete enge Fruchtfolgen und der damit einhergehenden, oftmaligen Anwendung von Herbiziden derselben Wirkstoffklasse, entwickeln sich vermehrt Unkrautresistenzen (Heap, 2014; Ghanizadeh & Harrington, 2021; Sharma *et al.*, 2021). Außerdem werden durch die enge Fruchtfolge bestimmte Unkrautarten überproportional gefördert und treten damit häufiger auf. Zudem wirkt eine verringerte Intensität der Bodenbearbeitung förderlich auf diese Problematik (Cardina & Doohan, 2002; Renton & Flower, 2015; Weisberger *et al.*, 2019).

Für eine nachhaltig effektive Kontrolle von Unkräutern und Ungräsern sind konsequente Bekämpfungsstrategien unerlässlich. Vorbeugend sollte dieser Problematik mit einer weiten Fruchtfolge begegnet werden, wodurch verhindert wird, dass einzelne Unkrautarten gezielt gefördert werden und sich zum Problem entwickeln. Weiterhin wird durch eine größere Anzahl von Fruchtfolgegliedern ein häufigerer herbizider Wirkstoffwechsel ermöglicht, die Gefahr der Unkrautresistenzentwicklung würde sinken (Heap, 2014; Ghanizadeh & Harrington, 2021; Sharma *et al.*, 2021). Weiterhin kann eine tiefe, wendende Bodenbearbeitung den Unkrautdruck reduzieren (Cardina & Doohan, 2002; Renton & Flower, 2015; Weisberger *et al.*, 2019). Bei Winterungen ist ein tendenziell späterer Saatzeitpunkt zu bevorzugen. Durch das Anlegen eines „falschen" Saatbetts vor der eigentlichen Saat kann das Unkrautpotential für die kommende Vegetationsperiode reduziert werden. Dabei wird der Boden bereits einige Wochen vor der Saat in einen „saatfertigen" Zustand gebracht, Unkräuter und Ungräser werden zum Keimen angeregt und kurz vor der eigentlichen Saat der Kultur mit einem Totalherbizid kontrolliert. Die Saat erfolgt anschließend mit möglichst wenig Bodenbewegung, um zu vermeiden, dass neue Unkrautsamen durch einen Lichtreiz zum Keimen angeregt werden (Moss & Clarke, 1994; Lemerle *et al.*, 1995; Chauvel *et al.*, 2001; Kreye, 2004; Moss *et al.*, 2007; Hanzlik & Gerowitt, 2012; Moss & Hull, 2012; Moss, 2017; Damm, 2018). Zur Weiteren effizienten Unkraut- und Ungraskontrolle werden im Herbst bodenaktive Wirkstoffe im Vorauflauf angewendet. Kommt es dennoch zum schadschwellenüberschreitenden Auflaufen von Unkräutern bzw. Ungräsern sollte eine Behandlung mit einem blattaktiven Wirkstoff im

Nachauflauf erfolgen, gleiches gilt für eine Behandlung mit einem blattaktiven Wirkstoff im Frühjahr. Überschreitet das Unkrautaufkommen den Schadschwellenwert nicht, ist eine aktive Unkrautbekämpfung unter ökonomischen, ökologischen und Biodiversitäts-Gesichtspunkten nicht sinnvoll (Moss & Clarke, 1994; Chauvel *et al.*, 2001; Moss *et al.*, 2007; Moss & Hull, 2012; Moss, 2017).

Im Raps ist insbesondere das erhöhte Aufkommen von Raukearten und Ungräsern, wie beispielsweise Ackerfuchsschwanz und Weidelgräsern problematisch (Niknam *et al.*, 2003; Chauvel *et al.*, 2009; Bushong *et al.*, 2011; Roberts, 2011; Lemerle *et al.*, 2014b; Aboutalebian *et al.*, 2017; Landau *et al.*, 2017). Daneben werden durch einen häufigen Rapsanbau die folgenden angepasste Unkräuter stärker gefördert: Ackerhellerkraut, Gänsefußarten, Klettenlabkraut, Taubnesselarten, Kamillearten, Gewöhnliche Vogelmiere, Ehrenpreisarten, Ackerstiefmütterchen und Hirtentäschelkraut (Bullied *et al.*, 2003; Hanzlik & Gerowitt, 2012; Aboutalebian *et al.*, 2017; Landau *et al.*, 2017; Salisbury *et al.*, 2018). Bei der Verwendung gewöhnlicher Herbizide ist die Wirksamkeit insbesondere gegenüber Raukearten oft nicht ausreichend und / oder die Herbizidverträglichkeit des Rapses niedriger (Klingenhagen, 2014; Golebiowska & Badowski, 2015). Lassen sich Unkräuter und Ungräser über gewöhnliche Herbizidstrategien im Raps nicht mehr ausreichend kontrollieren, können alternative Bekämpfungsstrategien herangezogen werden.

Eine Möglichkeit besteht dabei im Einsatz des Clearfield®-Herbizid-Systems. Es kann insbesondere bei der Bekämpfung von kreuzblütigen Problemunkräutern, wie Raukearten, Ackerhellerkraut oder Hirtentäschelkraut, sehr hohe Bekämpfungserfolge erzielen, bei einer gleichzeitig sehr guten Kulturverträglichkeit (Adamszki *et al.*, 2010; Klingenhagen, 2014; Tozzi *et al.*, 2016). Minderwirkungen des Clearfield®-Herbizids gegenüber vor allem einkeimblättrigen Ungräsern, lassen sich im Bedarfsfall über eine Applikation von Graminiziden ausgleichen (Schwabe *et al.*, 2021). Aus Resistenzsicht problematisch ist der Wirkungsmechanismus der Clearfield®-Herbizide. Sie gehören zu den ALS-Hemmern. Das Resistenzrisiko beim Einsatz von ALS-Hemmern ist im Allgemeinen relativ hoch. Bei gewöhnlichen Herbizidstrategien kommen ALS-Hemmer beim Rapsanbau nicht zum Einsatz, werden jedoch unter anderem im Getreide- und Maisanbau standardmäßig angewendet. Für einen langfristigen Erhalt der Wirksamkeit sollten ALS-Hemmer idealerweise nicht jedes Jahr angewendet werden (Holt *et al.*, 1993; Tranel & Wright, 2002; Shaner, 2014; Moss, 2017; Löbmann *et al.*, 2021).

Um das Resistenzrisiko zu verringern, aber dennoch die Vorteile des Clearfield®-Systems bei aufkommender Notwendigkeit nutzen zu können, empfiehlt sich das folgende Vorgehen: Bei bestehenden Problemen mit der Bekämpfbarkeit von kreuzblütigen Unkräutern sollten zunächst Clearfield®-Rapssorten angebaut und eine gewöhnliche Vorauflaufherbizid-Strategie genutzt werden. Wird im zeitigen Frühjahr festgestellt, dass kreuzblütige Unkräuter die Schadschwelle überschreiten, dann kann schlagspezifisch eine Entscheidung über eine Clearfield®-Herbizid Applikation getroffen werden. Es wird dadurch nur im Bedarfsfall ein Clearfield®-Herbizid angewendet, das Resistenzrisiko steigt nicht automatisch. Dabei ist im Vorhinein nicht von Ertragsnachteilen auszugehen. Bisherige Studien konnten zeigen, dass eine gewöhnliche Vorauflaufstrategie einer Clearfield®-Herbizidstrategie im Herbst im Hinblick auf den Ertrag ebenbürtig sein kann (Schwabe *et al.*, 2021). Weiterhin führt eine Clearfield®-Herbizid Applikation zu späteren Entwicklungsstadien des Raps nicht zu Ertragsdepressionen und Clearfield®-Rapssorten sind gewöhnlichen Rapssorten nicht notwendigerweise im Hinblick auf Ertragsparameter unterlegen (Tozzi *et al.*, 2016; Durigon *et al.*, 2020). Allerdings sind die chemischen Kontrollmöglichkeiten von Clearfield®-Durchwuchsraps in den Folgekulturen eingeschränkt. Die Herbizidtoleranz des angebauten Clearfield®-Raps wird mindestens teilweise an die nachfolgende Generation vererbt. Neben der Toleranz gegen den im Clearfield®-Herbizid in Deutschland verwendeten Wirkstoff Imazamox, sind zudem Kreuztoleranzen gegen andere ALS-Hemmer feststellbar. Die würden in anderen Kulturen für eine wirksame Bekämpfung von nicht-Clearfield®-Durchwuchsraps sorgen (Krato *et al.*, 2012). Für Landwirte ist es deshalb empfehlenswert agronomische Bedingungen zu schaffen, durch die das Auftreten von Clearfield®-Durchwuchsraps verhindert bzw. vermindert wird. Mittelbare Möglichkeiten dazu sind der Anbau von Clearfield®-Raps-Sorten mit einer niedrigen Neigung zur Ausbildung sekundärer Dormanz, die Verwendung verlustarmer, optimal eingestellter Erntetechnik und eine angepasste Bodenbearbeitungsstrategie (Gruber *et al.*, 2004, 2010; Weber *et al.*, 2014; Huang *et al.*, 2016b, 2018). Unmittelbar zur Verhinderung von Durchwuchsraps beitragen könnte die Anwendung von Nährstoffen und Gibberellinsäure. In dieser Dissertation konnte nachgewiesen werden, dass sowohl Nährstoffe als auch Gibberellinsäure die Ausbildung sekundärer Dormanz, wie auch die Überdauerungsfähigkeit von Rapssamen vermindern (Schwabe *et al.*, 2019). Diese Ergebnisse bestätigen Erkenntnisse bisheriger Studien mit Samen von anderen Spezies (Finch-Savage & Leubner-Metzger, 2006; Arefi *et al.*, 2012; Farooq *et al.*, 2012; Muhammad *et al.*, 2015; Shu *et al.*, 2015). Wenn es unter Feldbedingungen mit Applikationstechniken gelingt Ausfallrapssamen in Kontakt mit Mikronährstoffen bzw. Gibberellinsäure zu bringen, ist in den Folgekulturen mit keinem Durchwuchsraps mehr zu rechnen bzw. nur noch mit einem stark verringerten Potential (Schwabe *et al.*, 2019).

Treten in dem beschriebenen System Unkräuter auf, die sich aufgrund von Resistenzen weder durch Clearfield®-Herbizide noch durch andere, praxisüblichere Rapsherbizide kontrollieren lassen, besteht die Möglichkeit einer mechanischen Unkrautkontrolle. Gleiches gilt für das Auftreten von Clearfield®-Durchwuchsraps in einem Kulturrapsbestand. Eine geeignete Option der mechanischen Unkrautkontrolle in Raps ist Hacken (Schwabe *et al.*, 2022). Die Reihenweite des Raps sollte dazu erhöht werden und mindestens 24 cm betragen, um Raum für die Hackschare zu schaffen. Den Erkenntnissen dieser Dissertation folgend, führt eine Erhöhung der Reihenweite in Raps dabei nicht zu Ertragsdepressionen, da die Kompensationsfähigkeit und Konkurrenzstärke von modernen Rapshybridsorten stark ausgeprägt ist. Ergebnisse bisheriger Studien konnten damit bestätigt werden (Lemerle *et al.*, 2017; Schwabe *et al.*, 2021). Hacken ermöglicht zwischen den Reihen eine sichere Bekämpfung von chemisch nicht kontrollierbaren Unkräutern, es lässt sich sowohl im Herbst als auch im Frühjahr durchführen. Auch wenn Unkräuter in der Reihe verbleiben, geht damit nicht zwangsläufig eine Ertragsdepression einher (Schwabe *et al.*, 2022).

Als Erweiterung bisheriger Strategien besitzt das Hacken in Raps hohes Potential. Als einziges Werkzeug der Unkrautbekämpfung in Raps ist Hacken allerdings nur bedingt empfehlenswert, denn: Die Effektivität des Hackens ist wetterabhängig, die höchste Wirksamkeit wird bei trockenen Bedingungen und bei Unkräutern in einem frühen Entwicklungsstadium erreicht. Weiterhin können negative Auswirkungen auf den Rapsertrag bei einem stark erhöhten Unkrautaufkommen und damit auch einer erhöhten Anzahl von verbleibenden Unkräutern innerhalb der Reihen nicht ausgeschlossen werden. Insbesondere wenn große Rapsflächen gehackt werden sollen, verschärft sich die Problematik - Im Vergleich zur Pflanzenschutzspritze haben Hackgeräte eine niedrigere Arbeitsbreite und Arbeitsgeschwindigkeit. Der ideale Hackzeitpunkt in einem frühen Entwicklungsstadium der Unkräuter lässt sich dadurch auf der gesamten Fläche schwieriger treffen, vor allem dann, wenn feuchte Bedingungen den Hackeinsatz erschweren oder weiter hinauszögern. Die Folge wäre eine abnehmender Wirkungsgrad des Hackens (Bond & Grundy, 2001; Beckie, 2006; Kurstjens, 2007; Gummert *et al.*, 2012;

Melander *et al.*, 2013; Fogliatto *et al.*, 2017; Pannacci *et al.*, 2017; Redlick *et al.*, 2017; Andersen & Kuennen, 2019; Schwabe *et al.*, 2022).

Wenn auf einem konventionellen landwirtschaftlichen Betrieb mit einer gewöhnlichen Herbizidstrategie im Raps die Effektivität der Unkrautbekämpfung abnimmt und vermehrt einzelne, schwerbekämpfbare Unkrautarten auftreten, dann lässt sich zusammengefasst von den Erkenntnissen der in dieser Dissertation enthaltenen drei Publikationen die folgende agronomische Empfehlung ableiten:

Für die gesamte Rapsanbaufläche sollten Clearfield®-Sorten mit einer niedrigen Dormanzneigung gewählt werden. Gesät mit einem Reihenabstand von mindestens 24 cm. Zunächst käme anschließend die betriebsübliche Herbizidstrategie zum Einsatz. Beim Auftreten von herbiziden Minderwirkungen kann nachfolgend schlag- oder teilschlagspezifisch eine Entscheidung über die zusätzliche Anwendung eines Clearfield®-Herbizids und / oder die Durchführung eines Hackvorgangs getroffen werden. Sowohl das Clearfield®-System als auch das Hacken als mechanische Unkrautkontrollmöglichkeit werden dabei als sinnvolle Erweiterungen in die bisherige chemische Unkrautbekämpfungsstrategie integriert. Um die Unkrautkontrolleffizienz in den Folgefrüchten nicht negativ zu beeinflussen, ist es dabei von entscheidender Bedeutung ganzheitliche Strategien zu ergreifen, um das Auftreten von Durchwuchsraps zu verhindern, dazu gehören eine angepasste Bodenbearbeitungsstrategie, ein verlustarmer Erntevorgang und möglicherweise zukünftig die Anwendung von Nährstoffen bzw. Gibberellinsäure zur Verhinderung der Ausbildung von sekundärer Dormanz durch Ausfallrapssamen (Gruber & Claupein, 2006; Gruber *et al.*, 2010; Weber *et al.*, 2014; Huang *et al.*, 2016a; Schwabe *et al.*, 2019, 2021, 2022).

# 7 Zusammenfassung

Raps ist nach Soja weltweit die zweitbedeutendste Ölpflanze. Infolge des European Green Deal der Europäischen Union und der damit verbundenen zukünftig stärkeren Förderung erneuerbarer Energien ist davon auszugehen, dass die Bedeutung des Anbaus von Raps weiter zunimmt.

Aufgrund des auf konventionellen landwirtschaftlichen Betrieben in Deutschland lastenden Preisdrucks wurden Anbausysteme unter ökonomischen Gesichtspunkten, mitunter zu Lasten der Nachhaltigkeit, umgestellt. Infolgedessen bestehen Fruchtfolgen oftmals aus wenigen, monetär gewinnbringenden Kulturen, der Anteil von Sommerungen in der Fruchtfolge wurde stark reduziert. Der Rapsanbau ist unter wirtschaftlichen Gesichtspunkten attraktiv, sein Anteil in der Fruchtfolge wurde erhöht. Die Intensität der Bodenbearbeitung wurde verringert, mechanische Unkrautbekämpfung findet kaum statt. Der Unkrautbekämpfungserfolg ist stark abhängig von der Wirksamkeit zahlenmäßig begrenzter herbizider Wirkstoffe. Durch die einseitigen Fruchtfolgen und die niedrigere Bodenbearbeitungsintensität werden bestimmte Unkrautarten stärker gefördert, gleichzeitig werden diese mit wenigen herbiziden Wirkstoffen kontrolliert. Es entwickeln sich angepasste, schwer kontrollierbare und zum Teil herbizidresistente Unkrautpopulationen. Aus diesem Grund liegt der Zweck dieser Dissertation in der Evaluierung alternativer Unkrautmanagementsysteme in Kulturraps, wobei zudem Möglichkeiten zur prophylaktischen Verhinderung des Auftretens von Durchwuchsraps als Unkraut in der Fruchtfolge untersucht werden sollten.

Ziele dieser Dissertation waren: (i) Das Potential des Hackens als mechanisches Unkrautkontrollverfahren und die (ii) Anwendung des Clearfield®-Systems in Raps im Vergleich zu gewöhnlichen, praxisüblichen Herbizidstrategien zu evaluieren. (iii) Die Fokussierung der Durchwuchsrapsproblematik. Aus Clearfield®-Raps resultierender Durchwuchsraps lässt sich in den Folgekulturen aufgrund vererbter Herbizidtoleranzen schlechter chemisch kontrollieren. Es wurde untersucht, inwieweit verschiedene Samenbehandlungen bei Raps die Entwicklung sekundärer Dormanz und damit sowohl Überdauerungsfähigkeit der Samen als auch die Durchwuchsrapsproblematik reduzieren. Der Zielsetzung folgend wurden verschiedene Feld- und Laborversuche durchgeführt, deren Ergebnisse in drei wissenschaftlichen Publikationen veröffentlicht worden.

Publikation I: In einem zweijährigen Feldversuch wurde die Leistungsfähigkeit des Clearfield®-Systems im Raps unter verschiedenen Bewirtschaftungsintensitäten im Vergleich zu einem praxisüblicheren Vorauflaufherbizidsystem evaluiert. Das Clearfield®-System ist ein alternatives Unkrautmanagementsystem für Kulturraps. Dabei handelt es sich um eine Kombination aus einem breitwirksamen Nachauflauf-Herbizid und einer Clearfield®-Rapssorte, die eine Toleranz gegenüber dem Herbizid aufweist. Die Toleranz gegenüber dem Clearfield®-Herbizid wurde durch konventionelle, gentechnikfreie Züchtungsverfahren in Clearfield®-Rapssorten implementiert. Auf Nicht-Clearfield®-Rapssorten besitzen Clearfield®-Herbizide eine letale Wirkung.

Publikation II: In Labor- und Feldversuchen wurde die Wirkung von keimungsfördernden Substanzen (Nährstoffe und Gibberellinsäure) auf die Dormanzentwicklung von Rapssamen und auf deren Überdauerungsfähigkeit untersucht.

Publikation III: In einem dreijährigen Feldversuch wurde Hacken als Unkrautkontrollverfahren mit einer praxisüblichen Herbizidstrategie verglichen.

Die in der Einleitung aufgestellten Hypothesen wurden durch die in den Versuchen erlangten Erkenntnisse sowohl bestätigt als auch widerlegt.

In Publikation I aufgestellte Hypothesen:

(i) Das Clearfield®-Herbizid und die Herbizide einer praxisüblichen Vorauflaufstrategie zeigen eine ähnliche Effizienz; (ii) die Bewirtschaftungsintensität hat einen Effekt auf die Unkrautdichte, beeinflusst aber nicht den Ertrag; (iii) die Herbizidstrategie hat keinen Einfluss auf den Ertrag.

*Bei höheren Bewirtschaftungsintensitäten erreichten beide Herbizid-Systeme eine vergleichbare Effizienz. Bei niedrigeren Bewirtschaftungsintensitäten, insbesondere die Saatdichte und die Bodenbearbeitung betreffend, ließen sich Unkräuter mit dem reinen Clearfield®-System weniger effizient kontrollieren und der Ertrag viel teilweise geringer aus. In höheren Bewirtschaftungsintensitäten war im Vergleich zu niedrigeren ein höherer Ertrag und ein geringeres Unkrautaufkommen feststellbar; vermutlich durch eine bessere Unkrautbekämpfung durch die wendende Bodenbearbeitung und durch günstigere Auflaufbedingungen in der Pflugsaat.*

In Publikation II aufgestellte Hypothesen:

(i) Alle getesteten Substanzen reduzieren die Induktion von sekundärer Dormanz; (ii) die getesteten Substanzen reduzieren die Induktion sekundärer Dormanz unterschiedlich stark; (iii) die getesteten Substanzen haben einen Effekt auf die Induktion sekundärer Dormanz unabhängig davon, ob die getesteten Rapssamen von Sorten mit einer hohen oder niedrigen Neigung zur sekundären Dormanzentwicklung stammen; (iv) wenn eine Sorte zur Ausbildung von einer hohen sekundären Dormanz neigt, wird deren Induktion stärker durch die getesteten Substanzen reduziert, als bei Samen von einer Sorte mit einer niedrigen Neigung zur Ausbildung sekundärer Dormanz.

*Die meisten getesteten Substanzen reduzierten sowohl die Induktion sekundärer Dormanz als auch die Überdauerungsfähigkeit von Rapssamen. Die Effizienz der Reduktion war von der Art der Substanz und der Rapssorte abhängig. Am wirkungsvollsten erwiesen sich gibberellinsäurehaltige Substanzen gefolgt von Mikronährstoffbeizen und Kaliumnitrat.*

In Publikation III aufgestellte Hypothesen:

(i) Durch Hacken wird die gleiche Effizienz in der Unkrautkontrolle erreicht wie durch Herbizide; (ii) unabhängig davon, ob Herbizide oder Hacken als Unkrautkontrolle eingesetzt werden, lässt sich der gleiche Rapsertrag realisieren.

*Die Unkrautbiomasse war im Vergleich zum Herbizideinsatz höher, wenn Hacken als Unkrautbekämpfungsmaßnahme zum Einsatz kam. Ursächlich dafür ist wahrscheinlich die witterungsabhängige Effizienz des Hackens und dessen nur teilflächige Anwendbarkeit. Unkräuter die in oder nahe an der Saatreihe auflaufen, können nicht erfasst werden. Dennoch ließen sich zwischen dem Hacken als Unkrautbekämpfungsmaßnahme und der reinen chemischen Unkrautbekämpfung keine Ertragsunterschiede feststellen, die Konkurrenzstärke der verwendetet Sorten war vermutlich groß genug für die Gewährleistung dieser Ertragsstabilität.*

Sowohl durch Hacken, als auch durch die Anwendung des Clearfield®-Systems unter höheren Bewirtschaftungsintensitäten ließen sich im Vergleich zu praxisüblichen Herbizidstrategien ähnlich hohe Rapserträge erzielen, auch wenn die Effizienz der Unkrautbekämpfung niedriger war. Solange auf einem konventionellen landwirtschaftlichen Betrieb keine schwerbekämpfbaren Unkräuter auftreten und eine herkömmliche Herbizidstrategie vorhandene Unkräuter effektiv kontrolliert, ist eine Veränderung des Unkrautmanagementsystems weniger vorteilhaft; denn das Clearfield®-System erhöht den Selektionsdruck auf Unkräuter, das Auftreten von Unkraut-Herbizidresistenzen wird wahrscheinlicher. Zudem lässt sich Clearfield®-Durchwuchsraps in den Folgekulturen chemisch schwieriger kontrollieren. Die Effizienz des Hackens ist wetterabhängig, Unkräuter werden nur zwischen den Reihen erfasst und die Flächenleistung ist niedriger.

Wenn allerdings schwerbekämpfbare Unkräuter die Effizienz bestehender, herkömmlicher chemischer Bekämpfungsstrategien zunehmend minimieren, können sowohl Hacken als auch die Anwendung des Clearfield®-Systems in Kombination mit einer gewöhnlichen Herbizidstrategie die Möglichkeiten der Unkrautkontrolle erweitern und deren Effizienz steigern. Bei der Anwendung des Clearfield®-Systems sollten Strategien ergriffen werden, die das Auftreten von Clearfield®-Durchwuchsraps in den Folgefrüchten minimieren. Es konnte gezeigt werden, dass keimungsfördernde Substanzen, insbesondere Gibberellinsäure, die Induktion sekundärer Dormanz verhindern, ebenso wie die Überdauerungsfähigkeit von Rapssamen und damit das theoretische Potential besitzen zu einer Verminderung der Durchwuchsrapsproblematik beizutragen.

Insgesamt betrachtet können sowohl das Hacken als auch die Anwendung des Clearfield®-Systems als alternative Unkrautmanagementsysteme etablierte Methoden der Unkrautbekämpfung in Kulturraps im Bedarfsfall sinnvoll erweitern. Daneben hat der Einsatz keimungsfördernder Substanzen bei Rapssamen das theoretische Potential gezeigt, zu einer Verringerung von Durchwuchsraps als Unkraut in der Fruchtfolge beizutragen.

# 8 Summary

Oilseed rape is the world's second most important oil crop after soybeans. In the course of the European Green Deal of the European Union and the associated stronger promotion of renewable energies in the future, it can be assumed that the importance of oilseed rape cultivation will continue to increase.

Due to the price pressure on conventional farms in Germany, cultivation systems have been changed from an economic point of view, partly to the detriment of sustainability. As a result, crop rotations often consist of a few monetarily profitable crops and the proportion of spring crops in the crop rotation is reduced. Oilseed rape cultivation is attractive from an economic point of view, and its share in the crop rotation has been increased. The intensity of tillage and mechanical weed control has been reduced. The weed control success is strongly dependent on the effectiveness of numerically limited herbicidal active agents. Due to monotonous crop rotations and the lower tillage intensity, certain weed species are promoted more strongly, while at the same time these are controlled with only a few herbicidal active agents. Adapted, difficult-to-control, and in some cases herbicide-resistant weed populations develop. For this reason, the purpose of this thesis is to evaluate alternative weed management systems in oilseed rape, while also investigating options for prophylactic prevention of the emergence of volunteer oilseed rape as a weed in crop rotation.

The objectives of this thesis were: (i) To evaluate the feasibility of hoeing as a mechanical weed control method and the application of the Clearfield® system in oilseed rape as a comparison to common, field herbicide strategies. (ii) To focus on the volunteer oilseed rape issue. Volunteers resulting from Clearfield® oilseed rape are more difficult to control chemically in subsequent crops due to inherited herbicide tolerance. The potential of different seed treatments in oilseed rape to reduce the development of secondary dormancy, and therefore seed persistence in the soil and the volunteer oilseed rape issue, was investigated. Following these objectives, several field and laboratory experiments were conducted to generate data for three published scientific papers.

Paper I: A two-year field trial was conducted to evaluate the performance of the Clearfield® system in oilseed rape under different management intensities compared to a more commonly used pre-emergence herbicide system. The Clearfield® system is an alternative weed management system for oilseed rape. It is a combination of a broad-spectrum post-emergence herbicide and a Clearfield® oilseed rape variety that has tolerance to the herbicide. This tolerance was implemented in Clearfield® oilseed rape varieties through conventional, non-GM breeding techniques. Clearfield® herbicides have lethal effects on non-Clearfield® oilseed rape varieties.

Paper II: An investigation was made through laboratory and field trials on the effect of germination-promoting substances (nutrients and gibberellic acid) on the development of secondary dormancy of oilseed rape seeds and on their persistence in the soil.

Paper III: In a three-year field trial, hoeing as a weed control method was compared with a commonly used herbicide strategy.

The hypotheses made in the introduction were both confirmed and refuted by the findings obtained in the trials.

Hypotheses stated in paper I:

(i) The Clearfield® herbicide and herbicides of a common practice pre-emergence strategy show similar efficiencies; (ii) Management intensity has an effect on weed density but does not affect yield; (iii) Herbicide strategy does not affect yield.

*At higher management intensities, both herbicide systems achieved comparable efficiencies. At lower management intensities, especially in terms of seeding density and tillage, weeds were less efficiently controlled with the Clearfield®-system, and yields were partially lower. At higher management intensities, higher yields and lower weed emergence were observed compared to lower intensities, presumably due to better weed control by plowing and more favorable emergence conditions due to a higher tillage intensity.*

Hypotheses stated in paper II:

(i) All tested substances reduce the induction of secondary dormancy; (ii) the tested substances reduce the induction of secondary dormancy to different extents; (iii) the tested substances have an effect on the induction of secondary dormancy, regardless of whether the tested oilseed rape seeds originate from varieties with a high or low tendency, to develop secondary dormancy; (iv) if a variety tends to develop high secondary dormancy, its induction is reduced to a greater extent by the tested substances than in seeds from a variety with a low tendency to develop secondary dormancy.

*Most of the tested substances reduced both the induction of secondary dormancy and the survivability of oilseed rape seeds. The efficiency of the reduction depended on the type of substance and the oilseed rape variety. Substances containing gibberellic acid proved most effective, followed by micronutrient treatments and potassium nitrate.*

Hypotheses stated in paper III:

(i) Hoeing achieves the same weed control efficiency as herbicides; (ii) regardless of whether herbicides or hoeing are used as weed control, the same oilseed rape yield can be realized.

*Weed biomass was higher compared to herbicide application when hoeing was used as a weed control measure. This is probably due to the weather-dependent efficiency of hoeing and its only partial surface applicability. Weeds emerging in or close to the seed row cannot be controlled. Nevertheless, no yield differences were found between hoeing as a weed control measure and pure chemical weed control. The competitive strength of the varieties used was most likely large enough to ensure this yield stability.*

Both hoeing and applying the Clearfield® system under higher management intensities resulted in similarly high oilseed rape yields compared to conventional herbicide strategies, although weed control efficiency was lower. As long as no hard-to-control weeds occur on a conventional farm and a common herbicide strategy effectively controls existing weeds, changing the weed management system is less beneficial. Because the Clearfield® system increases selection pressure on weeds, the occurrence of weed herbicide resistance becomes

more likely. In addition, Clearfield® volunteer canola is more difficult to control chemically in subsequent crops. Hoeing efficiency is weather dependent, weeds are only captured between rows, and area performance is lower.

However, when difficult-to-control weeds increasingly minimize the efficiency of existing, conventional chemical control strategies, both hoeing and the use of the Clearfield® system in combination with a common herbicide strategy can expand weed control options and increase their efficiencies. When applying the Clearfield® system, strategies should be employed to minimize the occurrence of Clearfield® volunteer oilseed rape in subsequent crops. It has been shown in this thesis that germination-promoting compounds, particularly gibberellic acid, prevent the induction of secondary dormancy, as well as the ability of oilseed rape seeds to persist, and therefore, have the theoretical potential to contribute to a reduction in the volunteer oilseed rape occurrence problem.

Overall, both hoeing and the application of the Clearfield® system as alternative weed management systems can usefully complement established methods of weed control in oilseed rape, where necessary. In addition, the use of germination-promoting compounds in oilseed rape seeds has demonstrated the theoretical potential to contribute to a reduction of volunteer oilseed rape as a weed in crop rotations.

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# Eidesstattliche Erklärung

**Eidesstattliche Versicherung**
**gemäß § 8 Absatz 2 der Promotionsordnung der Universität Hohenheim zum Dr.sc.agr.**

1. Bei der eingereichten Dissertation zum Thema:
   „Untersuchung alternativer Unkrautmanagementsysteme für Kulturraps unter Einbeziehung der Durchwuchsrapsproblematik“
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Die Richtigkeit der vorstehenden Erklärung bestätige ich. Ich versichere an Eides Statt, dass ich nach bestem Wissen die reine Wahrheit erklärt und nichts verschwiegen habe.

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