Oilseed rape in high-intensity crop rotations

Dissertation
zur Erlangung des
Doktorgrades der Agrarwissenschaften (Dr. agr.)

der

Naturwissenschaftlichen Fakultät III
Agrar- und Ernährungswissenschaften,
Geowissenschaften und Informatik

der Martin-Luther-Universität Halle-Wittenberg

vorgelegt von

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Geb. am 28.10.1988 in Naumburg (Saale)

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Verteidigung: 21.02.2022

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AAFC	Agriculture and Agri-Food Canada
ai	active ingredient
ANOVA	analysis of variance
ASN	ammonium sulphate nitrate
C	carbon
DS	disease severity
FAO	Food and Agriculture Organization of the United Nations
GRDC	Grains Research and Development Corporation
LSD	least significant difference
N	nitrogen
ND	Nitrates Directive
NUE	nitrogen use efficiency
OECD	Organisation for Economic Co-operation and Development
OSR	oilseed rape (*Brassica napus* L.)
PCC	preceding crop combination
R	correlation coefficient
RED	Renewable Energy Directive
Rlm	resistance to *Leptosphaeria maculans*
S	sulfur
TSW	thousand seed weight
UFOP	Union for the Promotion of Oil and Protein Plants / Union zur Förderung von Oel- und Proteinpflanzen e.V.
USDA	U.S. Department of Agriculture
WFD	Water Framework Directive
WRa	Winterraps (*Brassica napus* L.)
WW	winter wheat / Winterweizen (*Triticum aestivum* L.)

1. Introduction

1.1 Background

In 2019, the United Nations (2019) stated that global population is expected to reach 9.7 billion in 2050, 26 % higher than today. Moreover, the Food and Agriculture Organization (FAO, 2009) predicted that urbanization will continue at an accelerated pace, and about 70 % of the world's population will be urban in 2050. In order to feed an urbanized population with higher incomes and accompanying changing of food consumption patterns, global agricultural production needs to increase by 60 % from its 2005 – 2007 levels (Alexandratos and Bruinsma, 2012). Along with a growing bio-based economy there is a surging demand for agricultural raw materials (Bastos Lima, 2018). At the same time, increasing social criticism is pointing towards current production practices which are held responsible for various environmental harms. Consequently, agriculture is facing enormous challenges to feed a growing population as well as a growing bio-based economy and concurrently produce in an environmentally friendly manner.

In this context, the oil crop sector became one of the most dynamic parts of global agriculture during the last several decades (Alexandratos and Bruinsma, 2012). Oil crops deliver edible oils for food purposes, feedstocks for the biofuel and chemical industries and their high-protein meals are a valuable fodder in livestock production. The most important oil crops are oil palm, soy bean and oilseed rape (OSR) contributing to almost 81 % of the total vegetable oil production worldwide (USDA, 2020a). Since the 1990s the cultivation area of these crops expanded by 100.5 million ha and today amounts to 181.4 million ha worldwide (FAOStat, 2020). To meet the requirements for vegetable oils for 2028 the OECD-FAO Agricultural Outlook (2019) projected a further increase of the production of up to 239.8 million t. Alexandratos and Bruinsma (2012) projected in their report "World Agriculture Towards 2030/2050" a demand for vegetable oils of up to 282 million t in 2050, which would comply to an annual growth rate of approximately 1 % of the 2017 production level stated in the OECD-FAO Agricultural Outlook (2019). To satisfy the demand of the 2050 world population, there is the probable need to produce an additional 80 million t of vegetable oil, in comparison to the current production.

The most important and most productive oil crop of the temperate growing regions worldwide is OSR (*Brassica napus* L.)[1], which is providing sufficient amounts for the present and for the future demand of vegetable oils. The major producers worldwide are Canada, China, the European Union (EU), India and Australia (FAOStat, 2020).

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[1] *Brassica napus* L. is grown as spring type and winter type, and it is also known as canola or rapeseed. For standardization hereafter it is referred to as oilseed rape without specification of the growing type (except for accepted manuscripts in chapter 2 and chapter 3).

1.2 Global oilseed rape production

The OSR production volume has increased remarkably in most of the major growing countries in recent years. Globally, it is the third most important oil crop behind oil palm and soy bean. In total, the production quantity more than doubled from the 1960s and amounted to 75 million t in 2018 (FAOStat, 2020)[2], which corresponds to 28.1 million t oil equivalent (USDA, 2020b). More than 87 % comes from Canada, the European Union, China, India and Australia (Fig. 1).
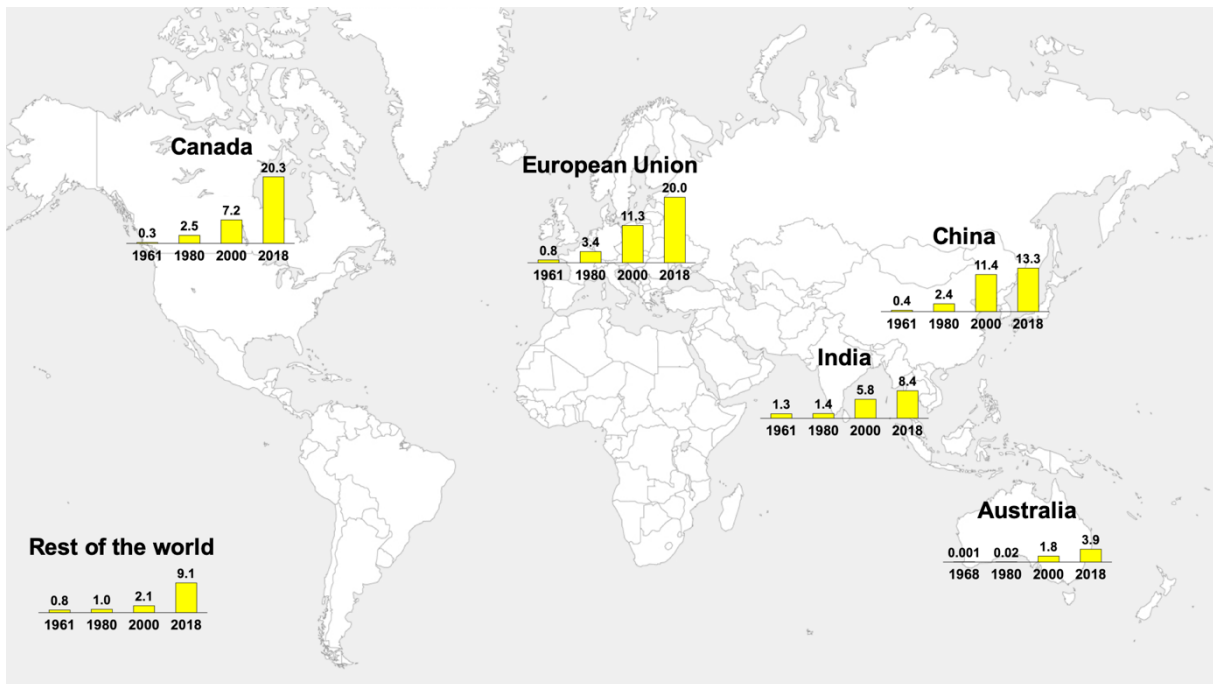
Figure 1: Global development of the oilseed rape production quantity (million t) in major growing areas (FAOStat, 2020)

The rapid growth of the OSR crop is the result of numerous factors. One of the major factors for the rapid advance of OSR was the improved value of rapeseed oil and seed meal as a result of intensive breeding efforts (Friedt and Snowdon, 2009). The major limitations of OSR in the middle of the last century were high contents of erucic acid (C22:1, cis 13-docosenoic acid) which has a bitter taste and, in high doses, has implications on cardiac health as well as high quantities of glucosinolates in the seeds, which made rapeseed meal unsuitable as a feedstock in livestock production (Friedt and Snowdon, 2009). In 1964, Canadian researchers discovered low erucic acid content in the seeds of the German spring rapeseed cultivar "Liho" (Stefansson and Hougen, 1964) and the first zero-cultivar "Oro" (eruca acid free) was released in 1968 (Morrison et al., 2016). A further milestone was the identification of the Polish spring rape variety "Bronowski" as a low glucosinolate form (Kondra and Stefansson, 1970) and in 1974 the first double low (low erucic acid and low glucosinolate) cultivar "Tower" was released in Canada (Morrison et al., 2016). Friedt and

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[2] In 2020 preliminary data of the USDA (2020b) predict a drop of the production volume to 68.2 million t which can primarily be attributed to a declined acreage in Europe, Australia and Canada.

Snowdon (2009) highlighted these quality improvements as the beginning of the advance of OSR to one of the most important oil crops in temperate regions worldwide.

About a decade later first hybrid cultivars were commercially released in China in 1985 (Fu and Zhou, 2013) followed by Australia in 1988 (Salisbury et al., 2016), Canada in 1989 (Morrison et al., 2016), India in 1994 (Prakash et al., 2003) and Europe in 1995 (Frauen et al., 2003). Hybrids are characterized by a higher seed yield potential which is based on heterosis effects between parental lines (Friedt and Snowdon, 2009). Today OSR hybrids are covering large parts of commercial OSR production worldwide (Wittkop et al., 2009; Kirkegaard et al., 2016a; Morrison et al., 2016). Moreover, considerable progress has been achieved in the development of genetically modified cultivars (Friedt and Snowdon, 2009) and now herbicide resistant OSR cultivars are predominant in Canadian and Australian cropping systems (Kirkegaard et al., 2016a; Morrison et al., 2016). Further breeding progress which contributed to improved yields of the crop has been achieved through resistance breeding against diseases (Hwang et al., 2016; Peng et al., 2015; Potter et al., 2016), nutrient use efficiency (Bouchet et al., 2016; Stahl et al., 2017) and pod shattering (Salisbury et al., 2016).

Although a large proportion of the increased OSR productivity is the result of breeding progress, it cannot exclusively be attributed to breeding. On a global scale, advances in agronomy associated with adapted and enhanced cultivation methods contributed to higher crop yields as well. There are numerous studies from across the world which reported the advances in agronomy of OSR (Kirkegaard et al., 2016a; Morrison et al., 2016; Hu et al., 2017). In Canada, altered tillage practises in combination with stubble management resulted in better snow trapping during winter and thus provided more soil water to OSR, improved the water use efficiency and increased seed yields (Cutforth et al., 2006). The adoption of mechanization for seeding and harvest processes, combined with high density planting, herbicide weeding, the application of controlled-release fertilizer and effective disease control have improved the yield per unit area in China considerably (Hu et al., 2017). Kirkegaard et al. (2016b) emphasized the importance of timely sowing for enhanced OSR seed yields in South-Eastern Australia. Also, in Germany, research effort in relation to timely sowing showed that the optimal sowing date is a prerequisite to achieve high seed yields (Sieling et al., 2017). As a consequence of the above-mentioned advances in global OSR production systems, seed yields increased across the major growing areas and worldwide the seed yield averaged 2.0 t ha^{-1} in 2018 (FAOStat, 2020) (Fig. 2).

Furthermore, apart from these outstanding advances in breeding and agronomy, political frameworks raised the demand for OSR over the past decades. Several countries across the world launched mandates to cover parts of their biofuel consumption for transport purposes by renewable energy sources to reduce environmental impacts of the transportation sector as well as

to reduce dependence on oil supplying countries (Sorda et al., 2010; Su et al., 2015). Especially, the Renewable Energy Directive (RED, 2009) of the European Union, which once specified a 10 % share of biofuels in the transport sector by the year 2020, now scaled back to the 5 – 7.5 % range, increased the global demand for vegetable oils.
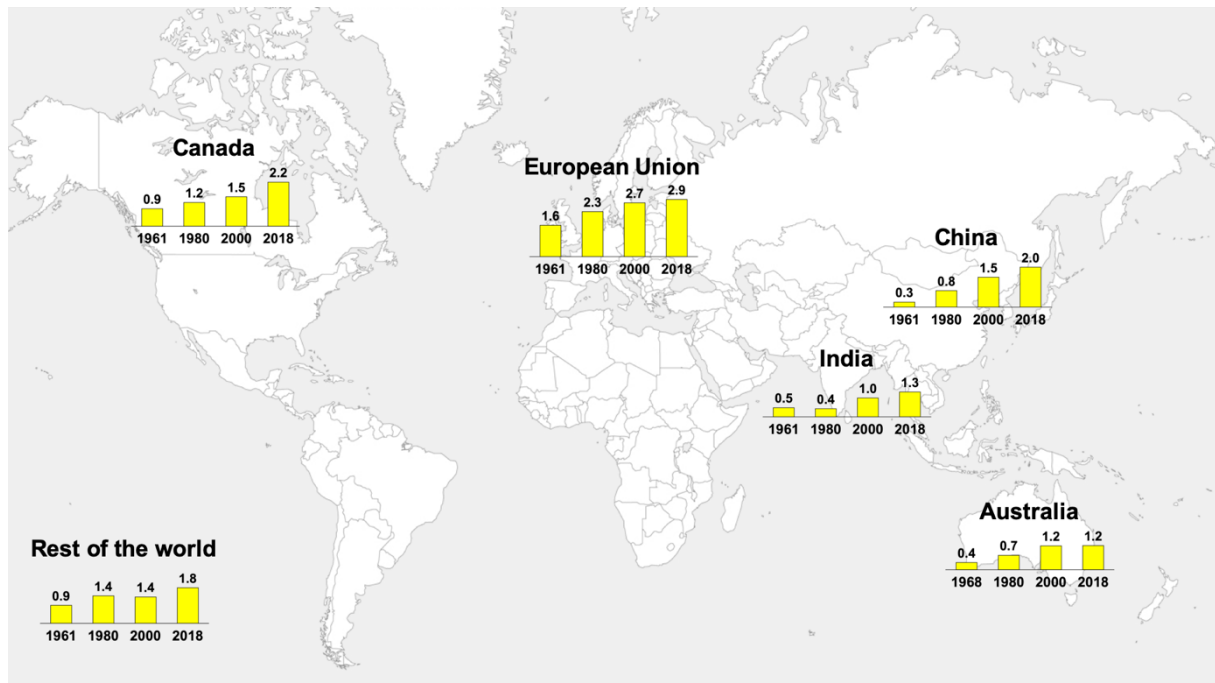
Figure 2: Global development of average oilseed rape seed yields (t ha⁻¹) in major growing areas (FAOStat, 2020)

Overall, all these factors made OSR a valuable cash crop and as a consequence the area of OSR accelerated over recent decades. In total, the growing area has more than quintupled since 1961 and the crop was grown on an area of 37.6 million ha in 2018 (Fig. 3) (FAOStat, 2020)[3].

1.3 The role of oilseed rape in crop rotations

Crop rotation is an ancient concept known for thousands of years to sustain crop productivity. The rotation of crops has several beneficial effects regarding nutrient availability, improved water supply, control of diseases, pests and weeds as well as allelopathic control functions (Karlen et al., 1994). However, the global food supplies are increasingly based on a decreasing number of crops, especially on energy dense crops (Khoury et al., 2014). This development as well as the opportunities enabled by pesticide and fertilizer input in modern crop production systems has prompted farmers to grow crops in shorter rotations than ever before (Bennett et al., 2012). This trend is also obvious for the cultivation of OSR and the simplification of OSR crop rotations was reported across the world (Marcroft et al., 2004; Sprague et al., 2006a; Kutcher et al., 2013; Harker et al., 2015a).

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[3] In 2020 preliminary data of the USDA (2020b) predict a drop of the harvested area to 34.75 million ha which can primarily be attributed to a declined acreage in Europe, Australia and Canada.
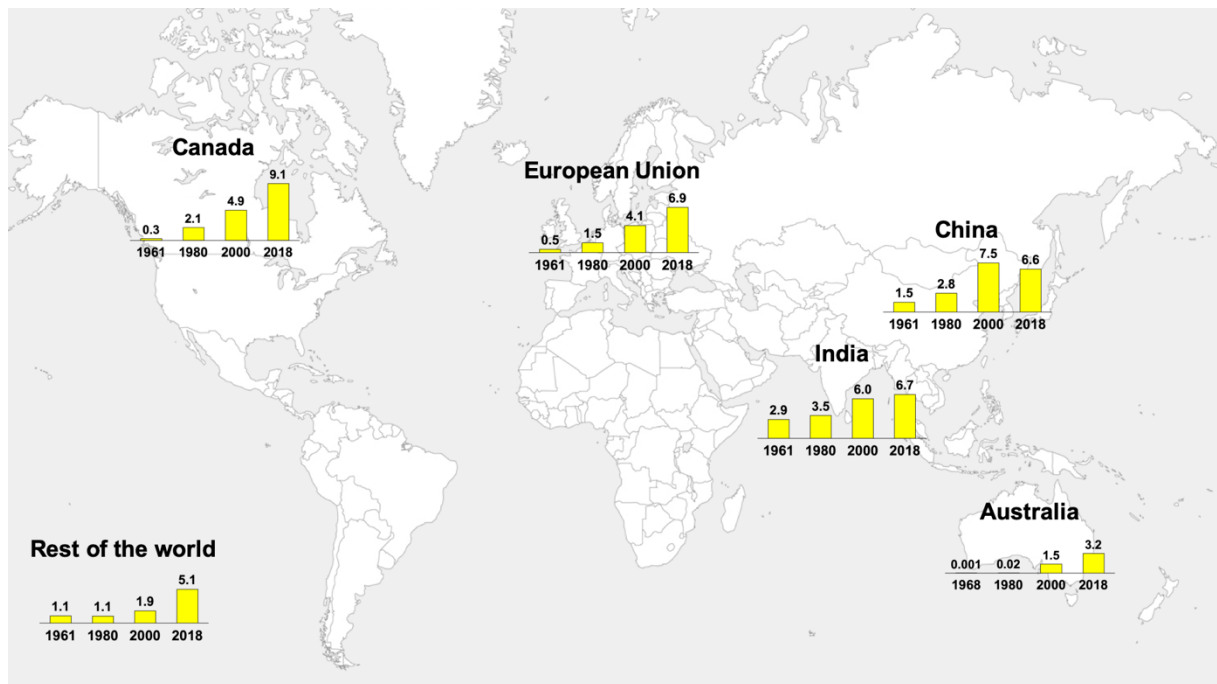
Figure 3: Global development of the oilseed rape acreage (million ha) in major growing areas (FAOStat, 2020)

Historically, the introduction of OSR in crop rotations was driven by the diversification of high-intensity wheat production systems since it is a favorable break crop for cereals. The beneficial impact of OSR in cereal production systems was quantified in numerous studies across the world and reviews on this topic were provided by Kirkegaard et al. (2008) and Angus et al. (2015).

In comparison to cereals, the impact of crop rotations and preceding crops on the productivity of OSR as well as the underlying principles are studied to a lesser extent. However, during recent years numerous studies investigated these effects as a consequence of the increased importance of OSR in global cropping systems (e.g. Harker et al., 2015a, b; St. Luce et al., 2015; Cwalina-Ambroziak et al., 2016; Gill, 2018; Harker et al., 2018; Hossard et al., 2018). The growing demand for vegetable oil for food and energy purposes changed the value of OSR in current cropping systems. Today it is not only a valuable break crop for cereal based crop rotations, it is an even more valuable cash crop due to its economic returns. Consequently, traditional crop rotations growing OSR every fourth year (West et al., 2001; Kutcher et al., 2013) were more and more abandoned and today it is not uncommon to grow OSR every second year or even in monoculture (Harker et al., 2018).

1.3.1 Impacts of break crops and crop rotations on oilseed rape seed yield

With the increasing economic value of the crop and the expansion of the OSR growing area in global cropping systems, the scientific focus has shifted to investigate the impacts of previous crops and crop rotations on OSR. Predominately these experiments were conducted across Europe, North America and to a lesser extent in Asia and Australia.
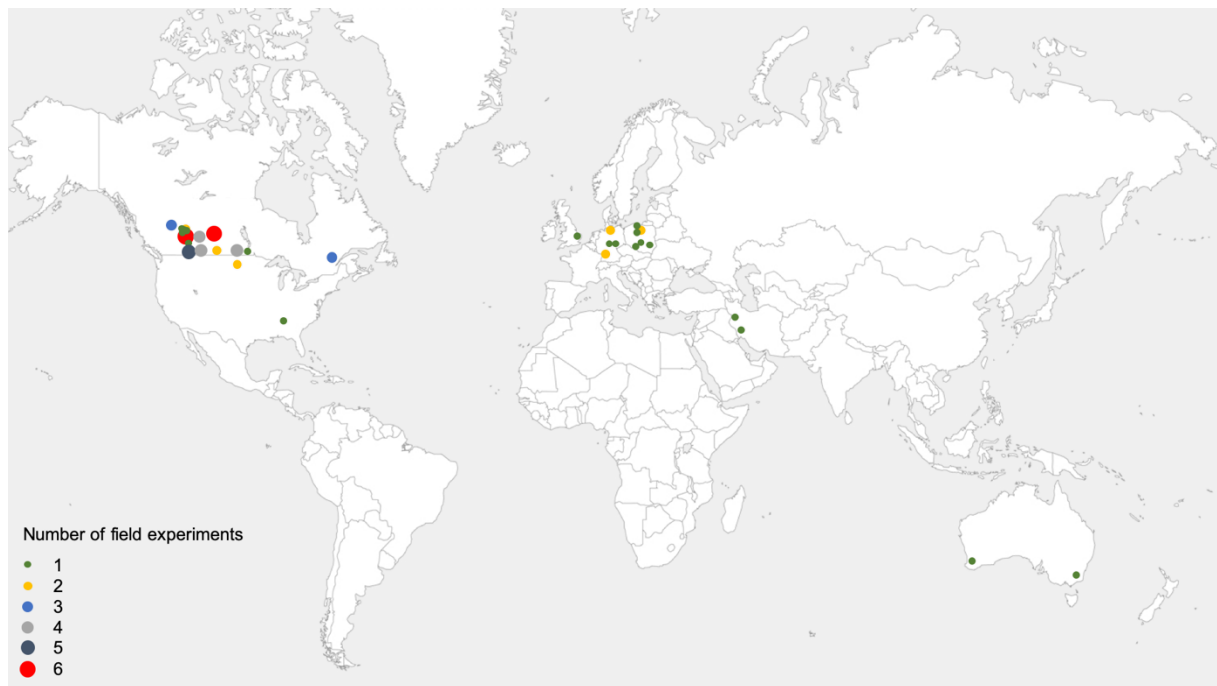
Figure 4: Number and location of crop rotation and preceding crop field experiments conducted to investigate the impact on seed yield of oilseed rape (based on Table 1 of Hegewald et al., 2018)

Figure 4 gives an overview of the experimental locations and the number of experiments which focused on the impact of break crops or crop rotations on OSR seed yield. In Europe, OSR crop rotation experiments were conducted across Germany (Kübler, 1985; Kaul, 2004; Rathke et al., 2005; Sieling and Christen, 2015), Poland (Gonet and Płoszyńska, 1987; Różyło and Pałys, 2011a; Jaskulska et al., 2014; Fordoński et al., 2015; Cwalina-Ambroziak et al., 2016) and the United Kingdom (Stobart, 2012). In North America most of the studies have been carried out across the Canadian Prairies (e.g. Kutcher et al., 2013; O'Donovan et al., 2014; Harker et al., 2015a, b, 2016, 2018).

In general, these studies reported that OSR seed yields increased when other crop species were included in the rotation and when the cropping frequency of OSR decreased. In a long-term crop rotation experiment Sieling and Christen (2015) determined a mean yield for continuous OSR of 3.33 t ha^{-1} and observed 7.5 % to 17 % higher yields for OSR which was excluded for one or up to four years in the rotation. These results were supported by the findings of Stobart (2012) who demonstrated 12 % higher yields for OSR grown in an alternate OSR-winter wheat (WW)[4] rotation and 20 % higher yields for OSR grown after a two-year break with WW-WW as compared to continuous OSR (2.79 t ha^{-1}). Similar relations between crop rotation length and yield response

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[4] Wheat (*Triticum aestivum* L.) is grown as winter type and spring type. In Europe both types are grown with winter wheat being predominant. In Australia the predominant type is spring wheat, which is grown over winter and in Northern America spring types are the most common growing type. Hereinafter wheat is differentiated into winter wheat and spring wheat for European studies and is for simplification just referred to as "wheat" for Australian and North American studies.

were reported by Canadian studies (Kutcher et al., 2013; Harker et al., 2015a). Harker et al. (2015a) found that continuously grown OSR (2.77 t ha^{-1}) suffered yield disadvantages of 10 % and 16 % respectively in comparison to OSR that was grown in two-year and three-year rotations. The benefit of longer crop intervals was also confirmed by Kutcher et al. (2013) who found increasing yields for an open-pollinated cultivar as the frequency in the rotation decreased. Similar to the open-pollinated cultivar in this study, yield of a hybrid cultivar was lowest when grown in monoculture, showed similar yields in two- and four-year rotations and was highest in the three-year rotation following peas in a wheat-pea-OSR rotation.

The superior effect of preceding legumes on OSR crops was described in numerous studies (Kaul, 2004; Johnston et al., 2005; Rathke et al., 2005; Williams et al., 2014; Fordoński et al., 2015; Malik et al., 2015; Sieling and Christen, 2015). The benefit of legumes in cropping systems is well-known (Peoples et al., 2009; Gan et al., 2015) and is mainly attributed to higher availability of nitrogen (N) after legume crops, but also to non-N factors like phosphorous mobilization, improved soil structure, availability of soil water and soil biology. Positive yield benefits due to residual N of previous legumes (pea, faba bean, lentil) were described in several OSR crop rotation studies (Rathke et al., 2005; O'Donovan et al., 2014; Williams et al., 2014). Additional to these yield benefits all these studies reported that legumes contributed to reduce N fertilization rates in following OSR crops. Aside from N benefits, Kaul (2004) described that the long period between harvest of peas and sowing of OSR enabled an additional tillage practice as well as an earlier sowing date of OSR as compared to a preceding flax crop. Better seed bed conditions after the preceding pea crop in this experiment led to a better seed emergence, higher plant densities and higher yields of OSR (3.85 t ha^{-1}) that followed peas in comparison to OSR (2.53 t ha^{-1}) following flax. In Canada, Miller et al. (2003a) observed higher yields for OSR following pea and lentil as compared to OSR that followed wheat and mustard in the dry season of their experiment. This effect was attributed to a lower extraction of soil water of pea and lentil and in consequence these crops conserved more soil water for the subsequent OSR crop (Miller et al., 2003b). Sieling and Christen (2015) observed highest OSR seed yields when OSR followed a preceding pea crop (3.9 t ha^{-1}). Moreover, they demonstrated that the negative yield effect of a high OSR percentage in the rotation was mitigated when OSR was grown on the stubble of a previous pea crop.

The impact of preceding crops on OSR seed yield was also shown for cereal crop species. The yield of OSR in an alternate OSR-barley rotation (3.67 t ha^{-1}) was 10 % higher as the yield of OSR grown in an OSR-WW rotation (Sieling and Christen, 2015). Furthermore, the yield of OSR in an OSR-WW-barley rotation (3.82 t ha^{-1}) was 5 % higher than the yield of OSR grown in an OSR-WW-WW rotation. The authors hypothesized that due to later harvest of wheat, the straw had less time for decomposition and therefore allelochemical substances released by decomposing wheat straw

might have hampered OSR growth. This theory is supported by the review of Wu et al. (2001) who described that an adequate time gap between wheat straw decomposition and sowing of the succeeding crop seems to be a prerequisite for a healthy growth. Similar findings on the yield response of OSR grown after wheat and barley were reported from an experiment conducted at the Northern Great Plains, where OSR grown after barley outyielded OSR grown after wheat by 13 % and 7 % in both growing seasons (Krupinsky et al., 2006). However, Malik et al. (2015) reported contrasting findings from an Australian field site and found higher seed yields for OSR following wheat in comparison to OSR that followed barley.

1.3.2 Factors of yield decline in short oilseed rape rotations

Yield losses due to shorter OSR crop rotations or OSR monocultures are commonly ascribed to higher incidences and severities of diseases (Kübler, 1985; Johnston et al., 2005; Kutcher et al., 2013; Peng et al., 2013; Harker et al., 2015a, b; Peng et al., 2015), insect pests (Evans and Scarisbrick, 1994; Dosdall et al., 2012; Harker et al., 2015a) or weed infestations (Cathcart et al., 2006; Różyło and Pałys, 2011a, b; Harker et al., 2016).

Major constraints due to unfavorable crop rotations are caused by blackleg (Harker et al., 2015a) (described in further detail in section 1.5.2) and by clubroot (*Plasmodiophora brassicae*) (Peng et al., 2014, 2015). Two experiments at a highly clubroot infested field site at Normandin (Canada) have shown that longer cropping breaks resulted in lower disease severity indexes, decreased concentrations of *Plasmodiophora brassicae* resting spores in the soil, less stunting and wilting symptoms, smaller clubs and higher yields (Peng et al., 2013, 2015). However, seed yield of susceptible and moderate susceptible cultivars was too low for commercial production, but even resistant cultivars grown in monoculture showed substantial yield losses varying from 28 – 32 % in comparison to OSR that was grown in three-, four- and five-year rotations (Peng et al., 2015). Other important diseases like sclerotinia stem rot (*Sclerotinia sclerotiorum* (Lib.) de Bary) and verticillium stem riping (*Verticilium longisporum*) showed no consistent relation to crop rotations. Hence, the development of these diseases is probably more related to environmental conditions (Wahmhoff et al., 1999; Jenks et al., 2010; Kutcher et al., 2013; Cwalina-Ambroziak et al., 2016).

Investigations across five field sites over a three-year period in the Canadian Prairies have shown that the damage caused by root maggots (*Delia* spp.) increased with an increasing cropping frequency of OSR in the rotation (Dosdall et al., 2012). In the third year of the study continuous OSR showed the highest ratings for feeding channels and the lowest yield in comparison to OSR grown in an OSR-wheat-OSR rotation and a pea-barley-OSR rotation. Furthermore, the results revealed that root maggot damage in OSR grown in consecutive years increased significantly over time. In the further course of this experiment, Harker et al. (2015a) confirmed the earlier findings

and found that root maggot damage ratings decreased as rotational diversity increased. In contrast to the previous study, root maggot damage did not accelerate as the study progressed, rather year-to-year variability in root maggot populations and predator species abundance in specific years are responsible for damage severity (Harker et al., 2015a). European studies indicated that higher proportions of OSR in the landscape tended to increase the crop damage by root maggot and pollen beetle (*Brassicogethes aeneus*) (Valantin-Morison et al., 2007; Rusch et al., 2013). The proportion of land in a given area is related to crop rotation patterns, which means that the more land planted with OSR annually over the same cropping area results in higher OSR cropping frequencies in crop rotations (Harker et al., 2018). In this context the results of Evans and Scarisbrick (1994) are of particular interest. At a field site in Edinburgh (UK) the authors observed a six-day delayed infestation with pollen beetles when the following OSR crop was cultivated 1,600 m away from the previous OSR field in comparison to a field adjacent to the one where OSR was grown in the year before. The delayed migration of the pollen beetles to the isolated field made an insecticide application unnecessary while it was necessary in the adjacent field.

Large-scale surveys on weeds in Europe indicated a varying weed composition in relation to the proportion of OSR in crop rotations (Hanzlik and Gerowitt, 2011, 2012; Fried et al., 2015). Crop rotation experiments in Poland supported these findings and showed typical OSR weeds like *Viola arvensis*, *Capsella bursa-pastoris* and *Papaver rhoeas* at their experimental sites (Różyło and Pałys, 2011b). Furthermore, it was shown that despite the control of weeds with herbicides in autumn and spring OSR that was grown in the third consecutive year had the highest number of weed individuals (88.2 m^{-2}) and the highest weed biomass (266 g m^{-2}). OSR that was grown in a WW-WW-OSR rotation showed 25 % less weed individuals, a 23 % lower weed biomass per m^2 and had a 16 % higher seed yield than OSR (1.8 t ha^{-1}) that was grown in three consecutive years (Różyło and Pałys, 2011a, b). At three experimental sites across Alberta (Canada) Cathcart et al. (2006) examined weed populations before seeding as well as before and after in-crop herbicide application in continuous OSR and OSR grown in one of two, one of three and one of four years and found highest weed densities for continuous OSR at each assessment date. Averaged over all sites, highest OSR yield was grown in a one of three- (2.3 t ha^{-1}) or a one of four-year (2.3 t ha^{-1}) rotation and lowest for the continuous OSR (1.8 t ha^{-1}). Harker et al. (2016) showed that diverse crop rotations and optimal cultural control practices combined with a reduced herbicide input led to similar wild oat densities, aboveground wild oat biomass, wild oat seed densities in the soil as a repeated OSR-wheat rotation under a full wild oat herbicide rate regime. Moreover, the experiments indicated higher yields for more diverse OSR rotations in comparison to the repeated OSR-wheat rotation with a full herbicide regime.

Further studies described that additional inputs were not able to compensate for the negative effects of an unfavorable cropping history on the seed yield of OSR (Christen and Sieling, 1995; Sieling and Christen, 1997; Kutcher et al., 2013). Christen and Sieling (1995) found no interaction between crop rotation and additional fertilizer and fungicide treatments, while crop rotation had a significant impact on OSR seed yield. Another experiment on the impact of different N fertilization rates and N distribution patterns during the cropping season on six OSR cultivars grown after different preceding crop combinations supported the previous findings of Christen and Sieling (1995) and showed no compensation effect when OSR that was grown in an unfavorable rotation received more fertilizer (Sieling et al., 1997). These results are of particular interest since OSR is considered as a crop with a low N efficiency requiring high N amounts to build up biomass but low offtake by the seeds resulting in high N surplus values which enhance the risk of nitrate leaching, the pollution of waters and N_2O emissions (Sieling and Kage, 2010; Walter et al., 2014). However, recent studies showed contrasting results and gave evidence that higher agronomic inputs rescued yield loss in continuous OSR and therefore compensated negative effects of shorter rotations (Cwalina-Ambroziak et al., 2016; Harker et al., 2018).

1.4 Yield formation of oilseed rape

The seed yield of OSR per area is a result of plant population density, the number of pods per plant, the number of seeds per pod and the individual seed weight (Diepenbrock, 2000). Further information on secondary yield components is given in Figure 5.
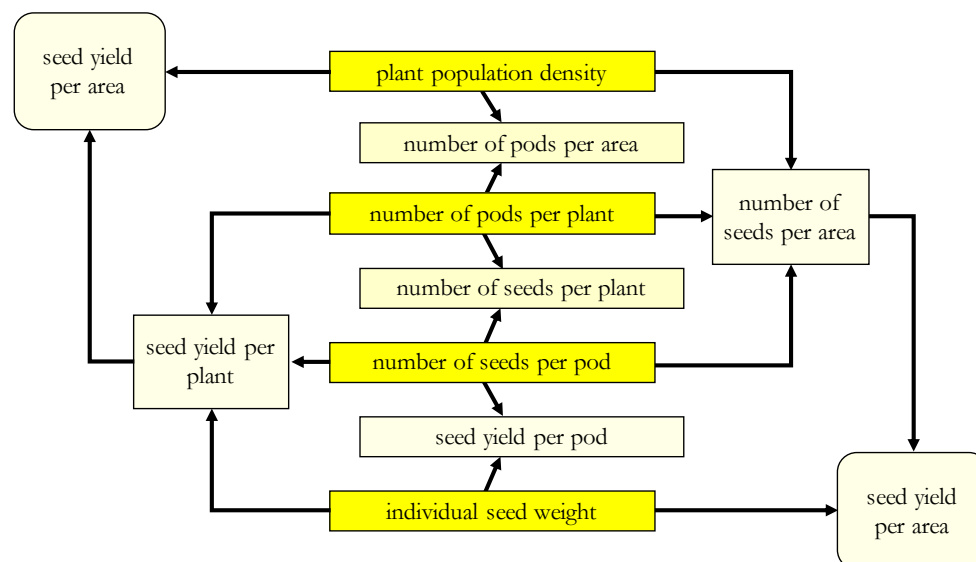

Figure 5: The yield components of oilseed rape (adopted from Diepenbrock and Grosse, 1995)

Plant density has the greatest effect on seed yield but the yield structure is very plastic and adjustable across a wide range of populations (Diepenbrock, 2000). Optimal plant population densities vary depending on environment, time of sowing, whether open-pollinated or hybrid cultivars were

cultivated and whether winter types or spring types were grown (Angadi et al., 2003; French et al., 2016; Roques and Berry, 2016). Hybrid cultivars are usually grown with less plants per unit area than open-pollinated, and spring cultivars are sown with higher seeding rates than winter types (Roques and Berry, 2016). Modern hybrid cultivars need about 30 plants per m^2 to achieve economic optimum yields while 50 plants are recommended for open-pollinated cultivars (French et al., 2016; Roques and Berry, 2016).

The number of pods per plant is the most responsive of all the yield components (Diepenbrock, 2000) and is determined by the availability of assimilates during flowering (Habekotté, 1993; Labra et al., 2017; Zhang and Flottmann, 2018). OSR plants grown under low plant densities develop higher numbers of pods than OSR plants grown in high densities and therefore compensate for differences in the plant population mainly through increased branching (Leach et al., 1999; Angadi et al., 2003; Zhang et al., 2012) while pod numbers on the terminal shoot remain constant across a wide range of populations (Diepenbrock, 2000). To achieve maximum yields the development of $6,000 - 8,000$ pods per m^2 is necessary (Berry and Spink, 2006).

The number of seeds per pod varies along the terminal raceme and the primary branches and decreases from the terminal raceme to branches of lower order (Diepenbrock, 2000). Pods can contain from 30 (Clarke, 1979) to a maximum of 40 (Rakow, 1978) seeds and on average $15 - 25$ seeds are developed in each pod (Diepenbrock, 2000; Angadi et al., 2003; Zhang et al., 2012; Zhang and Flottmann, 2016). Seed number per pod reflects the high degree of plasticity of OSR and a higher number of seeds per pod is developed in populations with lower plant densities (Zhang et al., 2012).

Thousand seed weight (TSW) is primarily determined by the genetic potential (Kennedy et al., 2011) and is negatively correlated with the number of pods per plant as well as the number of seeds per pod (Léon and Becker, 1995). In general, the TSW is between $1.3 - 7$ g (Kennedy et al., 2011). TSW of seeds of the main raceme is higher than that of seeds developed at branch racemes (Zhang et al., 2012). Dense crops, where main raceme and the uppermost branches contributed predominantly to seed yield, showed a higher TSW (Leach et al., 1999). Recent results demonstrated plasticity of TSW (Labra et al., 2017; Zhang and Flottmann, 2018) in response to reduced seed numbers caused by assimilate constraints during flowering, but the degree of compensation depends on environmental conditions (Zhang and Flottmann, 2018).

1.4.1 Impacts of break crops and crop rotations on oilseed rape yield formation

Assessing OSR yield components associated with the collection of crop samples, counting of pods, identifying the number of seeds per pod and analyzing TSW is a labour intensive and time-consuming work and consequently only few studies investigated the impact of break crops and

crop rotations on yield formation parameters of OSR (Christen and Sieling, 1995; Sieling et al., 1997; Sieling and Christen, 1997; Różyło and Pałys, 2011a; Kutcher et al., 2013; Stobart and Bingham, 2013).

Christen and Sieling (1995) determined 71,521 seeds per m^2 when OSR was following a preceding pea crop in a five-year rotation with an OSR proportion of 40 % within the rotation, while the number of seeds per m^2 for an alternate OSR-WW rotation was 14 % lower and declined by 16 % when OSR was grown in monoculture. However, the effect of different crop rotations on the yield component seeds per m^2 was not statistically significant in this study. Later experiments showed that OSR grown after the preceding crop combinations WW-barley (79,990 seeds per m^2) and WW-WW (79,450 seeds per m^2) had a significantly higher number of seeds per m^2 than OSR grown after a one-year break following the preceding crop combinations OSR-barley (69,460 seeds per m^2) and OSR-WW (63,640 seeds per m^2) (Sieling and Christen, 1997). Furthermore, Sieling and Christen (1997) described that significantly higher TSW of OSR grown after a one-year break partly mitigated the negative effect of the lower number of seeds per m^2. More detailed investigations on yield components of OSR in relation to crop rotations showed that the number of pods and the seed yield of higher category branches as well as the total number of pods per plant contributed to significant yield differences, while the number of seeds per pod and the TSW were unaffected (Sieling et al., 1997). Sieling et al. (1997) have shown that OSR which followed the preceding crop combination pea-WW yielded 694 g m^{-2} while yield declined to 371 g m^{-2} when OSR was following OSR-OSR. Furthermore, at maturity OSR grown after pea-WW accumulated a total biomass of 1,727 g m^{-2} and exceeded the biomass of OSR grown in the third consecutive year by 76 %.

Differences in yield formation patterns in relation to rotational intensity was also reported by Stobart and Bingham (2013). The authors investigated the impact of crop rotations on yield components of OSR in two years of their study and demonstrated variations between the cropping seasons. The first year showed a higher number of primary branches, pods per main stem and total number of pods when OSR was grown in monoculture as compared to OSR grown after WW-WW and OSR grown in an alternate OSR-WW rotation, while no differences were found for the total number of plants at maturity and for the TSW. However, by using the yield data and the determined yield components of the specific cropping season Stobart and Bingham (2013) calculated an average of 19 seeds per pod for OSR in the three-year rotation, 18 seeds per pod for OSR in the two-year rotation and 11 seeds per pod for continuous OSR. The total number of seeds per m^2 was 60,105 for OSR after WW-WW, 61,673 for the alternate OSR-WW rotation and 50,179 for continuous OSR. The second year was influenced by extreme weather conditions with a harsh winter followed by drought conditions in the next spring. As a consequence, plant density was lower and secondary and tertiary branching was apparent, but showed no differences for OSR

grown in different crop rotations. The yield advantage of OSR (1.71 t ha^{-1}) grown in the three-year rotation was ascribed to a higher number of seeds per m^2 (39,093) and a higher number of seeds per pod (15).

Inconsistent results were reported from a field site in Poland (Różyło and Pałys, 2011a). OSR that was grown in an OSR-WW-WW rotation was characterized by significantly larger plants at maturity and a higher seed yield, but showed a lower TSW and a lower number of branches than OSR that was grown continuously. No differences were observed for the number of pods per OSR plant between the crop rotation treatments and no information was given on the final plant density at maturity.

The study of Kutcher et al. (2013) described the population density of OSR plants in relation to crop rotation and found lower densities for OSR grown in an alternate OSR-wheat rotation and OSR grown in a four-year rotation with wheat-pea-wheat in comparison to OSR that was grown continuously, in a three-year rotation following wheat-pea and in a four-year rotation following wheat-flax-wheat. The higher density for continuous OSR was explained by a higher number of OSR volunteers.

1.5 Blackleg disease (*Leptosphaeria maculans*) of oilseed rape

Blackleg, caused by the ascomycete fungal pathogen *Leptosphaeria maculans*, is a threat to global OSR production (West et al., 2001). The disease has been reported to be a major constraint to Canadian, Australian and European OSR production causing more than $900 million economic losses per growing season worldwide (Fitt et al., 2008). The severity of the disease and the extent of yield losses of OSR vary greatly, depending on weather conditions, geographic region, cultivars grown and especially on fungal populations. Depending on disease severity yield losses can be substantial and increase by 1.8 g per plant for each unit increase of the disease severity score which corresponds to 17.2 % single plant yield loss and 13 % pod loss (Hwang et al., 2016). Severe epidemics caused heavy yield losses during the second half of the 20th century (Gugel and Petrie, 1992). As a consequence, major effort is being made to prevent the spread of the disease into countries or regions where *Leptosphaeria maculans* has not been identified, such as China (Fitt et al., 2008; Fernando et al., 2016).

1.5.1 Epidemiology of *Leptosphaeria maculans*

Leptosphaeria maculans is a residue-borne pathogen harbored on infected stems of OSR (Hall, 1992). The fungus has the ability to survive on OSR residues in the soil (Bokor et al., 1975) and infected residues persist as a source of inoculum until their full decomposition (Kutcher et al., 2013) (Fig. 6).
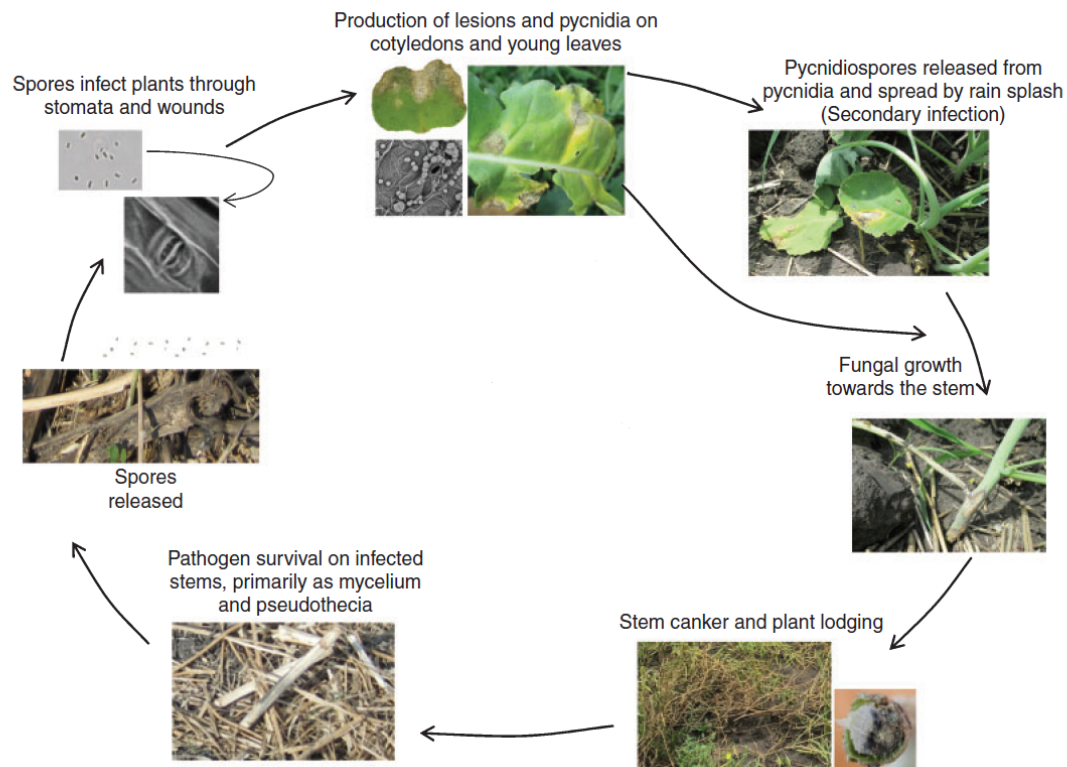
Figure 6: Life cycle of the pathogen *Leptosphaeria maculans* (adopted and modified from Zhang and Fernando, 2018)

The rate of residue breakdown depends on environmental conditions and residues can be completely decomposed within two years under the wet and mild climate in the UK (West et al., 1999) while the decomposition varies from one year in South-Eastern Australia to four years in South-Western Australia (Barbetti and Khangura, 1999; Marcroft et al., 2004). In Canada, *Leptosphaeria maculans* may persist on OSR residues for up to seven years after the crop is harvested and is able to produce viable ascospores over this period (Petrie, 1995). The epidemiology of blackleg differs between continents and regions caused by differences in climate, growing season, cultivars and especially fungal populations (West et al., 2001; Fitt et al., 2006). Wind-borne ascospores released from pseudothecia in crop residues are reported to be the primary source of inoculum (Salisbury et al., 1995; West et al., 2001). The period of ascospore release varies from region to region but usually coincides with the presence of young plants and is associated with environmental conditions, especially rainfall (Guo and Fernando, 2005; Savage et al., 2013). Ascospores are released from April to the end of August in Australia, from May to August in Western Canada, from May to August and September to November in Eastern Canada, from September to April in Western Europe and from September to November and in April in Eastern Europe (West et al., 2001).

Spores are dispersed by wind and usually spread less than 1 km from source, but their aerodynamic properties suggest that they may travel considerable distances (West and Fitt, 2005). Wind-borne

ascospores adhere to the leaf surface of young OSR plants, germinate and infect plants by fungal hyphae via stomatal pores or wounds, colonize the intercellular spaces between the mesophyll as a biotroph, but behind the hyphal front, the fungus becomes necrotrophic and causes initial leaf lesions (Hammond et al., 1985; Hammond and Lewis, 1987). Leaf lesions or phoma leaf spots first appear as pale green spots, which enlarge to $1-2$ cm in diameter, often turning pale brown containing tiny dark marks, so called "pycnidia", that produces pycnidiospores in the asexual phase of the fungus (Hammond et al., 1985; West et al., 2001). Pycnidiospores disperse by rain splash and cause secondary infections (Salisbury et al., 1995; Howlett et al., 2001). Rain simulation experiments showed that most pycnidiospores could be detected in the first 10 cm from the source but dispersed up to 40 cm (Travadon et al., 2007). Further studies reported that spore dispersal can be as far as 105 cm from inoculated rows (Barbetti, 1976) and 216 cm from plants grown from infected seeds (Hall et al., 1996). Pycnidiospores can pose a main inoculum source, spread and exacerbate the severity of the disease (Ghanbarnia et al., 2011).

Following initial infections of the leaves of young plants, the fungus spreads down the petioles towards the stem base. The fungus invades and kills cells of the stem cortex (Hammond et al., 1985), resulting in the blackened stem canker symptoms that may completely girdle the base of the stem, hence the name "blackleg" (Howlett, 2004). Blackleg lesions at the stem (crown canker) often have a distinct dark brown or purple margin. Further lesions on upper parts of the stem originate from leaf spots on leaves produced later in the season (Hammond et al., 1985) and are referred to as "phoma stem lesions" to describe symptoms on the stem > 5 cm above the crown (West et al., 2001). Girdling of both crown cankers and stem lesions weakens stems, causes lodging and premature ripening due to disrupted water transport (Davies, 1986; Salisbury et al., 1995; Zhou et al., 1999). As an extension of the stem canker phase of the *Leptosphaeria maculans* life cycle the pathogen is able to infect the roots and causes root rot (Sprague et al., 2009, 2010). Infections of pods are less common but can cause premature ripening and splitting (Petrie and Vanterpool, 1974), but more importantly can infect the seed and pose a major risk to spread the disease to other areas (Fernando et al., 2016; Van de Wouw et al., 2016).

After harvest, the pathogen colonizes the senescent stem tissue and develops pseudothecia in residues (West et al., 2001). Mature pseudothecia are able to release ascospores and infect subsequent OSR crops.

1.5.2 Impacts of break crops and crop rotations on blackleg disease of oilseed rape

Potential impacts of high-intensity OSR cropping on the blackleg disease risk became obvious across France, Australia and Canada where resistant cultivars failed or showed heavy yield depressions due to a rapid erosion of blackleg resistance in commercial crops. Rlm1 harboring cultivars lost resistance within five years after their commercial release in France (Rouxel et al.,

2003). In Australia, 'sylvestris' resistance was rendered ineffective within three years of commercial release of the cultivar (Sprague et al., 2006a, b). Shifts in the virulence of *Leptosphaeria maculans* populations in Canada became evident when resistant and moderate resistant cultivars showed heavy disease symptoms and severe yield depressions (Hwang et al., 2016; Zhang and Fernando, 2018). All studies in common pointed out that growing OSR in short rotations supported the resistance breakdown.

Resistance erosion of OSR cultivars due to shortened crop rotations was also indicated in field experiments of Kutcher et al. (2013) and Harker et al. (2015), who investigated the impact of different crop rotations on blackleg disease of OSR across the Canadian Prairies. Although both studies used resistant rated cultivars for their studies, blackleg incidence and severity increased as the crop diversity in the rotation decreased and most severe disease symptoms were commonly reported for OSR that was grown in monoculture. Harker et al. (2015) assumed that higher disease severity ratings of resistant cultivars reflected a resistance breakdown or at least a gradual erosion of resistance with time. This presumption supports the findings of Rouxel et al. (2003), Sprague et al. (2006a) and Zhang and Fernando (2018) who linked major gene resistance breakdown to high OSR cropping frequencies in their specific research areas. In addition, previous studies conducted across the Prairies confirmed the negative effect of shortened crop rotations on blackleg disease of OSR (Guo et al., 2005, 2008) and Johnston et al. (2005) stated that OSR that was grown on its own stubble had higher blackleg disease ratings as compared to OSR that was produced on the stubble of other crop species.

The Canadian observations are in good accordance to European results on blackleg disease of OSR (Kübler, 1985; Sieling et al., 1997; Cwalina-Ambroziak et al., 2016). Using regression analysis Kübler (1985) observed increased blackleg incidence with an increased frequency of OSR in crop rotations (R = 0.8897). On average over the harvest year blackleg incidence was lowest when OSR was grown in a four-year rotation (35 %), increased to 40 % when OSR was grown in a three-year rotation and showed 47 % infested plants when OSR was grown in an alternating rotation with WW. Similar relations were observed by Sieling et al. (1997) who described lowest blackleg disease ratings (0 – 9 scale) when OSR was following the preceding crop combinations WW-WW (1.3) and pea-WW (1.5). Blackleg ratings tend to be higher for the preceding crop combinations OSR-WW (1.9), WW-OSR (2.1), pea-OSR (1.7), and showed significantly higher disease ratings for the preceding crop combination OSR-OSR (3.8). Recent investigations in Poland have shown that it is not possible to eliminate the negative effects of an unfavorable crop rotation on blackleg disease (Cwalina-Ambroziak et al., 2016). Although the observed blackleg incidence was low in this experiment it was shown that twice the plants were infested with blackleg when OSR was grown in monoculture as compared to OSR that was grown in a four-year crop rotation. Furthermore,

the results indicated that high input rates of fungicides could not eliminate the negative effects of an OSR monoculture and 6.7 % of the OSR plants grown in monoculture showed blackleg disease symptoms, while OSR which was grown in a four-year rotation and received a lower fungicide dosage showed only 3.9 % infected plants.

According to Kutcher et al. (2013) the increase of blackleg incidence and severity with an increased OSR cropping frequency is a consequence of the pathogen biology. The benefit of crop rotation in the control of blackleg disease depends on the length of time the infected residues require to degrade. Kutcher et al. (2013) emphasized that OSR monocultures or short OSR rotations prevent full stubble decomposition, therefore, enable the pathogen reproduction, the accumulation of infested stubble in fields and consequently increase the inoculum, the pathogen population and as a result contribute to a greater risk for future crop infections. Furthermore, Rouxel et al. (2003) and Sprague et al. (2006b) indicated that larger pathogen populations resulted in increased selection pressure on the pathogen to overcome resistance of OSR cultivars. To avoid resistance breakdown in short rotations, at least, it is suggested to rotate OSR cultivars with different complements of blackleg resistance genes (Marcroft et al., 2012). Using pot experiments Marcroft et al. (2012) demonstrated that OSR cultivars which were exposed to stubble from a cultivar with a different complement of resistance genes showed a reduced plant mortality than OSR cultivars that were exposed to stubble of cultivars with the same complements of blackleg resistance genes. Field studies across three sites using three different cultivars were consistent to the pot experiments and fewer plants died when OSR was sown into stubble of cultivars with different complements of resistance genes. Since 2013, resistance gene information has been provided for farmers in Australia. This information is updated and released biannually in spring and autumn to growers in the GRDC (Grains Research and Development Coorporation) Blackleg Management Guide (Susan Sprague, personal communication) and provides information for farmers to choose cultivars with different resistance groups for their rotations (GRDC, 2019). Recently, Western Canada Canola and Rapeseed Recommending Committee adopted this strategy, so that seed companies could use a resistance group on their label (Zhang and Fernando, 2018).

In contrast to the previous findings on the impact of crop rotation on blackleg disease, Marcroft et al. (2004) suggested that crop isolation instead of extended rotation lengths reduced blackleg severity on OSR. Here, OSR sown in fields which were not grown with OSR for at least three years had similar blackleg infection levels as OSR that was grown in an OSR-wheat-OSR rotation, while the distance of OSR fields of the previous season to OSR fields of the following season had a substantial impact on disease infections. OSR crops sown adjacent to fields with OSR stubble of the previous growing season showed severe blackleg disease symptoms. Blackleg severity decreased markedly in the first 100 m of field distance and declined further for a distance of up to 500 m,

while plants grown in distances of $500-1,000$ m showed similar disease levels. Model-based assessments across the Picardie region in France are consistent to the field studies in Australia (Hossard et al., 2018). The simulations highlighted crop isolation as the second-best control option after mouldboard ploughing and showed a minor impact of extended crop rotations. Yield loss decreased by 1.5 % changing the field distance from 0 m to 1,000 m and showed the lowest pathogen population size in the isolated field sites. However, Hossard et al. (2018) emphasized the difficulty of the implementation of such isolation practice since it requires more year-to-year planning, coordination between farmers' management, cropping plans and leads to problems to achieve the annual target field acreage.

1.6 Aims and scope

The introduction demonstrates that yield of OSR declines when the crop is grown in short rotations or in monoculture as compared with more diverse rotations. Moreover, the mechanisms of yield decline are well understood and are primarily attributed to an increased disease incidence, weed infestations and pests. However, it is not known to what extent the seed yield of OSR declines with each year the crop is succeeding itself. To investigate this issue a crop rotation field trial based on the crop rotation WW-WW-WW-OSR-OSR-OSR and a long-term OSR monoculture was established in 2003 at the experimental farm Etzdorf (Saxony-Anhalt, 11° 45.443'E, 51° 26.095'N) of the Martin Luther University Halle-Wittenberg. The experimental design enabled the annual investigation of four different preceding crop combinations before the OSR crop: WW-WW (first OSR crop), WW-OSR (second OSR crop), OSR-OSR (third OSR crop) and the OSR monoculture. The objective of this study was to quantify the impact of an increased OSR cropping intensity in terms of yield, yield components and blackleg disease on a field site in the Hercynian dry region of Central Germany. The study aims to examine the following research questions:

1. To what extent does OSR seed yield decline with each year of consecutive cropping and is there still a yield difference between OSR that is grown in the third successive year and a long-term OSR monoculture?

2. Is it possible to avoid yield depressions of successively grown OSR by the application of a higher N fertilization rate?

3. Is it possible to explain the yield decline with certain yield components and what yield component shows significant changes?

4. Will the incidence and severity of blackleg disease increase with each year the crop is following itself despite the protection with fungicides?

5. How does OSR benefit from break crops and crop rotations on a global scale?

The first part of the study (Chapter 2, Hegewald et al., 2016) aims to find answers to research questions number 1 and 2. Therefore, the experimental data of the years $2005 - 2014$ of the crop rotation experiment was evaluated in terms of seed yield, oil content, oil yield and N use efficiency. A further objective was the investigation of the impact of a recommended N fertilization rate and a reduced N fertilization rate on OSR in high-intensity rotations as the crop shows a low N use efficiency which increases the risk for N losses, especially when OSR seed yields were low due to unfavorable cropping conditions.

The second part of the study (Chapter 3, Hegewald et al., 2017) focuses on the effects of an increased cropping intensity on yield formation parameters as the information on this topic is extremely scarce. The impact on blackleg disease, which is one of the most important OSR diseases in Germany and on a global scale was also investigated. Furthermore, this part also deals with the impact of a recommended fertilization rate and a reduced fertilization rate on OSR in high-intensity crop rotations. Therefore, chapter 3 aims to investigate research questions number 1 to 4.

The third part of the study (Chapter 4, Hegewald et al., 2018) had the objective to examine research question 5 and to provide a detailed overview about the impact of crop rotations and break crops on OSR seed yields by evaluating and reviewing global crop rotation experiments across the major growing regions. Further objectives of this part of the study were to emphasize the factors of yield decline in short rotation systems and to highlight the importance of crop rotations for a sustainable OSR production in future.

2. Impacts of high intensity crop rotation and N management on oilseed rape productivity in Germany

Hannes Hegewald, Barbara Koblenz,
Monika Wensch-Dorendorf and Olaf Christen

3. Yield, yield formation, and blackleg disease of oilseed rape cultivated in high-intensity crop rotations

Hannes Hegewald, Barbara Koblenz,
Monika Wensch-Dorendorf and Olaf Christen

4. Impacts of break crops and crop rotations on oilseed rape productivity: A review

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5. General discussion

In the following sections the results of the three papers are discussed with regard to the defined research questions.

5.1 Yield of oilseed rape as affected by break crops and crop rotations

With regard to research question 1 the studies demonstrated that OSR is suffering substantial yield depressions when the crop was grown successively (Hegewald et al., 2016, 2017). From 2005 – 2016, the highest yield (4.18 t ha^{-1}) at the experimental farm in Etzdorf was observed when OSR was grown after a three-year break of WW-WW-WW while the yield decreased by 5 % when OSR was grown in the second consecutive year following the crop combination WW-OSR, by 9 % when OSR was grown in the third consecutive year following the preceding crop combination OSR-OSR and was reduced by 11 % when OSR was grown in monoculture. The yield of OSR grown in monoculture was not significantly different from OSR following the preceding crop combination OSR-OSR. Due to the experimental design, these results demonstrate that a three-year consecutive cultivation of OSR leads to the same yield level as a long-term OSR monoculture. Although the design of the experiment differs from conventional crop rotation experiments focusing on the impact of consecutive cropping, the results are in good accordance to rotational studies as demonstrated by the literature review (Hegewald et al., 2018). Over a wide range of crop rotation experiments across different growing areas, it was shown that OSR is susceptible to short rotations and shows yield benefits when the crop is grown in longer crop intervals, such as two-year or three-year breaks as well as when it is grown after previous legume crops (research question 5).

From 2013 – 2016 recommended N fertilization (180 kg N ha^{-1}) led to yield benefits when OSR was grown after the three-year break (Table A1), while no impact on yield was found for OSR grown after WW-OSR, OSR-OSR or in an OSR monoculture receiving a recommended as well as a reduced N rate (120 kg N ha^{-1}) (Hegewald et al., 2016, 2017) and this in turn may increase the N surplus. Considering research question 2 of this study these results indicate that it is not possible to avoid yield depressions of successively grown OSR by higher N rates. Previously, Sieling and Christen (1997) reported that higher N rates could not compensate the negative effects of an unfavorable cropping history on the seed yield of OSR and therefore the results of this study support these previous findings. Besides economic consequences for farmers, due to the low yield response to additional nitrogen, there are further implications: Unused nitrogen in arable soils poses a potential risk for gaseous nitrogen emissions, runoff, nitrate leaching and therefore adverse environmental impacts (Cameron et al., 2013). In this context, especially in Europe OSR is under

growing pressure since the European policy has strict criteria in terms of greenhouse gas emission savings of biofuels (RED, 2009) to protect waters against pollution caused by nitrates from agricultural soils (ND, 1991) and to achieve good ecological and chemical status of all waters (WFD, 2000). In general, OSR is described as a crop with poor N efficiency having a high nitrogen demand in early growth stages and a low nitrogen removal with the seeds (Rathke et al., 2006). Great effort is in progress to improve N use efficiency in terms of genetic gains (Bouchet et al., 2016; Stahl et al., 2017, 2019) and agronomic measures (Sieling et al., 2017), to understand the dynamics of nitrous oxide emissions during the cultivation (Walter et al., 2014; Ruser et al., 2017) and after harvest of OSR (Vinzent et al., 2017; Kesenheimer et al., 2018) and to minimize nitrogen leaching in the form of nitrate into groundwater bodies by implementing improved N management strategies (Sieling and Kage, 2010; Engström et al., 2011). Walter et al. (2014) and Ruser et al. (2017) emphasized that critical N surplus values caused an exponential increase in yield-scaled N_2O emissions. Furthermore, Sieling and Kage (2010) described the high N losses via leaching due to high N surpluses as a consequence of the low N use efficiency and N leaching is positively correlated to N surplus values (De Notaris et al., 2018). In this context, it is crucial to cultivate OSR in favorable crop rotations to enhance the crop's N utilization and to meet the requirements of political frameworks of the European Union in relation to greenhouse gas savings as well as water protection.

This need will be further propelled in Germany due to the infringement proceedings initiated by the European Union against Germany for failure to fulfill its obligations under the Nitrates Directive (ND, 1991), which was brought before the European Court of Justice in 2016, where Germany was found guilty on breaching the EU's Nitrates Directive on June 21, 2018 (EUR-Lex, 2020). The infringement proceedings resulted in the novelty of the German fertilizer ordinance (2017) that entered into force on May 26, 2017 and allowed maximum N surplus values of 50 kg N ha^{-1} yr^{-1} (mean value over three sliding years) from 2020 onwards based on a farm-gate balance. However, in 2019 the European Union called Germany in a further warning to increase its effort to reduce nitrate levels in groundwater (Euractiv, 2019). This resulted in a further tightening of the rules concerning fertilization of the German fertilizer ordinance on May 1, 2020. This amendment removed the nitrogen balance as a control measure and now N fertilization is controlled by the determination of the N requirement of specific crops. German farmers are demanded to determine the nitrogen requirement of a specific crop based on the average yield of the last five harvest years to avoid overestimated N fertilization. Furthermore, farmers need to adjust the N fertilization depending on mineralized nitrogen content in the soil, nitrogen supply of the soil stock, nitrogen supply of organic fertilization of previous years and nitrogen supply of pre-crops or catch crops. However, even if the N balance is no longer the tool of control it is important

to avoid high N surpluses after OSR of > 90 kg N ha^{-1} yr^{-1} as described by Henke et al. (2007) and Sieling and Kage (2010) to fulfill the requirements of the Nitrates Directive (ND, 1991). Therefore, from a scientific perspective it is still important to avoid a high N balance, but typical crop rotations including OSR once every three years (OSR-WW-WW, OSR-WW-barley) or at even higher frequencies might not meet this objective. Indeed, since the German fertilizer ordinance entered into force in 2017 the OSR growing area in Germany declined from 1.3 million ha (FAOStat, 2020) to 0.87 million ha in 2020 (UFOP, 2019a). To what extent this decline is caused by the German fertilizer ordinance (2017) is questionable and the driving forces for this development are rather difficult sowing conditions over the last two years due to hot and dry summers as well as the negative consequences in terms of management of OSR pests related to the withdrawal of insecticides. Nonetheless, typical farming practices such as the cultivation of WW as a subsequent crop after OSR may need to be changed due to the low N utilization of cereals before winter that rarely exceeds 30 kg N ha^{-1} under the growing conditions of Northern or Central Europe (Sieling, 2019). Here, catch crops could function as a N transfer crop after OSR that fix high amounts of N before winter and transfer this N to the subsequent crop allowing a reduction of its fertilizer demand and the offtake of this N by harvest products (Sieling, 2019). The inclusion of catch crops in OSR crop rotations in turn would contribute to an increased diversification of crop rotations and could prevent N loss if the N release of the catch crop residues and the N demand of the subsequent crop overlap.

However, recent attention has been paid to agronomic inputs to compensate yield loss in continuous OSR (Cwalina-Ambroziak et al., 2016; Harker et al., 2018). More intensive agronomic inputs contributed to maintain seed yields on levels of rotated OSR. OSR grown in monoculture (6.31 t ha^{-1}) yielded equally to OSR grown in a four-year rotation (6.30 t ha^{-1}) with WW, pea and spring wheat in a high input system receiving higher rates of nitrogen, sulphur, phosphor and potassium as well as a different spectrum of pesticides to control weeds, pathogens and pests as compared to the low and medium input systems (Cwalina-Ambroziak et al., 2016). Intensified crop management associated with additional fertilizer, seeds, fungicides, tillage or chaff removal has proven to rescue yield loss in continuous OSR as compared to a standard practice (Harker et al., 2018). The yield of continuous OSR (3.3 t ha^{-1}) sown with higher seeding rates and treated with additional fertilizer was similar to the yield of OSR (3.4 t ha^{-1}) grown in a pea-wheat-OSR rotation. However, increased use of fertilizer, pesticides and other inputs may compensate the effects on yield decline to some extent, but it is simultaneously contrary to societal and political aims such as mitigation of greenhouse gas emissions and protection of water bodies, drinking water sources as well as preservation of biodiversity resources. Moreover, increasing agricultural input efficiency is a major issue to reduce negative environmental impacts of crop systems (Clark and Tilman, 2017).

In this context, the further results of Cwalina-Ambroziak et al. (2016) and Harker et al. (2018) are of particular interest. In the study of Cwalina-Ambroziak et al. (2016) OSR grown in the four-year rotation outyielded OSR grown in monoculture by 20 % receiving a low level of agricultural inputs and by 10 % receiving a medium level of agricultural inputs, achieving 5.02 t ha^{-1} and 5.65 t ha^{-1}, respectively.

Harker et al. (2018) showed that average yields of OSR preceded by a different crop were 11 % greater than the average of all additional input treatments in continuous OSR (9 treatments). These findings demonstrate that crop rotation is a prerequisite to achieve environmental goals, to reduce the environmental impact of OSR cropping systems and to produce high OSR seed yields in a sustainable way.

5.2 Oilseed rape yield components as affected by break crops and crop rotations

The differences among the yield components observed during the years 2015 – 2016 were less pronounced among the preceding crop combinations WW-WW, WW-OSR, OSR-OSR but showed a significant impact when OSR was grown in a long-term monoculture.

Over both years the plant density before winter exceeded the seeding rate (40 seeds m^{-2}), almost doubled in the 2014/2015 growing season and was 1.5 times higher in the 2015/2016 growing season. On average the highest population density was observed for OSR grown in monoculture (92 plants m^{-2}), while no differences were found for OSR following the preceding crop combinations WW-WW (74 plants m^{-2}), WW-OSR (63 plants m^{-2}) and OSR-OSR (74 plants m^{-2}). In both years the plant density decreased during the growing season. This might be the result of winterkill, premature dying due to intraspecific competition in a high plant density environment as well as blackleg disease. However, the final plant population showed a less clear result with a significant year by preceding crop interaction. In the 2015/2016 growing season hot temperatures restricted seed emergence and caused a poor seedling establishment, which might have lowered the final plant density especially when OSR was grown in consecutive years.

Due to the high frequency of OSR in this experiment and high dormancy of OSR it can be assumed, that seeds survived in the soil and therefore seed banks accumulated with a high potential for volunteer abundance. Previous studies have shown that OSR seeds can persist in soils for up to ten years or even longer (Lutman et al., 2003; Gruber et al., 2018). There is clear evidence that the potential to develop secondary dormancy is affected by the OSR genotype (Thöle and Dietz-Pfeilstetter, 2012; Schatzki et al., 2013; Gruber et al., 2018). The cultivars "Mohican" (2006 – 2009) and "Visby" (2010 – 2016) are described as cultivars with high secondary dormancy and low secondary dormancy, respectively (Thöle and Dietz-Pfeilstetter, 2012). Since dormancy level determines long-term seed survival and volunteer emergence in later years (Gruber et al., 2018), it

can be assumed that "Mohican" volunteers still contributed to plant populations in both study years. Apart from genotype, cropping frequency was described as another predominant factor for the long-term abundance of volunteers (Gruber et al., 2012), supporting the assumption of a high potential for volunteers in this study.

Volunteers can cause problems in the OSR crop itself by an increased competition for resources. Moreover, they reduce frost tolerance of a sown OSR crop due to increased crop density (Pekrun et al., 1998), and they can spoil the quality of special OSR types such as HOLL (High Oleic and Low Linolenic fatty acid oil profile) by seed admixture (Baux et al., 2011). Furthermore, because of genetic segregation in subsequent generations of hybrid cultivars (F2, F3) the vigor of volunteers is non-uniform. Growing OSR crops from F2 hybrid generations is associated with yield reductions, higher mortality and an impaired seed quality (Clayton et al., 2009). As a consequence, plant populations established in this experiment might be hampered by the presence of less vigorous plants. However, it can only be speculated to what extent volunteers contributed to final plant populations in this field trial, but plant density data of this study gave strong evidence that volunteers made up an integral part of plant populations at harvest, especially in the 2014/2015 growing season with final plant densities at harvest that were still exceeding the sowing rate.

High volunteer abundance was reported from an experiment in the UK, where volunteer populations were similar to established plant populations in single years and tended to increase with an increased cropping frequency of OSR (Stobart and Bingham, 2013). Accordingly, as described in our study, the authors assumed that a substantial proportion of the final plant population could be made up of volunteers, with consequences for crop competition, varietal dilution as well as for pests and diseases, since volunteers emerge from untreated seeds. In contrast to this study, final plant populations were lowest in continuous OSR and Stobart and Bingham (2013) presumed that slugs and seedling diseases such as *Rhizoctonia sp.* might be more severe in continuous OSR. Previously, Sieling et al. (1997) found lower plant densities when OSR was grown after pea-WW or WW-WW, while the number of OSR plants increased when OSR was grown at least once during the two previous years. Similar results were reported across Canadian field sites where continuous OSR had the highest plant population during 17 study years and significantly lower plant densities were reported for OSR grown in an alternate OSR-wheat and in an OSR-wheat-pea-wheat rotation (Kutcher et al., 2013). Both, Sieling et al. (1997) and Kutcher et al. (2013) assumed that volunteers contributed to higher plant densities and therefore these findings are in good accordance to this study.

Plant density is a decisive factor of the architecture of individual plants (Angadi et al., 2003; Leach et al., 1999). Table A5 shows the negative correlation between plant density and the development of primary branches ($R = -0.75$) and secondary branches ($R = -0.61$) of individual plants in this

experiment. Especially in the year 2015 when final plant populations exceeded the targeted plant density, OSR developed significantly less branches in comparison to the 2016 growing season (Table A3). Furthermore, low plant populations in 2016 significantly increased the development of secondary branches of OSR for all preceding crop combinations. Over both years primary branching was lowest when OSR was grown in monoculture (5.0). Higher branching was previously observed when OSR followed pea-WW as compared to OSR-OSR (Sieling et al., 1997) and higher yield of single plants was primarily attributed to higher category branches. Aside from pre-crop effects higher branching of OSR following pea-WW might be the result of a lower final plant population (66) as compared to OSR (80) following OSR-OSR. No significant differences were found by Sieling et al. (1997) for OSR that followed the preceding crop combinations WW-WW, OSR-WW, WW-OSR, pea-OSR. Stobart and Bingham (2013) could not find significant differences for the total number of branches m^{-2} when OSR was grown at different rotational intensities in the UK, but it was demonstrated that a higher proportion of secondary and tertiary branches was developed in a season where harsh winter and dry spring conditions led to low final plant populations and this supports the findings of the second season (2016) of this study. Results from a Polish field site reported somewhat different results (Różyło and Pałys, 2011a). Branching was significantly higher (7.2 branches per plant) when OSR was grown in the third consecutive year, decreased to 6.0 branches per plant when OSR followed OSR-WW and to 5.8 branches when OSR followed WW-WW. Since no information was given on the final plant populations in this study, it is hard to interpret these results in an appropriate way. Considering the studies of Sieling et al. (1997) and Stobart and Bingham (2013) as well as the findings of this study, it can be assumed that branching is primarily determined by plant density and to a lesser extent by crop rotation. However, plant densities are influenced by shorter crop rotation through an increased potential of volunteer abundance. Further investigations should clarify to what extent volunteers contribute to plant densities in short OSR rotations.

As previously observed by Angadi et al. (2003), Leach et al. (1999) and Zhang et al. (2012), increased branching led to a higher pod number of individual plants (R = 0.97, Table A5) in our study and, therefore, compensated for differences in final plant populations. Furthermore, our results have shown that OSR grown in monoculture developed a significantly lower number of pods per main stem (Table A4) and as a result of reduced branching in comparison to the other crop combinations the OSR monoculture had the lowest number of pods developed on primary branches. Consequently, over both years there was a significantly lower number of pods m^{-2} when OSR was grown in monoculture, while no differences were obvious for the other preceding crop combinations. Similarly, Sieling et al. (1997) observed the lowest number of main stem pods and primary branch pods when OSR was following an OSR-OSR preceding crop combination in

comparison to OSR that was following the crop combinations WW-WW, OSR-WW, WW-OSR, pea-OSR and the total number of pods per plant was significantly different to OSR following pea-WW. No differences for the total number of pods per plant were found by Różyło and Pałys (2011a) for OSR following WW-WW (44.7 pods per plant) and OSR following OSR-OSR (44.5), while OSR grown after WW-OSR had the lowest number of pods per plant (36.5). The results of Stobart and Bingham (2013) revealed evidence of differences in the crop structure of OSR in relation to the cropping intensity. The 2010 growing season showed a trend for greater numbers of pods in shorter rotations, which is different to the findings of this study, while no impact of rotational intensity on the total number of pods was observed in 2011.

Research question 3 of this study could not be fully clarified. The results reveal that certain yield components were influenced by the different preceding crop combinations such as plant density, the development of primary branches and the number of pods per area. However, although the lowest number of 7,587 pods m^{-2} was found for the OSR monoculture there was no significant yield difference in comparison to the other preceding crop combinations in the years 2015 – 2016 of this study. Furthermore, plant samples of an area of 0.25 m^2 and 0.5 m^2 were assessed for yield components in 2015 and 2016, respectively. Due to the heterogeneity in OSR crop stands greater sampling areas as well as a longer experimental period (at least three years) could provide more consistent results, but as described before the determination of yield components of OSR is a labor intensive and time-consuming work. Overall, the formation of OSR yield components is subject to a high level of plasticity and depends on various factors such as seasonal conditions, seeding rates, volunteers and cultivars which is why more research would be necessary to determine to what extent crop rotations influence the formation of OSR yield components as well as the underlying factors.

5.3 Blackleg disease of oilseed rape as affected by break crops and crop rotations
Both blackleg incidence and severity increased when OSR was grown in consecutive years (WW-WW: 73 %, 1.47; WW-OSR: 79 %, 1.62; OSR-OSR: 78 %, 1.82) and were most severe when OSR was grown in monoculture with 84 % of the plants showing disease symptoms with a mean severity score of 2.03 (research question 4). These findings are consistent with numerous studies conducted across the Canadian Prairies (Guo et al., 2005, 2008; Kutcher et al., 2013; Harker et al., 2015a, b) and various European countries (Kübler, 1985; Sieling et al., 1997; Stobart and Bingham, 2013; Cwalina-Ambroziak et al., 2016). These results are of particular interest since the cultivar "Visby", which was grown in the two years of the disease assessment, is described as a moderate resistant cultivar with a rating of 4 on a scale of 1 (low susceptibility) to 9 (high susceptibility) in the German variety list (Bundessortenamt, 2013) and received a robust fungicide treatment over both years. It

is therefore reasonable to assume that the disease tolerance of "Visby" degraded when OSR was grown in consecutive years and therefore caused more severe disease symptoms. The studies of Harker et al. (2015a) and Kutcher et al. (2013) confirm this assumption since both observed an increased incidence as well as more severe blackleg disease symptoms when blackleg resistant rated cultivars were grown in shorter rotations across several field sites in Western Canada. Harker et al. (2015a) presumed that these observations reflected a breakdown in resistance or at least a gradual erosion of resistance over time when OSR was grown in high-intensity crop rotations. Under monoculture or short rotations full decomposition of pathogen harboring crop residues is prevented, allowing the pathogen to complete and repeat its life cycle, resulting in larger pathogen populations (Kutcher et al., 2013). Depending on environmental conditions in the specific growing area decomposition of OSR crop residues requires between two to up to seven years (Petrie, 1995; Barbetti and Khangura, 1999; West et al., 1999). As a consequence of common production practices, infected OSR residues can accumulate in commercial fields which leads to larger pathogen populations that will result in the multiplication of a greater number of virulent isolates (Kutcher et al., 2010) which are able to overcome resistance.

Due to the high evolutionary potential of the pathogen, *Leptosphaeria maculans* adapts rapidly to selection pressure from sowing cultivars with major resistance by building virulent isolates (Van de Wouw et al., 2014). Resistance breakdown in commercial field sites was observed across the major production countries and Rlm1 became ineffective after a few years of widespread use in France (Rouxel et al., 2003), "sylvestris" became ineffective three years after commercial release in Australia (Sprague et al., 2006a, b) causing yield losses of 90 % and Rlm3 became ineffective in Western Canada resulting in increased disease severity (Zhang et al., 2016). All these studies reported that resistant cultivars harboring specific major resistance genes were grown on a large scale in specific regions and furthermore to a large extent in short crop rotation systems. Such breakdowns in resistance can be described as "boom and bust" cycles, where "boom" describes the phase where a cultivar with a single major resistance gene is grown extensively in a specific region and "bust" describes the phase when the pathogen adapts to the presence of this resistance gene and evolves to overcome or break down the resistance (McDonald and Linde, 2002). Investigations on the race spectra of *Leptosphaeria maculans* across areas in Northern Germany revealed that the major genes Rlm1, Rlm2, Rlm3 and Rlm4 were ineffective against 85 % out of 644 isolates, whereas Rlm9 harboring genotypes were ineffective at all and only Rlm7 resistance was still effective in these areas (Winter and Koopmann, 2016).

Considering time demand and high costs for breeding companies to develop new OSR cultivars with novel sources of resistance (Fitt et al., 2011), these results are a concerning signal for breeders and growers, and it is essential to preserve and prolong resistance. From knowledge on disease

control by crop rotation and host-pathogen interactions there is a need for the implementation of sophisticated management strategies to improve blackleg disease management by combining major with quantitative resistance (Huang et al., 2018), variety selection or rotation of varieties with different complements of resistance genes (Marcroft et al., 2012), pathogen monitoring in fields (Van de Wouw et al., 2014; Winter and Koopmann, 2016) and best agronomic practices (Kutcher et al., 2010, 2013; Harker et al., 2015a). In Australia, Marcroft et al. (2012) demonstrated that rotation of cultivars with different resistance genes minimized disease pressure by manipulating fungal populations. The study showed that plant mortality was lower for plants of a cultivar that were exposed to stubble from a cultivar with a different complement of resistance genes compared to the stubble of a cultivar with the same resistance gene. Recently, by manipulating stubble loads to simulate spatio-temporal effects, Bousset et al. (2018) have shown that the variation of resistance genes is a useful strategy to control blackleg in space and time. The principle of resistance gene rotation strategy takes advantage of the behavior of the pathogen population that selects for virulent individuals and therefore should minimize the build-up of isolates virulent to any particular resistance gene (Marcroft et al., 2012). Especially in short rotations this might be an appropriate strategy to control blackleg so that the Western Canada Canola and Rapeseed Recommending Committee adopted this strategy. Now seed companies use labels with information on specific resistance genes on their products (Zhang and Fernando, 2018). Moreover, intensive field monitoring for virulent populations averted resistance breakdown of the gene complement of Hyola related cultivars on the lower Eyre Peninsula in Australia in 2012, since farmers avoided growing these cultivars after the release of a warning of the GRDC and Lower Eyre Agricultural Development Association (Van de Wouw et al., 2014). Moreover, the GRDC provides a Blackleg Management Guide giving information on resistance gene complements of specific cultivars biannually for Australian farmers to avoid rotations with cultivars harboring identical resistance gene complements (Susan Sprague, personal communication).

Considering our results that demonstrated an increased blackleg incidence and severity when OSR was grown in consecutive years, as well as the findings of Winter and Koopmann (2016) in Northern Germany on the effectivity of several resistance genes the adoption of such programs could help German as well as other European OSR growers to make decisions that preserve and prolong resistance of existing cultivars. However, the successful implementation of such programs requires the identification of resistance gene complements of cultivars grown in Europe, field monitoring on changes in the virulence of pathogen populations as well as an information exchange on a trans-regional level.

5.4 The limitations of oilseed rape crop rotation field experiments

The impact of short rotations is not limited to the boundaries of a field where the crop is grown in high intensity. When a specific crop is grown in short rotations in a specific cropping area the more land is planted to this crop annually (Harker et al., 2018) the higher is the proportion of land of a specific crop in this area. Such cropping practices are resulting in an overall more uniform crop mixture at the landscape scale and contribute to landscape simplification that exacerbates biodiversity losses which lead to reductions in ecosystem services on which agriculture depends (Landis, 2017). Moreover, it increases vulnerability of cropping systems to pests (Rusch et al., 2016; Landis, 2017) and diseases (Stukenbrock and McDonald, 2008). Although the impact of the landscape scale was not subject of the present study, it is a non-negligible factor in the examination of OSR cropping systems, since numerous OSR pathogens are dispersed by wind (Fitt et al., 2006; Derbyshire and Denton-Giles, 2016) or farm equipment (Gossen et al., 2015), a broad spectrum of pest insects damaging OSR have the capability to fly (Williams, 2010; Dosdall and Mason, 2010) and specific weed species communities develop within intense production areas (Fried et al., 2015). These factors indicate that the implications of short rotations of OSR in specific growing areas could be more severe under practical conditions than under experimental conditions. This presumption is also supported by the breakdown of resistance against blackleg disease in several major growing areas around the world as a result of high-intensity OSR cropping (Rouxel et al., 2003; Sprague et al., 2006a, b; Zhang et al., 2016).

Despite the knowledge of the relation between high-intensity crop rotations and the proportion of crops in specific growing areas investigations on the interaction between high-intensity rotations, high-intensity cropping areas, disease dispersal, pest spread and weed infestations have been investigated to a very limited extent. To my knowledge the only studies referred to this subject so far were performed by Marcoft et al. (2004) considering the impact of crop rotations and field distances on blackleg disease as well as by Hossard et al. (2018), who examined the impact of field isolation distance, tillage practice, cultivar type and crop rotation in controlling blackleg disease in a model-based assessment.

This scarcity is due to the difficulty of experiments on the landscape level since they require large temporal and spatial scales, and are subject to a number of uncertainties in relation to environmental impacts, suitable agricultural areas, feasibility as well as analysis. It would be of great interest and scientific value to understand the functioning and the relation between crop rotations, proportion of crops in specific areas and the spread of diseases, pests and weed communities on the landscape level. However, to what extent such findings would lead to changes in a practical manner is questionable. Considering the allocation of crops on the landscape level would require a coordinated rotation of crops in time and space with a trans-regional cropping management that

would instruct farmers of those regions what crop to plant where and when. The implementation of such an allocation of crops would require political frameworks as well as a cooperation between farmers and other stakeholders that are involved in the agribusiness. Moreover, such actions would restrict the entrepreneurial freedom of farmers and therefore the implementation of an agricultural landscape design associated with the allocation of crops in growing regions is difficult in practice.

6. Conclusions

Overall, the study demonstrated that the cultivation of OSR in short rotations, or rather in consecutive years, is associated with considerable disadvantages for OSR growers.

The long-term field experiment at the experimental site Etzdorf has shown that growing OSR in consecutive years results in yield losses. From an economic point of view, yield losses may be acceptable due to the high economic benefit over the short term, but the consecutive cultivation of OSR is not recommendable over the long term, since it is related with further problems in terms of N efficiency and health status of the crop, especially in times when farmers are under growing criticism because of their production practices and their environmental impacts, due to the intensive use of fertilizer and pesticides. The further strengthening of the German fertilizer ordinance to fulfill the requirements of the European Nitrate Directive 91/676/EEC will increase the pressure on farmers to improve the N efficiency and thus will increase the need for nutrient efficient crop rotation systems that enable each crop to utilize its full yield potential. Moreover, although OSR received a full coverage of plant protection in our field study, blackleg disease increased with each consecutive growing year and was most severe when OSR was grown in monoculture. In times when the development of plant protection products with novel active ingredients are rare, more of these products are withdrawn from the market and limitations in their application are growing, the implementation of longer and diverse crop rotations is essential to improve the health status and the resilience of OSR growing systems.

The analysis of global crop rotation experiments across Europe, North America, Asia and Australia confirmed the findings of this field study and demonstrated the negative impacts of high-intensity OSR crop rotations in relation to yield, diseases, pests and resistance breakdown. However, since farmers have to grow the most profitable crops to stay in business and to finance their private burden, especially in countries with low subsidies, it is hard to find a way to get out of this dilemma. For the development of diverse cultivation systems economic and political factors within which agriculture is practiced need to offer a framework that enables farmers to grow crops in diverse systems with adequate reward. The study clearly demonstrated that successful cultivation of OSR needs appropriate break intervals to maintain yields and productivity. If scientific knowledge is ignored there is an increased risk for crop failure due to resistance breakdown, ineffectiveness of herbicides and fungicides, severe disease and pest epidemics and higher inputs to sustain productivity.

7. Summary

Oilseed rape (OSR) is the most important oil crop in Europe. In Germany, the OSR growing area expanded since the 1990s and reached its maximum of 1.55 million ha in 2007, while the total arable land was stagnating (FAOStat, 2020). Since 2017 the OSR growing area in Germany declined due to difficult sowing conditions over the last years and the negative consequences in terms of management of OSR pests related to the withdrawal of insecticides. Today, the OSR cropping area in Germany amounts to 873,000 ha (UFOP, 2019). Over the intervening years OSR was grown at high frequency in crop rotations and at high concentration in specific growing areas. Globally the oilseed rape area is expected to remain on a stable level around 35 million ha (USDA, 2020a).

To investigate the impact of short OSR rotations a field trial was conducted in 2002 at the experimental farm Etzdorf of the Martin Luther University Halle-Wittenberg (Saxony-Anhalt, Germany). The field trial was based on the crop rotation OSR-OSR-OSR-winter wheat (WW)-WW-WW. Due to the experimental design each plot started at another initial position within the crop sequence, and from 2005 on, the effects of the preceding crop combinations WW-WW, WW-OSR, OSR-OSR as well as a long-term OSR monoculture were examined. In addition to the preceding crop combinations, N fertilization treatments of 120 kg N ha^{-1} and 180 kg N ha^{-1} were added to the experimental design in the growing season 2012/2013 as subplots. From 2005 to 2014 investigations were carried out to determine yield, oil content, oil yield and N efficiency, while in 2015 and 2016 the investigations concentrated on biomass development, yield components and blackleg disease (*Leptosphaeria maculans*).

From 2005 – 2016 the highest yield (4.18 t ha^{-1}) was observed when OSR was grown after a three-year break of WW-WW-WW. The yield decreased by 5 % when OSR was grown in the second consecutive year following the crop combination WW-OSR, by 9 % when OSR was grown in the third consecutive year following the preceding crop combination OSR-OSR and was reduced by 11 % when OSR was grown in monoculture. Significantly higher yields were observed for OSR succeeding WW-WW (5 %) receiving 180 kg N ha^{-1}, while the yield of OSR following the preceding crop combinations WW-OSR, OSR-OSR, OSR monoculture was unaffected receiving a higher N fertilization in comparison to 120 kg N^{-1}. No significant differences were obvious for the oil content and consequently oil yield was highest when OSR was grown after WW-WW (1.93 t ha^{-1}) and lowest for the OSR monoculture (1.80 t ha^{-1}) during the 2005 – 2016 period. The investigations on yield formation in 2015 – 2016 demonstrated a significantly decreased biomass development, a decreased formation of pods and a lower number of seeds per m^2 for OSR grown in monoculture and, therefore, support the results of the long-term yield studies. Furthermore, the consecutive

cultivation of OSR led to a higher blackleg incidence and severity. Averaged over both years blackleg severity increased from OSR grown after WW-WW (1.47) to OSR grown after WW-OSR (1.62) to OSR grown after OSR-OSR (1.82) and was highest when OSR was grown in monoculture (2.03).

In addition to the field investigation at the experimental farm Etzdorf, the present study analyzed global field experiments in relation to the impact of different pre-crops and cropping breaks on the yield of OSR. Based on more than 550 comparisons the yield benefit of OSR growing after a break crop with OSR after OSR as well as OSR growing after two-year and three-year breaks with continuous OSR was quantified. The mean yield increase for barley, wheat and legumes was 0.22 t ha^{-1}, 0.3 t ha^{-1} und 0.46 t ha^{-1}, respectively. The mean additional yield after a two-year break was 0.53 t ha^{-1} and a three-year break led to a yield benefit of 0.47 t ha^{-1}. In general, yield depressions in short rotation systems were caused by an increased susceptibility to diseases, heavy weed infestations and a higher abundance of pest species.

To conclude, the field trial at the experimental farm Etzdorf, as well as the analysis of global OSR crop rotation experiments, have shown the positive impact of pre-crops and cropping breaks on OSR and revealed the problems that arise from short crop rotations and monoculture.

8. Zusammenfassung

Winterraps (WRa) ist die wichtigste Ölpflanze in Europa. In Deutschland ist die Rapsanbaufläche seit den 1990er-Jahren gestiegen und erreichte ihr Maximum von 1,55 Millionen ha im Jahr 2007, während die gesamtdeutsche Ackerfläche stagnierte (FAOStat, 2020). Seit 2017 ist die Rapsanbaufläche in Deutschland aufgrund der schlechten Aussaatbedingungen der letzten Jahre sowie der erschwerten Bestandesführung durch den Wegfall von Insektiziden stark rückläufig und beträgt heute etwa 873.000 ha (UFOP, 2019). Zwischenzeitlich erreichte der Raps jedoch einen hohen Anteil in der Fruchtfolge sowie eine hohe Anbaukonzentration in der Kulturlandschaft. Auf globaler Ebene verbleibt die Rapsanbaufläche Schätzungen zu Folge auf einem stabilen Niveau von etwa 35 Millionen ha (USDA, 2020a).

Um die Auswirkungen von engen Rapsfruchtfolgen zu untersuchen, wurde im Jahr 2002 am Versuchsstandort Etzdorf der Martin-Luther-Universität Halle-Wittenberg (Sachsen-Anhalt, Deutschland) der Winterrapskonzentrationsversuch angelegt. Der Versuch basiert auf der Fruchtfolge WRa-WRa-WRa-Winterweizen (WW)-WW-WW. Aufgrund des experimentellen Designs konnten ab dem Jahr 2005 in jedem Untersuchungsjahr die Vorfruchteffekte der Vorfruchtkombinationen WW-WW, WW-WRa, WRa-WRa sowie der Einfluss einer langjährigen WRa-Monokultur untersucht werden. Im Jahr 2013 wurde der Versuch um einen zweiten Untersuchungsfaktor erweitert und die Düngestufen 120 kg N ha^{-1} und 180 kg N ha^{-1} integriert. In den Jahren 2005 – 2014 wurden Untersuchungen hinsichtlich des Ertrags, Ölgehaltes, Ölertrags und der N-Effizienz durchgeführt, während in den Versuchsjahren 2015 – 2016 intensive Untersuchungen zur Bestandesentwicklung, der Ertragsstruktur sowie zum Befall mit der Wurzelhals- und Stängelfäule (*Leptosphaeria maculans*) durchgeführt wurden.

Über den gesamten Versuchszeitraum (2005 – 2016) wurde der höchste Ertrag für Raps (4,18 t ha^{-1}) ermittelt, der nach einer dreijährigen Anbaupause nach WW-WW-WW angebaut wurde. Der Ertrag sank um 5 % für Raps, der im zweiten Jahr nacheinander angebaut wurde, um 9 % für Raps, der im dritten Jahr nacheinander angebaut wurde, und um 11 % für Raps, der in einer langjährigen Monokultur angebaut wurde. Für den Zeitraum 2013 – 2016 konnte für die höhere N-Düngung ein signifikant höherer Ertrag für Raps nach WW-WW festgestellt werden (4,44 t ha^{-1}, +5 %), während bei den weiteren Vorfruchtkombinationen eine höhere Düngung zu keinem Mehrertrag führte. Für den Ölgehalt konnten keine signifikanten Unterschiede festgestellt werden und somit war der Ölertrag am höchsten für Raps, der der Vorfruchtkombination WW-WW (1,93 t ha^{-1}) folgte, und am niedrigsten in der langjährigen Monokultur (1,80 t ha^{-1}). Die Ertragsstrukturuntersuchungen in den Jahren 2015 – 2016 zeigten eine signifikant verringerte

Biomasseausbildung, einen geringeren Schotenansatz und eine geringere Kornzahl je m^2 in der Winterrapsmonokultur und bestätigten somit die langjährigen Ertragsergebnisse. Weiterhin wurde mit der wiederholten Selbstfolge des Winterrapses eine steigende Krankheitsanfälligkeit sowie eine steigende Befallsschwere für die Wurzelhals- und Stängelfäule ermittelt. Im Mittel über beide Jahre betrug die Befallsschwere für die Vorfruchtkombination WW-WW 1,47, für WW-WRa 1,62, für WRa-WRa 1,82 und für die WRa-Monokultur 2,03.

Neben den Untersuchungen im Rahmen des Feldversuches in Etzdorf wurden in der vorliegenden Arbeit weltweite Rapsfruchtfolgestudien bezüglich der Ertragswirkung unterschiedlicher Vorfrüchte und Anbaupausen ausgewertet. Auf Basis von über 550 Einzelvergleichen wurden die Ertragseffekte für Raps, der nach einer Vorfrucht angebaut wurde, mit Raps, der nach Raps angebaut wurde, quantifiziert. Weiterhin wurden der Einfluss einer zwei- und einer dreijährigen Anbaupause im Vergleich zu Raps in Selbstfolge ermittelt. Für die betrachteten Vorfrüchte Gerste, Weizen und Leguminosen wurde ein mittlerer Ertragszuwachs von 0,22 t ha^{-1}, 0,30 t ha^{-1} und 0,46 t ha^{-1} festgestellt. Eine zweijährige Anbaupause führte zu einem mittleren Mehrertrag von 0,53 t ha^{-1} und eine dreijährige Anbaupause zu einem mittleren Mehrertrag von 0,47 t ha^{-1}. Die Ursachen für die Mindererträge in engen Rapsfruchtfolgen liegen vor allem in einer zunehmenden Krankheitsanfälligkeit, stärkerer Verunkrautung sowie einem stärkeren Auftreten von Schadinsekten.

Insgesamt zeigen die Untersuchungen am Standort Etzdorf sowie die Analyse weltweiter Fruchtfolgeversuche den positiven Einfluss von Vorfrüchten anderer Kulturarten und längerer Anbaupausen auf den Raps und machen deutlich, welche Nachteile mit engen Fruchtfolgesystemen einhergehen.

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Appendix

Table A1. Seed yield (t ha⁻¹), oil content (%) and oil yield (t ha⁻¹) of oilseed rape grown under different preceding crop combinations and fertilizer treatments at the field trial Etzdorf, Germany, 2013 – 2016

Means followed by the same letter were not significantly different at $P \leq 0.05$. Lowercase letters indicate differences between preceding crop combinations. Uppercase letters indicate differences between the fertilizer treatments. WW, winter wheat; OSR, oilseed rape; PCC, preceding crop combination

Year	Fertilization level (kg N ha⁻¹)	Preceding crop combination			
		WW-WW (first OSR crop)	WW-OSR (second OSR crop)	OSR-OSR (third OSR crop)	OSR (monoculture)
		Seed yield (t ha⁻¹)			
2013 – 2016	120	4.22^{aB}	4.20^{abA}	4.25^{aA}	4.02^{bA}
	180	4.44^{aA}	4.06^{bA}	4.13^{bA}	4.07^{bA}
		Oil content (%)			
2013 – 2016	120	45.3	45.2	45.5	45.6
	180	45.1	44.9	45.1	45.1
		Oil yield (t ha⁻¹)			
2013 – 2016	120	1.82^{abB}	1.81^{abA}	1.85^{aA}	1.75^{bA}
	180	1.91^{aA}	1.73^{bA}	1.77^{bA}	1.75^{bA}

Table A2. Interaction effects of preceding crop combination (PCC), fertilization (F) and year (Y) on secondary yield components of oilseed rape at Etzdorf, Germany, 2015 – 2016

Treatments	Primary branches per plant	Secondary branches per plant	Total branches per plant	Primary branches per m²	Secondary branches per m²	Total branches per m²
Y	**<0.0001**	**<0.0001**	**<0.0001**	**0.0012**	**<0.0001**	0.3035
PCC	**0.0002**	0.0637	**0.0003**	0.5715	**0.0107**	0.1508
PCC*Y	**0.0062**	0.0701	0.0127	0.3326	0.1030	0.4640
F	0.4491	0.2700	0.8293	0.7712	0.3222	0.9755
PCC*F	0.3682	0.4245	0.7254	0.9697	0.0868	0.8487
PCC*F*Y	0.8069	0.9566	0.7083	0.7173	0.3408	0.8771
Treatments	Main stem pods per plant	Primary branch pods per plant	Secondary branch pods per plant	Main stem pods per m²	Primary branch pods per m²	Secondary branch pods per m²
Y	0.4756	**<0.0001**	**<0.0001**	**<0.0001**	0.8881	**<0.0001**
PCC	**0.0002**	**0.0002**	0.1140	0.4938	**0.0007**	**0.0325**
PCC*Y	0.0630	**0.0102**	0.3580	**0.0192**	0.3049	0.1772
F	**<0.0001**	0.3688	0.5809	0.1754	0.4007	0.4313
PCC*F	0.7730	0.5106	0.3944	0.7916	0.9221	0.3763
PCC*F*Y	0.8445	0.8441	0.5759	0.4334	0.9096	0.9899

Bolded P values are statistically significant (P ≤ 0.05)

Table A3. Branching of oilseed rape following different preceding crop combinations and receiving different N fertilization levels at Etzdorf (2015–2016), Germany

Means followed by the same letter were not significantly different at $P \leq 0.05$. N^-, 120 kg N ha^{-1}; N^+, 180 kg N ha^{-1}

Harvest year	Preceding crop combination	Primary branches per plant			Secondary branches per plant			Total branches per plant			Primary branches per m²			Secondary branches per m²			Total branches per m²		
		N⁻	N⁺	Ø	N⁻	N⁺	Ø	N⁻	N⁺	Ø	N⁻	N⁺	Ø	N⁻	N⁺	Ø	N⁻	N⁺	Ø
2015	WW-WW	6.3	6.3	6.3ᴬ	0.7	0.7	0.7	7.0	7.0	7.0	343	308	326	37	32	35	380	340	360
	WW-OSR	5.5	6.7	6.1ᴬ	1.1	0.7	0.9	6.6	7.4	7.0	355	336	346	77	35	56	432	371	402
	OSR-OSR	5.0	6.0	5.5ᴬᴮ	0.4	1.0	0.7	5.4	7.0	6.2	306	320	313	19	44	32	325	364	345
	OSR monoculture	3.7	3.8	3.8ᴮ	0.1	0.3	0.2	3.8	4.1	3.9	311	347	329	6	24	15	317	371	344
2016	WW-WW	6.4	6.0	6.2ᴬᴮ	2.7	4.9	3.8	9.1	7.5	8.3	279	318	298	117	249	183	395	399	397
	WW-OSR	6.9	7.3	7.1ᴬᴮ	10.5	9.1	9.8	11.5	12.2	11.9	254	265	259	381	298	339	416	422	419
	OSR-OSR	7.8	8.2	8.0ᴬ	8.0	8.0	8.0	12.5	12.3	12.4	269	296	282	264	276	270	422	432	427
	OSR monoculture	6.6	5.7	6.1ᴮ	5.5	7.8	6.6	9.1	8.4	8.7	240	209	224	187	282	235	321	305	313
Mean	WW-WW	6.4	6.2	6.3ᴬ	1.7	2.8	2.3	8.1	7.3	7.7ᴬ	311	313	312	77	141	109ᴮ	388	369	378
	WW-OSR	6.2	7.0	6.6ᴬ	5.8	4.9	5.3	9.1	9.8	9.4ᴬ	304	301	302	229	166	198ᴬ	424	396	410
	OSR-OSR	6.4	7.1	6.8ᴬ	4.2	4.5	4.3	8.9	9.6	9.3ᴬ	288	308	298	142	160	151ᴬᴮ	374	398	386
	OSR monoculture	5.2	4.8	5.0ᴮ	2.8	4.0	3.4	6.4	6.2	6.3ᴮ	275	278	277	97	153	125ᴮ	319	338	328
Mean fertilization	N⁻/⁺	6.0	6.3	–	3.6	4.0	–	8.1	8.2	–	294	300	–	136	155	–	376	375	–

Table A4. Pod development on main stem, primary branches and secondary branches of oilseed rape following different preceding crop combinations and receiving different N fertilization levels at Etzdorf (2015 – 2016), Germany

Means followed by the same letter were not significantly different at $P \leq 0.05$. N^-, 120 kg N ha^{-1}; N^+, 180 kg N ha^{-1}

Harvest year	Preceding crop combination	Main stem pods per plant			Primary branch pods per plant			Secondary branch pods per plant			Main stem pods per m²			Primary branch pods per m²			Secondary branch pods per m²		
		N^-	N^+	Ø	N^-	N^+	Ø	N^-	N^+	Ø	N^-	N^+	Ø	N^-	N^+	Ø	N^-	N^+	Ø
2015	WW-WW	46	50	48	139	151	145[A]	5	3	4	2,500	2,503	2,502[B]	7,439	7,473	7,456[A]	262	142	202
	WW-OSR	44	48	46	122	158	140[A]	6	2	4	2,799	2,403	2,601[B]	7,675	7,825	7,750	461	132	297
	OSR-OSR	39	46	43	95	131	113[AB]	1	5	3	2,549	2,479	2,514[B]	5,595	6,765	6,180	44	224	134
	OSR monoculture	35	38	36	52	56	54[B]	0	2	1	2,951	3,506	3,229[A]	4,335	5,066	4,701	22	147	85
2016	WW-WW	41	47	44	155	135	145[AB]	17	8	13	1,830	2,450	2,140[A]	6,796	7,089	6,942	745	440	592
	WW-OSR	41	50	46	179	207	193[AB]	40	33	37	1,565	1,905	1,735[AB]	6,506	7,208	6,857	1,405	985	1,195
	OSR-OSR	43	51	47	210	215	213[A]	33	35	34	1,474	1,880	1,677[AB]	7,143	7,582	7,363	1,053	1,091	1,072
	OSR monoculture	38	43	41	153	133	143[B]	13	14	14	1,454	1,600	1,527[B]	5,491	4,837	5,164	425	513	469
Mean	WW-WW	43	49	46[A]	147	143	145[A]	11	6	9	2,165	2,477	2,321	7,118	7,281	7,199[A]	503	291	397[AB]
	WW-OSR	43	49	46[A]	151	182	166[A]	23	18	20	2,182	2,154	2,168	7,091	7,517	7,304[A]	933	558	746[A]
	OSR-OSR	41	48	45[A]	153	173	163[A]	17	20	18	2,011	2,179	2,095	6,369	7,174	6,771[AB]	549	657	603[AB]
	OSR monoculture	37	40	39[B]	103	94	99[B]	7	8	7	2,203	2,553	2,378	4,913	4,952	4,932[B]	224	330	277[B]
Mean fertilization	$N^{-/+}$	41[B]	47[A]	–	138	148	–	14	13	–	2,140	2,341	–	6,372	6,731	–	552	459	–

Table A5. Correlation coefficient between yield and yield components of oilseed rape at Etzdorf (2015 – 2016); *, ** statistical significance at P < 0.05 and P < 0.01

	Plant density per m²	Primary branches per plant	Secondary branches per plant	Total branches per plant	Primary branches per m²	Secondary branches per m²	Total branches per m²	Main stem pods per plant	Primary branch pods per plant	Secondary branch pods per plant	Main stem pods per m²	Primary branch pods per m²	Secondary branch pods per m²	Pods per plant	Seeds per pod	Thousand seed weight	Pods per m²	Seeds per m²	Seed yield (t ha⁻¹)
Plant density per m²	1.00																		
Primary branches per plant	-0.75**	1.00																	
Secondary branches per plant	-0.61**	0.63**	1.00																
Total branches per plant	-0.71**	0.90**	0.86**	1.00															
Primary branches per m²	0.59**	-0.04	-0.39**	-0.20	1.00														
Secondary branches per m²	-0.53**	0.56**	0.94**	0.77**	-0.25*	1.00													
Total branches per m²	0.10	0.47**	0.32*	0.49**	0.70**	0.43**	1.00												
Main stem pods per plant	-0.37**	0.51**	0.13	0.31*	0.18	0.20	0.28*	1.00											
Primary branch pods per plant	-0.75**	0.96**	0.71**	0.95**	-0.15	0.63**	0.44**	0.49**	1.00										
Secondary branch pods per plant	-0.52**	0.67**	0.89**	0.90**	-0.27*	0.78**	0.42**	0.09	0.76**	1.00									
Main stem pods per m²	0.90**	-0.59**	-0.64**	-0.65**	0.77**	-0.51**	0.25	0.02	-0.62**	-0.56**	1.00								
Primary branch pods per m²	-0.08	0.58**	0.13	0.43**	0.68**	0.24	0.84**	0.57**	0.55**	0.23	0.20	1.00							
Secondary branch pods per m²	-0.46**	0.64**	0.85**	0.86**	-0.14	0.82**	0.56**	0.12	0.72**	0.96**	-0.46**	0.34*	1.00						
Pods per plant	-0.74**	0.94**	0.77**	0.97**	-0.17	0.69**	0.46**	0.48**	0.99**	0.83**	-0.61**	0.53**	0.79**	1.00					
Seeds per pod	0.24	-0.27	-0.42**	-0.32*	-0.03	-0.48**	-0.29	-0.11	-0.25	-0.35	0.17	-0.22	-0.38*	-0.29*	1.00				
Thousand seed weight	-0.18	0.11	-0.02	0.01	-0.10	-0.03	-0.15	0.28*	0.08	-0.02	-0.10	-0.03	-0.04	0.08	-0.04	1.00			
Pods pods m²	0.13	0.43**	0.11	0.35*	0.77**	0.23	0.90**	0.50**	0.42**	0.24	0.38*	0.96**	0.37**	0.42**	-0.21	-0.07	1.00		
Seeds per m²	-0.08	0.07	-0.08	-0.01	-0.03	-0.10	-0.08	-0.10	0.05	-0.05	-0.12	0.00	-0.06	0.02	0.09	0.01	-0.05	1.00	
Seed yield (t ha⁻¹)	0.55**	-0.46**	-0.57**	-0.50**	0.30*	-0.55**	-0.10	-0.05	-0.44**	-0.37**	0.56**	-0.04	-0.34**	-0.43**	0.19	0.01	0.07	0.06	1.00

Eidesstattliche Erklärung / Declaration under Oath

Ich erkläre an Eides statt, dass ich die Arbeit selbstständig und ohne fremde Hilfe verfasst, keine anderen als die von mir angegebenen Quellen und Hilfsmittel benutzt und die den benutzten Werken wörtlich oder inhaltlich entnommenen Stellen als solche kenntlich gemacht habe.

I declare under penalty of perjury that this thesis is my own work entirely and has been written without any help from other people. I used only the sources mentioned and included all the citations correctly both in word or content.

_____	_____
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Acknowledgments

I want to express my gratitude to Prof. Dr. Olaf Christen who gave me the opportunity to write my doctoral thesis in the framework of the research project "Mitigation of greenhouse gas emissions from rapeseed cultivation with special focus on nitrogen fertilization" to obtain the doctoral degree. In addition, I appreciate the chance given by Prof. Dr. Christen to represent my research results on several national and international conferences which was a great chance during my doctorate and provided me with new experiences, interesting encounters and knowledge.

In particular I want to thank Dr. Philipp Götze for his advice and help at any time as well as Dr. Matthias Hinz for the good conversations. I will always remember the discussions, talks and fun with my roommates Dr. Benjamin Pietzner, Dr. Julia Pöhlitz and Sarah Zahn. I would also like to thank Dr. Jan Rücknagel, Dr. Barbara Koblenz and all the other colleagues for a memorable time at the Department for Agronomy and Organic Farming, great collaboration and mutual support.

I also want to acknowledge the work of my technical assistant Martina Fuhrmann at the field trials and in the laboratory as well as the support of the employees of the Merbitz Research Centre for Agriculture and Nutritional Sciences with the installation of the field trials, field management and assistance during sampling and measurements. Furthermore, I would like to thank all students, especially Elisabeth Rittweger, without whose support the project would not have been possible.

Moreover, I thank Prof. Dr. Marcel Quint who was willing to supervise this thesis during the final stage.

I am particularly grateful to Joanne Lietz for proof reading.

Finally, I am deeply grateful to my partner Eva Wichmann who has always supported me, helped with proof reading and never stopped pushing me to finish this work.