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Analysing Farmers' Herbicide Use Pattern to Estimate the Magnitude and Field-Economic Value of Crop Diversification

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Abstract: We present an on-farm approach to measure the effect of crop diversification on farmers' field economic values. Eleven years of data (2010–2020) on the chemical herbicide use, tillage practices and crop yields of 17 farms in north-eastern Germany were examined for winter wheat (WW) and winter oilseed rape (WOSR). We used a common conceptual framework to classify farmers' crop sequences according to their susceptibility to weeds ('riskiness'). Linear mixed models were used to analyse the relationship between crop sequence, tillage practice (inversion/non-inversion) and the response variables 'total herbicide costs', 'crop yield' and 'economic income'. Our results indicate that farmers in the area surveyed commonly grow crop sequences with a high risk of weeds. The driving forces behind this classification are high ratios of winter cereals and WOSR in the sequences. The most interesting result of our analysis is that farmers' total herbicide costs (THC_{fy}) significantly decreased from a higher to a lower riskiness class. Diversified crop sequences decreased the THC_{fy} for WW by up to 12 EUR ha^{-1} and for WOSR by 19–56 EUR ha^{-1}. Considering the crop diversification effects, the combined influence of tillage and crop sequence seems to be important. Significant differences in crop yield between the riskiness classes were found in WW and WOSR solely in non-inversion tillage systems. Hence, the analysis of farmers' 'economic income' revealed the great impact of crop diversification for non-inversion tillage systems. Indeed, we found that simplifying both crop sequence diversity and tillage intensity implies higher herbicide costs and, thereby, higher economic input. The best strategy for reducing herbicide costs in WW and WOSR cropping is to increase the use of summer crops or field grass as previous crops.

Keywords: on-farm data; riskiness; herbicide costs; crop yield; tillage practices

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1. Introduction

European agricultural systems face increasing economic, ecological and societal challenges [1–3]. Farming activities are regularly exposed to unpredictable perturbations, i.e., changes in environmental or socioeconomic constraints which cannot be anticipated [4]. The ability of farming systems to deal with these challenges is referred to as resilience [5,6], which emphasises change, uncertainty and the capacity of systems to adapt [7]. Farmers' land use is a major driver of farming system resilience [8].

Crop diversification is able to improve cropping system resilience [9–11] and enhancing a farmer's viability [12,13] by reducing economic and production risks [14]. On-farm crop diversification activities are mainly driven by field-level crop rotation patterns [8,15]. Although, rotating crops in diverse patterns has a long tradition in agronomy, even today, crop diversification is topical as a crucial component of integrated agricultural management, implemented in the European reform of the Common Agricultural Policy 2023–27 [16], the Biodiversity Strategy 2030 [2] and the Farm to Fork Strategy [1]. The political focus on crop diversification is motivated by farmers' highly simplified crop rotations as well as the increased proportion of land farmed under monoculture over the past decades [8,17–21].

The life cycle of an arable crop is the main factor determining the potential crop management and available weed control tactics [22]. Surveys of various crop rotation designs have revealed the effects of crop diversification on arable weeds [23–27]. Crop diversification may reduce arable weed density by negatively affecting weed seed germination and weed growth [28]. Owing to the reduced number of crop species in crop rotations in recent decades, farmers are highly reliant on efficient weed control using synthetic herbicides. Herbicides are applicated in large amounts for crop protection in the European Union, especially in northern member states [29]. Indeed, plant diversity decrease in agroecosystems [30–33] and environmental and health issues [34–37] have led to a recent European legislative push for a reduction in pesticide use [1,2,16]. Furthermore, heavy reliance on herbicides is seen as the main driver for the expansion of herbicide resistance [38], as weeds are more likely to evolve resistance to herbicides when herbicide use is high [39–42]. Crop diversification may, however, offer a great opportunity to reduce the high dependence on herbicides in conventional farming [43,44].

To explore on-farm economical crop diversification effects, we collected extensive crop management data based on farmers' records in north-eastern Germany. The need to focus on the farm-level perspective is motivated by the demands of estimating the magnitude and field-economic value of crop diversification. Controlled field experiments are used to test and evaluate agronomic management practices. Political governance, however, requires a meaningful picture about the magnitude of on-farm crop diversification and pesticide use. This is especially relevant for policy impact evaluation purposes.

A previous study investigated the combined influence of tillage and crop sequence patterns on herbicide use intensity, measured by the Treatment Frequency Index (TFI) [43]. Here, we present a further step of the analysis by focusing on economic values instead of the herbicide use intensity. Up to now, estimating crop diversification effects on farmers' profitability has only been studied in a limited way [45]. Hence, diversified cropping systems may greatly reduce arable crop reliance on herbicides. We hypothesised that farmers' herbicide costs and economic income are likewise influenced by the previous crop system design. For this purpose, we investigated the relationship between crop sequence, the type of tillage practice (inversion/non-inversion) and farmers' total herbicide costs and economic income using the conceptual framework of Andert et al. [43]. According to Leteinturier et al. [19], Stein and Steinmann [21] and Glemnitz et al. [46], we use the term crop sequences in this study to indicate flexible and short-term cropping plans, instead of fixed cyclical crop rotations.

2. Materials and Methods

2.1. On-Farm Data Origin

We analysed a database constituted from farmers' records of 18 commercial farms for the period 2010–2020. The farms are situated in the federal state of Mecklenburg-Vorpommern (MV) in north-eastern Germany (Figure 1). The farms belong to a local on-farm network, which is guided by the Mecklenburg-Vorpommern Research Centre for Agriculture and Fisheries.

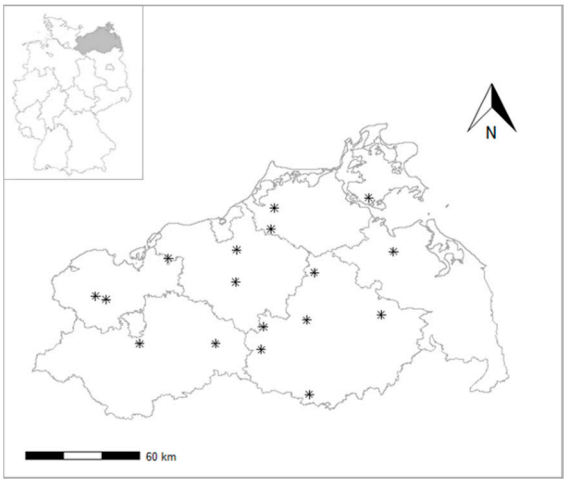


Figure 1. Location of farms (*) in the region of Mecklenburg-Vorpommern in north-eastern Germany.

2.2. Management Data

We analysed farmers' records of 3218 fields cultivated with winter wheat (WW) and winter oilseed rape (WOSR). We recorded 16,042 selective and non-selective herbicide treatments, with each record including the date of application, full name of the plant protection product, the applied dosage, the field size and size of the treated area. These crop management data were examined for plausibility.

The herbicide costs per field f and year y, HC_{fy}, were calculated as follows (see Formula (1)). Firstly, the applied herbicide dosage (L kg^{-1}, HD) was multiplied by the specific price of the herbicide product (EUR L^{-1} or EUR kg^{-1}, P). Product prices were derived from regional average prices. To take partial, area-specific herbicide treatments into account, it was, secondly, necessary to area-weight the treatment. Therefore, the field area treated ($A_f^{treated}$) was divided by the total area (A_f^{total}).

$$HC_{fy} = \left(HD_f \times P\right) \times \frac{A_f^{treated}}{A_f^{total}} \quad (1)$$

The herbicide costs per field f and year y (HC_{fy}) were summed for the total herbicide costs (THC_{fy}) per field f and year y (see Formula (2)).

$$THC_{fy} = \sum_{i=1,\ldots,n}^{n} HC_{fy} \quad (2)$$

The 'economic income' per field f and year y (EI_{fy}) in € ha^{-1} was calculated as follows (see Formula (3)). The crop yield (CY_{fy}) in t ha^{-1} was multiplied by the market crop price (P) in EUR t^{-1} and the result then reduced by the herbicide costs (HC_{fy}) and tillage costs (TC_{fy}). Data on tillage practices (inversion and non-inversion) and crop yield (CY_{fy}) were obtained from farmers' records. We used average market crop prices for quality winter wheat (160 EUR t^{-1}) and winter oilseed rape (380 EUR t^{-1}) and reference tillage costs [47]. For winter wheat, the tillage costs (TC_{fy}) were as follows: 70 EUR ha^{-1} for non-inversion tillage and 81 EUR ha^{-1} for inversion tillage systems. 68 EUR ha^{-1} refers to non-inversion tillage costs and 80 EUR ha^{-1} refers to inversion tillage costs in winter oilseed rape.

$$EI_{fy} = \sum_{i=1,\ldots,n}^{n}\left(CY_{fy} \times P\right) - HC_{fy} - TC_{fy} \quad (3)$$

2.3. Classification of Crop Sequences

In this study, we used the classification of crop triplets according to their riskiness of weeds, which was developed by Andert et al. [43]. The authors developed crop-specific

keys to classify crop sequences according to their susceptibility to weeds (i.e., 'riskiness'). The classification of riskiness is specified for weed infestation of the last crop in the sequence triplet. Andert et al. [43] considered the results of Bohan et al. [48], which revealed significant historical effects of past crops, sown in sequence, on weed seedbanks only for up to three years. In our study, the classification considered which pre-crop would increase or decrease the risk of weed infestations in WW and WOSR and how this risk would be altered by the second crop (Table 1). The classification considered two principles. The first of these is the alteration principle. This concerns the general sowing period (autumn, early spring, late spring) connected to the timing of the tillage practice before sowing. It is evident that alteration of the sowing periods between crops decreases the susceptibility of the crop sequence to adapted weeds. The second principle refers to the number of host crops: the higher the number of potential host crops present in a crop triplet, the higher is the susceptibility to weeds. For detailed information, see Andert et al. [43].

Table 1. Riskiness classes for weeds in a certain crop, according to its combination with the two preceding crops (pre-crop and pre-precrop). MA (maize), WC (winter cereals), SC (spring cereals), RT (roots and tubers), WOR (winter oilseed rape), L (legumes), FG (field grass) and SA (set-aside).

Leading Crop	Pre-crop	Pre-Precrop	Riskiness Class
Winter wheat	WC	WC	very high
	WOR	WC	high
	WOR/WC	RT/MA/SC/L/FG/SA	medium
	RT/MA/SC/L/FG/SA	WC/WOR	low
	RT/MA/SC/L/FG/SA	RT/MA/SC/L/FG/SA	very low
Winter oilseed rape	WC	WOR	very high
	WC	WC	high
	WC	RT/MA/SC/L/FG/SA	medium
	RT/MA/SC/L/FG/SA	WOR	low
	RT/MA/SC/L/FG/SA	RT/MA/SC/L/FG/SA	very low

2.4. Analysis

Our calculations and analyses were conducted using RStudio Team [49]. The extraction of crop triplets was conducted using R-package 'car' [50] and linear mixed modelling was performed using R-package 'lme4' [51].

Linear mixed models were used to analyse the relationship between crop sequence, tillage practice and the response variables 'total herbicide costs' (THC_{fy}), 'crop yield' (CY_{fy}) and 'economic income' (EI_{fy}) of field f in year y (see Formula (4)). Furthermore, we explored the combined influence of tillage and crop triplet riskiness on the response variables to check if the crop sequence effect is modified by the tillage practice. We set up separate models for winter wheat and winter oilseed rape.

$$THC_{fy}/CY_{fy}/EI_{fy} = \mu + RC_{fy} \times TI_{fy} + k_y + l_d + m_{bd} + \varepsilon_{fyklm} \quad (4)$$

RC denotes the fixed effect of crop triplet riskiness class on field f in year y, and TI is the fixed effect of tillage on field f in year y. The term $RC \times TI$ describes the interactions between crop triplet riskiness and tillage as well as the individual effects of RC and TI. Random effects are allowed by year k_y, region l_d and farm m_{bd}. Farm m_b is nested in region d. Epsilon (ε) is the random error term.

3. Results

3.1. Frequency of Crop Triplets

In general, winter wheat and winter oilseed rape are mainly grown in crop sequences with a high risk of weeds (Figure 2). For winter wheat (Figure 2A), the frequency of non-inversion tillage is predominant in all riskiness classes. In the 'high' riskiness class, however, 50% of the crop sequences in winter rape are ploughed (Figure 2B).

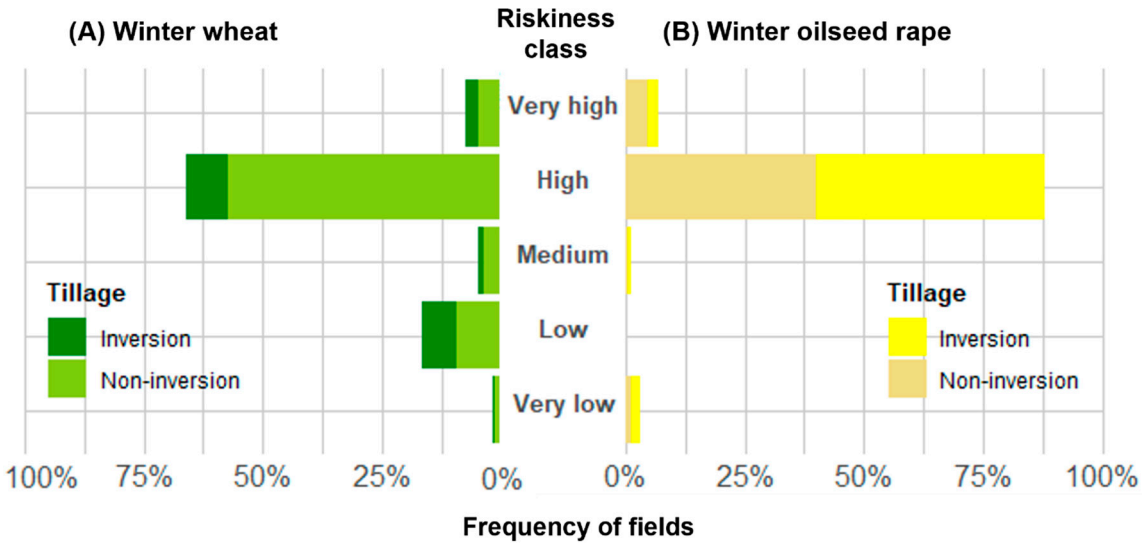


Figure 2. Frequency (%) of fields per riskiness class in (**A**) winter wheat and (**B**) winter oilseed rape.

For our further analyses, we deleted the riskiness class 'low' due to a frequency smaller than 1% (overall frequency 0.2%, non-inversion tillage frequency 0.0%, inversion tillage frequency 0.2%).

3.2. Crop Sequence Diversity Decreases Herbicide Costs

For WW and WOSR, the higher the riskiness class for weeds of a crop triplet, the higher were the 'total herbicide costs' (THC_{fy}) in the leading crop (Table 2). Regardless of the tillage system, the total herbicide costs of both crops significantly decreased from a higher to a lower riskiness class by up to 12 EUR ha^{-1} for WW and 19–56 EUR ha^{-1} for WOSR.

Table 2. Regression: Effect of crop sequence riskiness and tillage on 'total herbicide costs' (THC_{fy} in EUR ha^{-1}) in winter wheat and winter oilseed rape. Significance levels: * $p < 0.05$, ** $p < 0.01$ and *** $p < 0.001$.

		Winter Wheat		Winter Oilseed Rape	
	Tillage	**Non-Inversion**	**Inversion**	**Non-Inversion**	**Inversion**
		Estimate of THC_{fy} in EUR ha^{-1}		**Estimate of THC_{fy} in EUR ha^{-1}**	
Riskiness class	Very high	58.4	52.2	112.5	129.7
	High	+7.9 **	+5.0	+5.0	−19.1
	Medium	−1.1	+4.2	−19.0	−56.0 *
	Low	−11.6 ***	−8.1 *	-	-
	Very low	−12.3 *	−6.9	−22.7 *	−33.5 *
		Variance		**Variance**	
Random effects	Year	25.6 ***	37.2 ***	163.3	506.5
	Farm	116.8 ***	164.6 ***	796.1 ***	765.8
	Region	59.7	31.8	0.0	0.0
	Soil quality	2.1	58.6 **	27.5	0.0
	Residuals	444.1	335.3	1118.8	1950.7

Tillage significantly influenced total herbicide costs in WOSR (Table 2). It decreased by up to 20 EUR ha^{-1} ('medium' riskiness class) when fields were moldboard-ploughed compared to the non-ploughed WOSR fields. In WW, the largest differences between the two tillage levels used were detected in 'very high' and 'high' risk crop triplets.

3.3. Yield Analysis

The results for the crop yield models are presented in Table 3. The 'crop yield' (CY_{fy}) for inversion tillage systems did not react significantly to the riskiness of the crop triplet. Significant differences in crop yield between the riskiness classes were found in winter wheat and winter oilseed rape solely in non-inversion tillage systems. The yields of winter oilseed rape in crop triplets classified as having 'high' and 'very low' riskiness were estimated at 3.6 t ha^{-1} and 3.7 t ha^{-1}, respectively, which were higher than yields estimated for winter oilseed rape grown in crop triplets with 'very high' riskiness (estimate 3.3 t ha^{-1}).

Table 3. Regression: Effect of crop sequence riskiness and tillage on 'crop yield' (CY_{fy}) (t ha^{-1}) in winter wheat and winter oilseed rape. Significance levels: * $p < 0.05$, ** $p < 0.01$ and *** $p < 0.001$.

		Winter Wheat		Winter Oilseed Rape	
	Tillage	**Non-Inversion**	**Inversion**	**Non-Inversion**	**Inversion**
		Estimate of CY_{fy} in t ha^{-1}		**Estimate of CY_{fy} in t ha^{-1}**	
Riskiness class	Very high	7.5	7.3	3.3	3.7
	High	+0.4 ***	+0.3	+0.3 **	−0.1
	Medium	+0.3	−0.3	+0.3	0.0
	Low	+0.2	−0.1	-	-
	Very low	+0.2	+0.6	+0.4 *	−0.1
		Variance		**Variance**	
Random effects	Year	1.2 ***	1.0 ***	0.4 ***	0.4 ***
	Farm	0.4 ***	0.6 ***	0.1 ***	0.1 *
	Region	0.8 *	1.0 *	0.1	0.1
	Soil quality	0.1 **	0.1 *	0.1 ***	0.1 *
	Residuals	1.2	1.0	0.2	0.3

3.4. Field-Economic Analyses

For ploughed fields (inversion tillage), the 'economic income' (EI_{fy}) did not react significantly to the riskiness of the crop triplet (Table 4). For non-inversion tillage practices, however, the lower the riskiness class for weeds of a crop triplet, the higher was the 'economic input' for non-inversion tillage systems in WW and WOSR. For WOSR, the 'economic income' increased by 165 EUR ha^{-1} when comparing the crop triplets classified as 'very high' and the crop triplets classified as 'very low'. Significant differences in the EI_{fy} between the riskiness classes of 'very high' and 'high' were found in WW.

Table 4. Regression: Effect of crop sequence riskiness and tillage on 'economic income' (EI_{fy}) (EUR ha^{-1}) in winter wheat and winter oilseed rape. Significance levels: * $p < 0.05$, ** $p < 0.01$ and *** $p < 0.001$.

		Winter Wheat		Winter Oilseed Rape	
	Tillage	**Non-Inversion**	**Inversion**	**Non-Inversion**	**Inversion**
		Estimate of EI_{fy} in EUR ha^{-1}		**Estimate of EI_{fy} in EUR ha^{-1}**	
Riskiness class	Very high	1083.9	1018.0	1087.8	1193.3
	High	+40.1 *	+57.3	+101.7 **	−35.8
	Medium	+31.8	−36.2	+118.8 **	+50.5
	Low	+39.2	+122.1	-	–
	Very low	+28.2	+9.3	+165.0 **	−10.4
		Variance		**Variance**	
Random effects	Year	29480 ***	26427 ***	66130 ***	48943 ***
	Farm	12452 ***	7688 ***	22977 ***	7344 ***
	Region	16771 *	20208 *	92.62	10921
	Soil quality	1263 **	4172 *	8132 ***	0.0
	Residuals	30843	24912	36095	38941

4. Discussion

Previous studies have suggested integrated non-chemical methods to reduce both the treatment frequency and dosage of herbicides [20,43,52,53]. Our study further investigated whether farmers' herbicide costs and economic income of WW and WOSR were influenced by the previous crop sequence pattern and tillage practices. For this purpose, we analysed a unique field-level dataset from commercial farms in north-eastern Germany.

Indeed, the results reveal that crop sequence diversity significantly decreases farmers' herbicide costs in WW and WOSR (Table 2). Regardless of the tillage system, herbicide costs significantly decreased from a higher to a lower riskiness class depending on the crop sequence (Table 2). Thus, the hypothesis that farmers' herbicide costs and economic income are influenced by the previous crop system design was accepted based on the data set. Greater crop diversity reduces farmers' input costs in WW and WOSR production. A reduction in herbicide costs (for WW by up to 12 EUR ha^{-1} and for WOSR by up to 56 EUR ha^{-1}) may drive farmers' motivation for the adoption of diversified crop rotations due to the general high importance of farm profitability [54]. Moreover, our analyses indicated a higher 'economic income' in more diverse crop sequences (Table 4). Thus, the results of our study suggest that including a higher proportion of summer crops and/or field grass contributes to higher net farm incomes. In contrast, simplifying both crop sequence diversity and tillage intensity implies higher herbicides costs and, thereby, lower crop profitability. Hence, together with the on-farm study by Andert et al. [43], we provide evidence that diversified crop sequences are less dependent on chemical herbicides and, thus, farmers save costs by rotating crops. We support Colbach et al. [55] in their conclusion that well-reasoned integrated weed management can preserve crop production in cropping systems with reduced herbicide use. Our results and conclusion are confirmed by a previous on-farm evaluation of integrated weed management (IWM) tools for maize production, which attest IWM economic sustainability [56]. Diversified crop rotations may help reduce the overall farm business risk associated with crop sequences with a high risk of weeds, e.g., monocultures or simplified crop sequences with fewer crops [10,57,58].

However, farmers in the area surveyed commonly grow crop sequences with a high risk of weeds (Figure 2). The driving forces behind this classification are high ratios of winter cereals and winter oilseed rape in the sequences. Larger farm and field sizes and associated scale effects, logistical advantages (Baltic Sea harbors) and loamy sand to sandy loam soil types are the primary drivers for land allocation to winter cereals and winter oilseed rape in north-eastern Germany [59–61]. For the period 2012–2021, 20% of the arable land in Mecklenburg-Vorpommern was devoted to WOSR production and 31% to winter wheat. Market forces stimulated the specialisation and intensification of cropping systems, especially for cereals and oil crops [62]. Peltonen-Sainio and Jauhiainen [63] explored the substantial potential to shift from the recent European common cereal rotations towards more diverse crop sequencing patterns. However, it remains unclear what the alternatives are. There are only a few recommendations on how to diversify farm systems in ways which best fit the agroecological and socioeconomic challenges that farmers face [61]. Crop sequences which generated a high farm-economic profitability selected a mixture of grain legume, oilseed rape, cereal crops and/or field grass to manage weeds and generate profit [64,65]. For this reason, political support, in particular, and supportive market development are necessary for an increasing legume production in European arable farming. Maize plays an ambivalent role as a driver for simplified rotation practice in arable cropping systems, on the one hand, and as an element of diversified sequences, on the other hand [21].

How politicians and/or advisory services can motivate the majority of farmers who have yet to diversify their crop sequences remains unclear. Riemens et al. [22] supposed a learning curve was a barrier for farmers who want to implement alternative weed control tactics and long-term weed management strategies. High initial costs to purchase specialised equipment, insufficient knowledge and technical skills, the shortage of local infrastructure and a lack of marketing information regarding new crop varieties are still barriers to a higher magnitude of on-farm crop diversification [66,67]. Within the European

Union, the Common Agricultural Policy 2023–27 [16] may be a major driving force that affects on-farm diversification processes. In addition, however, the recent supply shortages and high prices may help motivate more farmers to consider more diverse crop sequences, which spread risks and buffer gross margins at the farming system scale [68].

5. Conclusions

The results of this study reveal the common 'state of farming practices' in intensive European cropping systems: high ratios of winter cereals and winter oilseed rape in crop sequences and, associated therewith, a high risk of weed infestation. We conclude that crop diversification is a promising strategy for farmers to reduce their synthetic herbicide input costs and, thereby, improve their economic income in arable farming. Thus, the diversification strategies imposed by the new European common agricultural policy (2023–27) may contribute to greater environmental and economic sustainability in European arable farming. In particular, the higher ambitions for crop rotation on all farms of at least 10 hectares are encouraged more than under the current "greening" system of the European common agricultural policy (2014–2020). Importantly, variability in farmers' field-level crop pattern responses should, in future, be clearly evaluated by the European member states.

Besides the political effort, farmers' intrinsic motivation for a redesign of weed management strategies is most valuable. In future research activities, on-farm evaluation of integrated weed management tools should be more central. Efforts must be taken by both agricultural scientists and advisory services to promote a redesign of farmers' cropping systems to enhance preventive weed control. Besides this, future lines of work should investigate the herbicide costs and economic income for each single crop of the crop sequence triplet and, ultimately, the overall 'crop sequence income'. These analyses will allow agricultural stakeholders to explore the overall economic benefit of crop diversification in arable farming.

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