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Agricultural Systems 201 (2022) 103454

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

Using a bio-economic farm model to evaluate the economic potential and pesticide load reduction of the greenRelease technology

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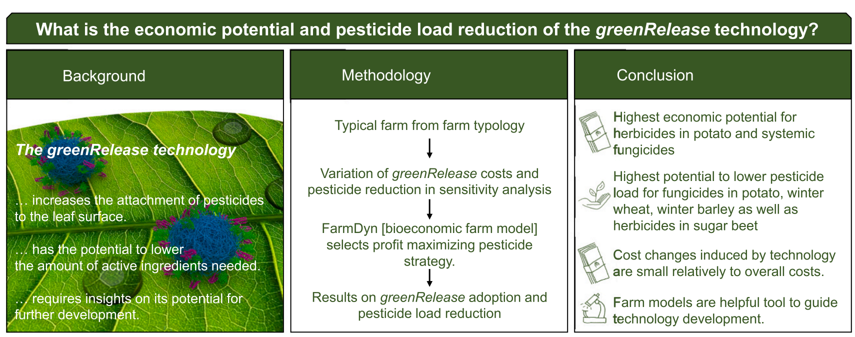
HIGHLIGHTS

- The greenRelease technology increases the adherence of pesticides to the leaf surface.
- We apply a bio-economic farm model to assess the economic potential and possible pesticide load reduction.
- The economic potential is highest for systemic fungicides in all assessed crops and herbicides in potato.
- Potential to lower the pesticide load is highest for fungicides in cereals and potato as well as herbicides in sugar beet.
- This research is the first broad analysis of greenRelease which can lower the environmental burden of pesticide use.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Dr Mark van Wijk

Keywords:
greenRelease
Bio-economic farm model
FarmDyn
Economic potential
Pesticide load
Pesticide risk indicator

ABSTRACT

CONTEXT: Policies and strategies at EU and national level aim at a reduced use of pesticides in agriculture, such as the Farm to Fork Strategy of the EU Commission. Technological progress can lower pesticide application and contribute to a sustainable bioeconomy. As an example, the greenRelease technology increases the attachment of the active ingredient of plant protection products to the leaf surface and slowly releases the active ingredient from a microgel container. Experiments under both controlled and field conditions have demonstrated the potential of the greenRelease technology to reduce pesticide use. As a so-called platform technology, the greenRelease concept can be applied to various crops and plant protection chemicals.
OBJECTIVE: To guide further development, this study analyses the greenRelease technology regarding its economic potential and its possible contribution to the reduction of environmental and health risks from pesticide use.

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https://doi.org/10.1016/j.agsy.2022.103454
Received 25 March 2022; Received in revised form 20 June 2022; Accepted 22 June 2022
Available online 12 July 2022

METHODS: To do so, we use a bio-economic farm model to assess the technology potential for a typical farm and spraying sequences of various crops in northwestern Germany.
RESULTS AND CONCLUSIONS: The results reveal that the economic potential of the greenRelease technology is highest for systemic fungicides in all assessed crops as well as for herbicides for potato cultivation. It is lowest for insecticides in winter barley and potato as well as for contact fungicides, due to the small doses and low product costs. The potential to lower possible environmental and health risks of pesticide use, indicated by the Danish pesticide load indicator, is highest for fungicides in potato, winter wheat, and winter barley as well as for herbicides in sugar beet cultivation. Relative to overall costs in arable farming, the cost changes induced by the greenRelease technology are minor, such that the environmental benefits will be key for promoting its application. However, the economic competitiveness of the technology increases if agri-environmental policies progressively internalize the negative externalities of pesticides use.
SIGNIFICANCE: This research is the first comprehensive economic and environmental assessment of the technology greenRelease which can contribute to lower the environmental burden of pesticide use in agriculture.

1. Introduction

Ongoing concerns related to environmental and human health impacts of pesticides call for a reduction of their use in agriculture and are reflected in policy strategies at EU and national level. The Farm to Fork Strategy of the EU commission, for example, proposes the decline of the overall use and risk of pesticides by 50% until 2030 (European Commission, 2020). The German National Action Plan on Sustainable Use of Plant Protection Products aims at a 30% reduction of the risk pesticides bear for the environment until 2023 (BMEL, 2013), implementing existing EU legislation (Directive 2009/128/EC). However, the impact of these policies has so far been limited (Möhring et al., 2020). Technological innovations can contribute to achieving such policy goals without increased pest pressure and related yield decreases and, thereby, foster the transformation towards a sustainable bioeconomy. An example provides the greenRelease technology, which improves the attachment of pesticides to the plant surface ensuring the rainfastness and reducing the amount of active ingredients needed by the controlled release of active ingredients. This novel formulation technology consists of two components. A microgel, which is a colloidal biocompatible polymer carrier, is loaded by a commercially used active ingredient and releases it under defined conditions over a longer period. In addition, an anchor peptide, located on the outer layer of the microgel, increases the rain fastness of the formulation on the leaf surface. Its main advantages are controlled release over a longer period, high rainfastness, and biocompatibility (Meurer et al., 2017; Jakob et al., 2019). First field trials with the greenRelease technology in apple production revealed a large reduction potential of fungicide use against apple scab (Jakob, 2021). The environmental impact of the technology is investigated in the greenRelease and the GreenToxyConomy projects (Johann et al., 2022).

As a so-called platform technology, greenRelease can be adapted to various crops, pests, and pesticides. Crop specific anchor peptides have already been identified for apple, sugar beet, potato, barley, soybean, cucumber, and orange leaves and have been tested under controlled and partly field conditions (Meurer et al., 2017; Schwinges et al., 2019; Pariyar et al., 2020). An assessment of the economic potential and environmental benefits is needed to decide which combinations of crops, pests and pesticides are developed towards market readiness as a costly and time-consuming process. However, such an assessment requires information on technology characteristics such as pesticide reduction potential or product cost, which cannot be provided before the actual development and assessment in field trials. We propose here a bio-economic simulation approach which systematically assesses possible ranges of technology characteristics and their impact on relevant economic and environmental parameters. This narrows down the crop-pest-pesticides combinations to the most promising ones, highlights possible trade-offs and can help to stop further development early if it becomes obvious that a break-even point cannot be reached.

Bio-economic farm models capture in detail the economic and bio-physical dimension of farming activities, putting the decisions of the farmer on input and technology use in the center. They are a powerful tool for ex-ante assessments of technology impacts (Janssen and van Ittersum, 2007) as they quantify relevant economic and environmental indicators to assess a novel technology as for example greenRelease. These types of models have been widely applied to analyze adoptions of specific farm operations, such as water lifting technologies (Bizimana and Richardson, 2019) or the use of sexed semen in dairy production (Pahmeyer and Britz, 2020) as well as systemic changes, such as conversion to organic farming (Kerselaers et al., 2007).

Based on bio-economic modeling combined with a systematic sensitivity analysis, this paper analysis the greenRelease technology regarding its economic potential and its potential contribution to the reduction of environmental and health risks from pesticide use. The insights can guide the further development of the technology. The pesticide risk assessment is based on the Danish Pesticide Load indicator which calculates sub-indicators on human health, ecotoxicology and environmental fate for different pesticides (Kudsk et al., 2018). The German Rheinische Revier serves as a case study. In this region, a sustainable bioeconomy is currently promoted to help mitigating the structural change caused by the phase out of coal use for electricity generation (Kommission Wachstum, Strukturwandel und Beschäftigung, 2019). However, as dominant crops of German agriculture are assessed, the findings are of interest and valid beyond the case study region.

2. Material and methods

To assess the greenRelease technology, a typical arable farm and spraying sequence are defined for the case study region. For this farm, the greenRelease costs and the pesticide reductions enabled by the technology are varied in a Monte-Carlo sampling approach (Fig. 1).

For all costs and reduction levels, the bio-economic farm model FarmDyn (Britz et al., 2021) provides results for the adoption decision on the greenRelease technology and the pesticide load reduction. Subsequent, the methodology is described in detail.

2.1. Case study region

The greenRelease technology is studied for a typical arable farm in the Rheinische Revier, located in the German federal State of North Rhine-Westphalia in the west of Germany. This region is characterized by intensive arable farming due to high yield potentials, and crop rotations dominated by cereals, sugar beet, and potato production (Appendix A1). We understand the Rheinische Revier as the 19 communes which are neighboring the lignite mining areas and coal-fired power plants (N.A., 2019). Germany's government decided to fade out energy production from coal over the next two decades, implying fundamental structural changes. The development of a strong regional bioeconomy, based on numerous initiatives along the whole value chain (e.g. N.A., 2021a) is seen as one pillar to support this transition (Kommission

Wachstum, Strukturwandel und Beschäftigung, 2019). This creates promising conditions for the introduction of innovative technologies to the farming sector, such as greenRelease.

The typical farm is chosen based on the farm typology from Kuhn and Schäfer (2018). The typology covers for each soil-climate region in North Rhine-Westphalia the relative importance of different farm types, differentiated by farm specialization, size and stocking density. In the soil-climate region 141, which largely overlaps with the Rheinische Revier (Appendix A3), the arable farm types "Cereals, oilseeds, protein crops and root crops combined (162)" and "Various field crops combined (166)" are most frequent with regard to the number of farms and occupied land share. They differ slightly only in observed crops shares (Appendix A4, Appendix A5). Combined with agronomic crop rotation restrictions (Baeumer, 1990), we derive crop shares for the typical farm of 40% winter wheat, 20% winter barley, 25% sugar beet, and 15% potatoes. We select a farm size of 70 ha, being the most dominant one according to land covered and second with regard to number of farms. However, as scale effects do not play a role in the analysis, the selected farm size is of minor importance.

The greenRelease technology needs to be designed and validated for the particular crop, requiring a specific anchor peptide, and the selected active ingredient, demanding a specific microgel container. Any modifications for regional conditions are not required. Therefore, the results of the analysis are of interest beyond the Rheinische Revier as the assessed crops are of large importance in Germany covering around 45% of the arable land in 2021 (Destatis, 2021). Furthermore, soil and climate similar to the conditions in the Rheinische Revier can be found in other parts of Germany (Roßberg et al., 2007).

2.2. *Pesticide use and greenRelease technology*

Based on literature and expert communication, we assess typical spraying sequences for potato, sugar beet, winter wheat, and winter barley in the Rheinische Revier, i.e. the plant protection products and their doses typically used for a given crop in the region (Table 1). The spraying sequence of sugar beet is dominated by three passages with herbicides. Two further applications of insecticides reflect that no seed treatment with neonicotinoids takes place. Finally, a single fungicide application against various leaf diseases is applied at the end of the spraying sequence. Potato cultivation is dominated by the use of different systemic and contact fungicides against *Phytophthora infestans*. Moreover, two insecticides are applied against beetles and lice. Pre-emergence herbicides are applied once, followed later by an herbicide for desiccation. In addition, a product for sprout control is used in potatoes. Winter wheat and winter barley have similar spraying sequences with the same herbicides applied once in autumn. In winter barley, insecticides are additionally applied in autumn against various biting and sucking insects. Fungicide against diseases such as rusts and mildew are the most used product groups in the cereal crops, with three applications in winter wheat and two applications in winter barley. In addition, growth control products for increased plant stability, which are currently not subject to the greenRelease technology, are applied twice.

Experts from the greenRelease development team screened the pesticides and judged which active ingredients are theoretically applicable for the greenRelease technology. The relevant products are marked in Table 1. As they differ fundamentally from their mode of action, the pesticides are grouped as herbicides, insecticide, contact fungicides, and systemic fungicides. The latter summarizes all active ingredients, which enter the plant leaf, covering locally systemic and systemic fungicides. The focus on specific crops, which is linked to the development of certain anchor peptides, as well as the selection of a pesticide product group are fundamental decisions in the technology development path of greenRelease.

2.3. *Modeling approach*

The bio-economic farm model FarmDyn[1] is applied to assess the described scenarios of the greenRelease technology in a large-scale sensitivity analysis. The model is based on mixed-integer linear programming and returns the profit maximizing farming activities assuming a fully informed and rational decision taker. It allows to capture economic and environmental flows of farming activities in detail, which is the most important model attribute for the study at hand. FarmDyn has been used for diverse applications, such as compliance costs calculation (Kuhn et al., 2019) or technology impact assessment (Pahmeyer and Britz, 2020), and been extensively described in scientific literature (see Britz et al., 2021 for recent overview).

Besides the profit maximal adoption decisions and the environmental indicator (section 2.4), the model returns total variable costs per farm, plant protection costs per farm and crop specific plant protection costs. Note that the farm-level approach focuses on the farmer as the decision unit and, therefore, only considers direct (application) costs. Costs through adverse effects on the ecosystem (e.g. pollination and soil productivity) or other (external) costs (e.g. for water filtration) are not covered by the analysis (section 4). Cropping shares are fixed to the observed ones of the typical farm described in section 2.1.

The choice of using the greenRelease technology or not is the endogenous decision variable in a large-scale sensitivity analysis, farming activities or further management choices are kept constant. When economically feasible, the model adopts the technology for all pesticide products in a product group and for a specific crop (e.g. for all herbicides in sugar beet). A Monte-Carlo sampling with 1000 model runs is conducted for the cost of greenRelease and its effectiveness. Based on the expertise and interest of the greenRelease development team, a pesticide reduction effect between 10% and 90% is assessed to address the still uncertain technology characteristics. However, experiments under controlled conditions and field trials showed that such high reduction rates are possible without yield impacts (not published yet). The reduction is also reflected in a lower need and costs for plant protection products. However, additional costs occur for the greenRelease technology per passage. They enter the sensitivity analysis with a range from 5 to 50 Euro ha^{-1} $passage^{-1}$. The costs of plant protection are hence composed of the costs for greenRelease and the (reduced) plant protection products. All other costs of a passage are kept unchanged. Importantly, greenRelease does not require investments in new machinery and knowledge from farmers as the same pesticides and application processes are used.

A uniform distribution is assumed for the cost of greenRelease and its

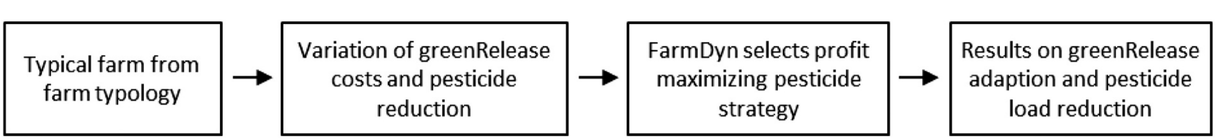

Fig. 1. An overview on the methodology used to test the applicability and effectivity of the GreenRelease technology

[1] The analysis is done with repository version 2357 of FarmDyn.

Table 1
Overview on spraying sequences in the baseline and products with potential for reduction with greenRelease.

Application passage	Product group	Product	Application rate
Sugar beet			
1	Herbicide	Betasana SC*	1.5 l ha^{-1}
	Herbicide	Kezuro SC*	0.9 l ha^{-1}
	Herbicide	Goltix Gold*	0.9 l ha^{-1}
	Herbicide	Stemat*	0.5 l ha^{-1}
	Herbicide	Hasten (Additive)	0.8 l ha^{-1}
	Herbicide	Debut*	0.02 kg ha^{-1} + 0.17 l ha^{-1}
2	Herbicide	As passage 1 but Debut 0.025 kg ha^{-1} *	
3	Insecticide	Pirimor*	0.3 kg ha^{-1}
4	Herbicide	As passage 1 but Debut 0.025 kg ha^{-1} *	
5	Insecticide	Teppeki*	0.14 kg ha^{-1}
6	Fungicide	Mercury Pro*	1.0 l ha^{-1}
Potatoes			
1	Herbicide	Boxer	4.0 l ha^{-1}
	Herbicide	Sencor Liquid*	04 l ha^{-1}
2	Fungicide	Zorved Endavia*	0.4 l ha^{-1}
3	Fungicide	Rival Duo*	2.0 l ha^{-1}
	Fungicide	Carneol*	0.4 l ha^{-1}
4	Fungicide	Revus Top*	0.6 l ha^{-1}
	Insecticide	Coragen*	0.06 l ha^{-1}
5	Fungicide	Carial Flex*	0.6 kg ha^{-1}
	Fungicide	Ranman Top*	0.5 l ha^{-1}
6	Fungicide	Tanos*	0.7 kg ha^{-1}
	Fungicide	Shirlan*	0.4 l ha^{-1}
7	Fungicide	Ranman Top*	0.5 l ha^{-1}
	Fungicide	Cymbal Flow*	0.5 l ha^{-1}
8	Sprout control	Fazor	5 kg ha^{-1}
9	Fungicide	Revus Top*	0.6 l ha^{-1}
	Insecticide	Mospilan*	0.25 kg ha^{-1}
10	Fungicide	Shirlan*	0.4 l ha^{-1}
	Fungicide	Cymbal Flow*	0.5 l ha^{-1}
11	Fungicide	Banjo Forte*	1.0 l ha^{-1}
	Fungicide	Signum*	0.25 kg ha^{-1}
12	Fungicide	Ranman Top*	0.5 l ha^{-1}
13	Fungicide	Shirlan*	0.4 l ha^{-1}
	Herbicide	Shark*	1.0 l ha^{-1}
Winter wheat			
1	Herbicide	Herold SC*	0.4 l ha^{-1}
	Herbicide	Lentipur 700*	1.23 l ha^{-1}
2	Growth regulator	CCC 720	1.0 l ha^{-1}
3	Fungicide	Mirage*	1.1 l ha^{-1}
	Fungicide	Folpan*	1.5 l ha^{-1}
	Growth regulator	CCC 720	0.3 l ha^{-1}
	Growth regulator	Moddus	0.15 l ha^{-1}
4	Fungicide	Revytrex*	1.5 l ha^{-1}
5	Fungicide	Traciafin*	0.6 l ha^{-1}
	Fungicide	Soleil*	0.75 l ha^{-1}
Winter Barley			
1	Herbicide	Hersold SC*	0.4 l ha^{-1}
	Herbicide	Lentipur 700*	1.25 l ha^{-1}
2	Insecticide	Karate Zeon*	0.075 l ha^{-1}
3	Fungicide	Kayak*	1.25 l ha^{-1}
	Growth regulator	Prodax	0.5 kg ha^{-1}
4	Fungicide	Revytrex*	1.5 l ha^{-1}
	Fungicide	Comet*	0.5 l ha^{-1}
5	Growth regulator	Composan	0.4 l ha^{-1}

Note: Product with potential for application with greenRelease technology marked with *; Application passage is a passage on the field with tractor and crop sprayer, applying one or multiple pesticides.
Source: Sugar beet: Landwirtschaftlicher Informationsdienst Zuckerrübe (personal communication, 09.10.2020), validated by Thomas Böcker (LWK (Chamber of Agriculture) NRW, personal communication, 28.06.21); winter wheat and winter barley: LWK NRW (2021), validated by Thomas Böcker (LWK NRW, personal communication, 28.06.21); potato: Barbara Mindermann (LWK NRW, personal communication, 19.07.21).

effectivity as the goal is to capture the economic potential of the technology in the range of possible technology characteristics. This also reflects that the true distribution is vastly unknown. Pesticide prices, which interact with the economic potential of the greenRelease technology, are based on price catalogues of suppliers and described in the supplementary material (Appendix A2). In addition, the break-even point of the technology, when using greenRelease does neither increase nor diminish the profit, is estimated. This reflects the sum of costs for greenRelease and for the required quantity of pesticides which equals the costs of the conventional pesticide use per passage.

2.4. *Pesticide load indicator*

The Danish Pesticide Load Indicator is introduced into FarmDyn to assess the potential of the greenRelease technology in reducing environmental and health risks from pesticide use. The Pesticide Load indicator has been developed and implemented in Denmark since 2013 and serves as an official indicator of the Danish government in measuring progress on pesticide risk reduction, as mandated by the EUs National Action Plans on pesticide risk reduction. It further serves as a basis for a risk-adjusted pesticide tax in Denmark and has therefore been intensively tested and validated (see Kudsk et al., 2018 for an overview).

The indicator is computed at the pesticide product level and can be aggregated to a crop, crop rotation, farm or national level. It is an indicator of potential risks (as the application context is not considered) and consists of three major sub-indicators, which are weighted equally – the Human Health Load, the Ecotoxicity Load and the Fate Load:

$$L = L_{Human} + L_{Ecotox} + L_{Fate} \quad (1)$$

The sub-indicators are computed based on active ingredients in the products, their concentration, and properties. Considered properties include potential human health effects based on H- phrases, short-term and chronic ecotoxicity based on eleven median lethal doses/concentrations and No Observed Effect Concentration parameters, as well as fate properties based on half-life in soil, the bioaccumulation factor and mobility and risk of leaching to the groundwater. For a detailed description of considered properties and indicator computation see Kudsk et al. (2018) and Möhring et al. (2021b). Properties of active ingredients are largely based on official EU dossiers for pesticide registration, which are compiled, summarized and continuously updated in the Pesticide Properties Database (Lewis et al., 2016).

We here use the version of the Pesticide Load indicator, with its original load and reference values as it is documented and implemented in the "PesticideLoadIndicator" R-Package (Möhring et al., 2021b; Kudsk et al., 2018; Möhring et al., 2021a) and an updated version of the Pesticide Properties Database from August 2021. Due to its consideration of a broad range of potential pesticide risks, as well as its extensive validation, scalability and transparency, the indicator has previously been used to assess potential risk reduction from changes in technologies, production practices and policies, also outside of Denmark (e.g. Möhring et al., 2019; Böcker et al., 2019a; Böcker et al., 2019b). The detailed values for the Pesticide Load and its sub indicators for all used plant protection products in the case study are provided in the supplementary material (Appendix A6).

3. Results

The results reveal at which costs and effectivity level a profit maximizing farmer adopts the greenRelease technology for a certain crop and product group (Fig. 2). The effectivity of the greenRelease technology is

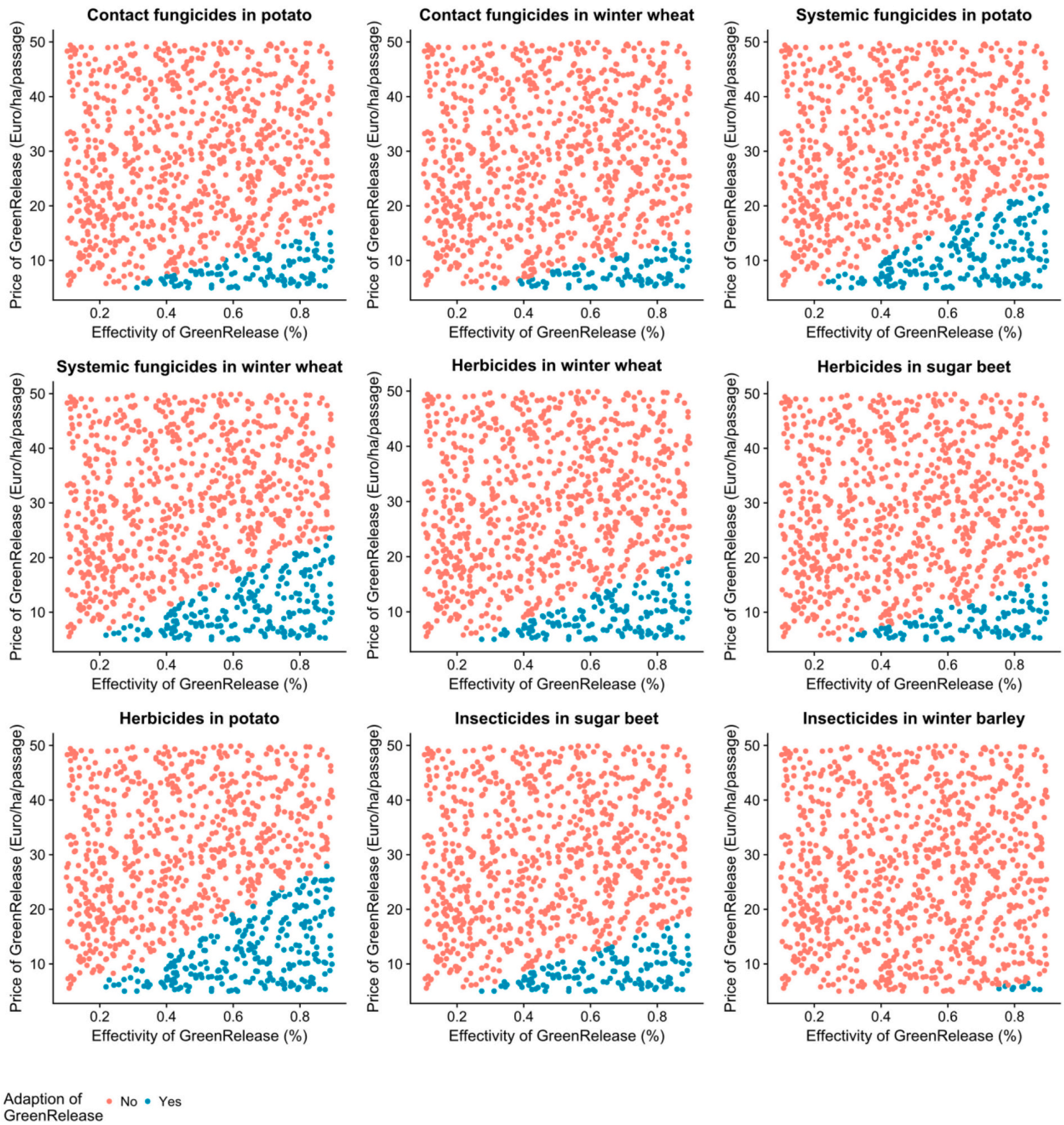

Fig. 2. Adoption of greenRelease technology for different crops in FarmDyn.
Note: The effectivity of greenRelease technology is understood as a reduction in the amount of pesticide applied.

understood as the reduction in the amount of pesticides applied. Adoption requires a cost advantage over the pesticide use without greenRelease. Results are presented by product group and discussed for each crop. In the following, the pesticide reduction and greenRelease prices are presented at which the technology is economically competitive, meaning that the farmer saves costs when using it instead of pesticides without greenRelease. In addition, a break-even point of the technology is estimated where the sum of the prices for greenRelease and for the reduced pesticides equals the costs of the conventional pesticide use per passage.

Contact fungicides are only of relevance in potato and winter wheat cultivation considering the defined typical spraying sequences. Their economic potential is relatively small. When used in potatoes, the greenRelease technology starts to be economically competitive at a reduction of around 30% and can realize a price of maximum 15 Euro ha^{-1} $passage^{-1}$ at a reduction of 90% (Fig. 2). The break-even point for contact fungicides in potato is 18 Euro ha^{-1} $passage^{-1}$. Similarly, in winter wheat, the technology requires a reduction of 30% to become competitive and can realize a maximum price for greenRelease of around 15 Euro ha^{-1} $passage^{-1}$. In this case, the break-even point is 16 Euro ha^{-1} $passage^{-1}$.

Systemic fungicides are applied in the typical spraying sequences of all analyzed crops and are the product group which has the highest economic potential for greenRelease. Furthermore, the potential is similar in all assessed crops (Fig. 2, winter barley and sugar beet in Appendix A7). greenRelease starts to become economically competitive at around 20% pesticide need reduction, with break-even price of around 20 Euro ha^{-1} $passage^{-1}$ at the maximum reduction of 90%. The break-even point for systemic fungicides is 26, 26, 27, and 25 Euro ha^{-1} $passage^{-1}$ for sugar beet, potato, winter wheat, and winter barley, respectively.

Herbicides are applied in potatoes as pre-emergence herbicide and crop desiccation in the typical spraying sequences, being the crop and product group combination with the highest economic potential. Here, greenRelease becomes economically competitive at a reduction of around 15% and prices can reach up to 25 Euro ha^{-1} passage^{-1} at a reduction level of 90%. Herbicide products only active via sprout and root, which are used in potato, are excluded from the greenRelease use. Winter wheat and winter barley show the same economic potential for the greenRelease technology, as the same herbicides and doses are applied (winter barley in Appendix A7). The technology becomes economically competitive at a reduction level around 30% and can be prized up to 20 Euro ha^{-1} passage^{-1} at its maximal assumed effectivity of a 90% reduction. The lowest economic potential is however found for sugar beet. In sugar beet, numerous herbicides are applied in relatively small doses and in three passages. This causes the lowest economic potential in this product group, as the greenRelease costs arise for every pesticide product and passage. Therefore, technology only starts to become economically competitive for herbicides a reduction level of 30%. The maximum assessed reduction of 90% allows prices of up to 15 Euro ha^{-1} passage^{-1} for greenRelease. The break-even point for herbicides is 18, 31, 21, and 21 Euro ha^{-1} passage^{-1} for sugar beet, potato, winter wheat, and winter barley, respectively.

The economic potential of insecticides is relatively small. The products have high prices per kg but variable costs are nevertheless quite low as the applied doses are very small. In potato and sugar beet, the greenRelease technology starts to become economically competitive at a reduction level around 30% and can realize a maximum price of below 20 Euro ha^{-1} passage^{-1} at a 90% reduction level (see Appendix A7 for potato). at the break-even point for insecticides is 18 and 20 Euro ha^{-1} passage^{-1} in potato and sugar beet, respectively. In winter barley, the economic potential is very low, as the technology is only competitive at the minimum price of around 5 Euro ha^{-1} passage^{-1} and a very high effectivity of about 80% reduction. In this case, the break-even point is 8 Euro ha^{-1} passage^{-1}.

To assess the impacts of the greenRelease technology on the cost structure of arable farming, central cost variables are provided for an exemplary greenRelease effectivity of 75% reduction and costs of 10 Euro ha^{-1} (Table 2). The results are only presented for herbicides, contact and systemic fungicides as the most promising product groups. Total costs of the farm are 116,750.90 Euro with 20,254.01 Euro for plant protection products. In relation to one ha, variable costs for plant protection products of 645.74 Euro ha^{-1}, 360.48 Euro ha^{-1}, 179.72 Euro ha^{-1}, and 151.77 Euro ha^{-1} occur for potato, sugar beet, winter wheat and winter barley, respectively. The greenRelease technology in herbicides lowers for instance the variable costs for plant protection products in sugar beet from 360.48 to 306.51 Euro ha^{-1}. Savings from its use with systemic fungicides, being applied in all assessed crops, range from a 3% cost reduction at crop level in sugar beet to a 23% reduction in winter wheat. In relation to the total variable costs, the costs for pest production products only account for 17%. Therefore, the cost reductions realized by the greenRelease technology are small in relation to the total cost burden. Precisely, we find a reduction of total farm variable cost by 1.50% from its application in herbicides, by 2.23% in systemic fungicides, and by 0.31% in contact fungicides.

Table 2
Overview on cost reductions under greenRelease technology for selected product groups, at 75% reduction of active ingredient use and 10 Euro cost for greenRelease per passage

	Baseline	Contact fungicides	Systemic fungicides	Herbicides
Variable costs of farm [Euro]	116,750.90	116,393.05 *-357.85*	114,144.47 *-2606.43*	114,995.24 *−1755.66*
Variable costs for pest products of farm [Euro]	20,254.01	19,896.16 *−357.85*	17,647.58 *-2606.43*	18,498.35 *−1755.66*
Variable costs for pest products – potatoes ha^{-1}[Euro]	645.74	617.55 *-28.19*	557.05 *-88.69*	618.02 *−27.72*
Variable costs for pest products – sugar beet ha^{-1} [Euro]	360.48	-	350.60 *-9.88*	306.51 *−53.97*
Variable costs for pest products – winter wheat ha^{-1} [Euro]	179.72	177.49 *−2.23*	139.09 *−40.63*	167.35 *−12.37*
Variable costs for pest products – winter barley ha^{-1} [Euro]	151.77	–	125.73 *-26.04*	139.41 *−12.36*

Note: Cost reductions compared to baseline are depicted in italic.

Under the current spraying sequence without the use of the greenRelease, potato cultivation has the highest potential environmental and health risks from pesticide use, with a pesticide load of 12.80 ha^{-1}, calculated in accordance with the Danish Pesticide Load Indicator (section 2.4). This is mainly caused by the high number of fungicide application against *Phytophthora* (Fig. 3). In contrast, the pesticide load of 5.97 ha^{-1} in sugar beet is mainly caused by the extensive use of herbicides in three passages while fungicides play a minor role. The spraying sequences of winter wheat and winter barley, having a pesticide load of 7.01 and 4.74 ha^{-1} respectively, are dominated by systemic fungicides, followed by herbicides. Growth and sprout control, which only contributes a larger share of the total pesticide load for winter wheat, is not foreseen for the use with the greenRelease technology.

The pesticide load of systemic fungicides shows the highest reduction potential for the greenRelease technology in potato and the cereal crops caused by their frequent use and their partly high pesticide load. Contact fungicides are only used in potato and winter wheat. In potato, fewer contact fungicide than systemic fungicide applications take place, but the total load is similar as certain contact fungicides have very high load values. Therefore, the reduction potential of the greenRelease technology for contact fungicides is also similar to systemic fungicides in potato. In sugar beet, only one fungicide is applied late in the growing season. It contributes around 15% to the total load such that the load reduction potential for fungicides is small.

In contrast, five different herbicides are applied three times in sugar beet and show the biggest potential for reduction. In potato, only two herbicides are applied in the beginning of the growing season but one having a very high load value. As this product is not active via plant leaf but via root and sprout, it is not applicable for the greenRelease technology at its current development stage. The reduction potential for herbicides in potatoes is therefore small for the typical spraying sequences. In winter wheat and winter barley, the same herbicides are applied and contribute 19% and 28%, respectively, of the total load. The load reduction potential is smaller than for fungicides in cereals but higher than for insecticides. The latter show in all crops only small contributions to the total pesticide load. This is caused by the very small doses and the low numbers of applications ranging from zero in winter wheat to two in sugar beet and potato. Hence, also the reduction potential for the greenRelease technology is low in relation to the total load of the spraying sequences. Comparing the total pesticide loads of different product groups across crops, the highest potential to lower the load is found in systemic and contact fungicides in potatoes and herbicides in sugar beet.

If greenRelease is applied simultaneously in all assessed product groups, the pesticide load reduction for a 10% to 90% effectivity is as follows: For potato, the pesticide load decreases from 12.80 ha^{-1} to the range of 11.83 to 4.06 ha^{-1}; for sugar beet, the pesticide load decreases from 5.97 ha^{-1} to the range of 5.37 to 0.60 ha^{-1}; for winter wheat, the pesticide load decreases from 7.01 ha^{-1} to the range of 6.41 to 1.56 ha^{-1}; for winter barley, the pesticide load decreases from 4.74 ha^{-1} to the range of 4.30 to 0.75 ha^{-1}.

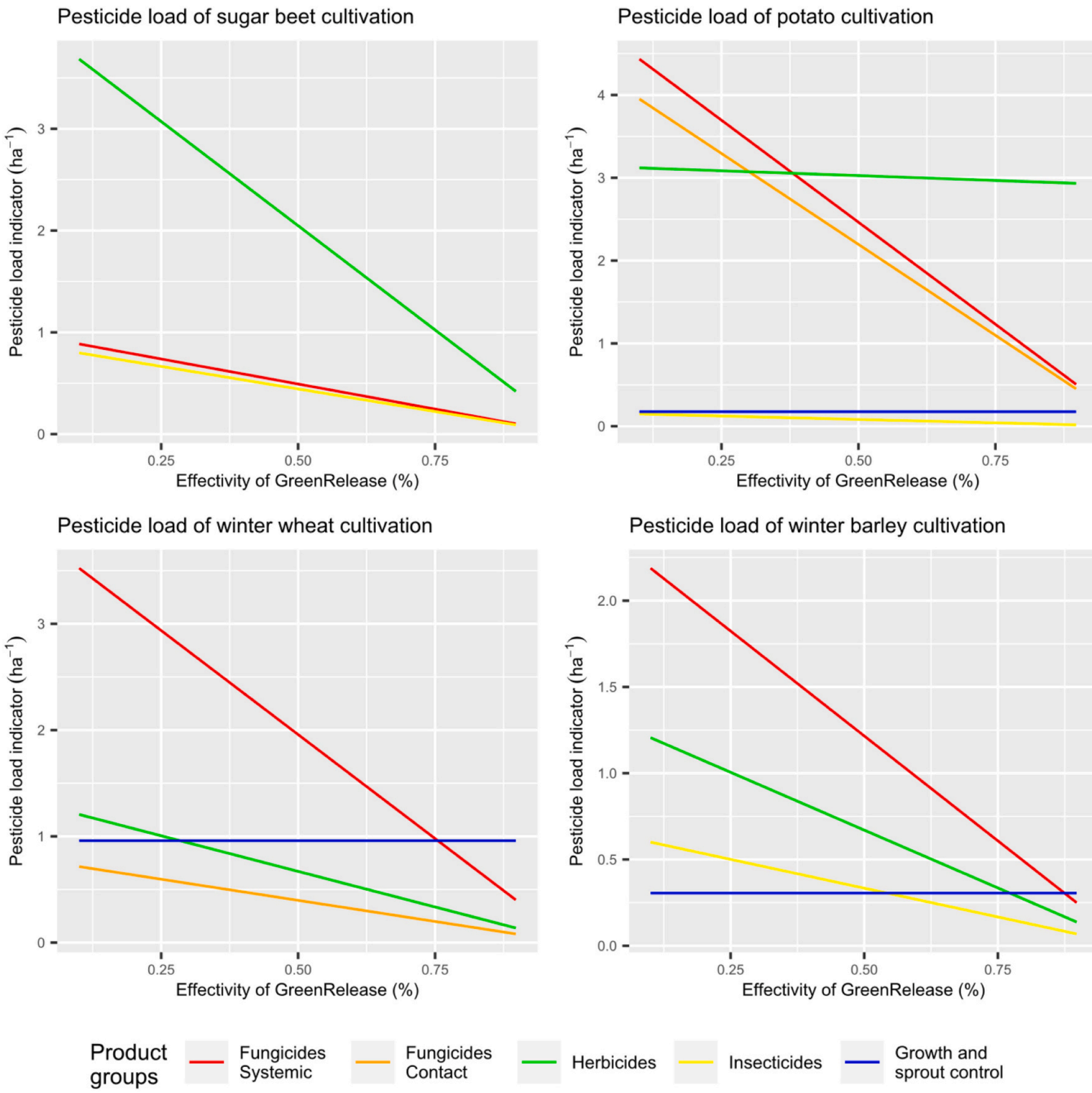

Fig. 3. Pesticide load indicator of different product groups in sugar beet, potato, winter wheat, and winter barley cultivation under varying greenRelease reduction levels.

4. Discussion

The analysis provides costs and effectivities at which the greenRelease technology is economically competitive to the current standard spraying sequence. The break-even points, when the prices for the technology and the required pesticides equals the costs the conventional pesticide use, range from 8 to 31 Euro ha^{-1} $passage^{-1}$. Systemic fungicides are applied in all crops and show a high and similar economic potential. Furthermore, systemic fungicides contribute the largest share to the total pesticide load of potato, winter wheat and winter barley. From an economic as well as environmental point of view, further technology development should thus focus on optimizing the greenRelease technology for its usage with systemic fungicides. Herbicides in potato show the highest economic potential but their use plays a minor role in the spraying sequence compared to fungicides. In addition, the reduction potential related to the environmental and health risk is low as the load of the applied herbicides is relatively small. Furthermore, part of the herbicides in potato are active only via sprout and root and, therefore, currently not applicable for the greenRelease technology.

The economic potential and risk reduction potential align well for systemic fungicides, which show the largest economic potential and a high reduction potential of the environmental and health risk according to the pesticide load indicator. This is not true for herbicides in potato, which are characterized by a large economic potential but only a minor reduction in the pesticide load. However, the reduction potential of the load has to be judged in relation to the overall crop shares. The pesticide load of total wheat production in the Rheinische Revier is for example 160,837, a use of greenRelease in all product groups and a 50% effectivity causes a reduction of 69.520. For potato, with by far the highest pesticide load at crop level, the regional reduction potential is 27,221, caused by its lower crop share (see Appendix A1 for calculation). Hence, a focus of the greenRelease technology on winter wheat as the most present crop has the higher potential for an overall reduction of the environmental burden of pesticide use.

This is of special importance in the light of policies related to pesticide reduction targets, as for example reflected in the 50% pesticide use reduction goal of the EU commissions' Green Deal (European Commission, 2020). Although monitoring the effect of pesticide policies in EU member states is difficult, evidence suggest an insufficient decline of pesticide risks as argued by Möhring et al. (2020) and the need for further reduction efforts. Policy makers can, on the one hand, promote technologies such as greenRelease with funds for research and development, information for farmers, or subsidies. On the other hand, instruments which aim at internalizing the negative externalities of pesticide use cause pesticide costs to rise and, thereby, increase the economic competitiveness of pesticide reducing technologies. An example for such an instrument is the risk-based tax on pesticides being in place in Denmark (Kudsk et al., 2018). For the current German legal framework, our study thus illustrates that market entry of an innovative technology such as greenRelease, despite a high potential for reducing pesticide application amounts, risks and run-off, requires a low production price. Even if policy aims at reduced pesticide use, there are no mandatory reduction measures or risk-based taxation in place. Such instruments would favor technologies such as greenRelase. Alternatively, their use could be subsidized. In the current situation with the externalization of negative impacts of pesticide use, the additional or saved costs induced by greenRelease are small compared to overall variable costs. We argue therefore that the environmental benefits of the technology need to be in the center when promoting the technology to investors and farmers. However, the validation of field trials should also cover a possible reduction of passages, not considered here, due to the better adherence of pesticides to the plant leaf. This is especially relevant for fungicides use against *Phytophthora* in potato with very short intervals between passages. A reduced number of passages, especially in parts of the growing season with work peaks, can reduce labor costs and workload of farmers and, thereby, increase the benefits of greenRelease.

However, this study allows to identify the product groups and crops with a higher economic potential which allows the technology to enter the market at a higher price. This is especially relevant at its early introduction when production costs are likely to be higher and scale effects are not realized yet. When excluding herbicides in potato and insecticides in winter barley as outliers, the break-even points range between 16 and 27 Euro ha^{-1} $passage^{-1}$ and are hence relatively similar between crop and product combinations. Therefore, decisions on the further development of the technology should also reflect possible cost differences for developing the microgel container and anchor peptides for specific crop and pesticide combinations, not being part of the study at hand. This also needs to cover sunk costs as the technology has been already successfully tested for copper as a contact fungicide in first field trials (N.A., 2021b). For new product and crop combinations, experiments under controlled conditions are needed to prove the benefit of greenRelease and avoid unwanted consequences. If successful, follow-up field experiments provide better estimates for the possible pesticide reduction. Jointly with our results, this allows to judge the economic potential of the technology and the pesticide use reduction precisely.

The results are of interest beyond the Rheinische Revier as there are no regional technology modifications needed, the assessed crops are of high importance in Germany and beyond, and similar agronomic conditions are found in other regions. Finally, the treatment index of the considered pesticide use is generally comparable with German averages (JKI, 2022, Appendix A8). Besides different soil and climate conditions, heterogeneity of pesticide use can be amongst other caused by risk behavior, and interaction with further agronomic decisions such as soil cultivation. In the Rheinische Revier, the herbicide use seems to be lower than national averages, while fungicide use in cereal and potatoes as well as insecticide use in sugar beet are higher (Appendix A8). This is linked to differences in regional pest pressure, amongst others caused by wetter conditions than in other parts of Germany. But it also reflects the high yield potential and intensive cultivation in our example region. This does not influence the transferability of the estimates of the economic potential or the break-even points. However, the impact of the technology on the overall costs as well as the total pesticide load reduction might slightly change for the assessed crops in other regions. If more precise estimations of the economic potential of the greenRelease technology is needed in the future, spraying sequences of a larger farm sample and for multiple years should be assessed. Furthermore, additional crops such as rape seed could be included, which may return a different prioritization of pesticide product groups. The legally required documentation of the applied pesticides, often part of digital farm management tools, is the obvious source for a follow-up study. However, data protection and other aspects hinder access to such data for researchers (Mesnage et al., 2021) while surveys are at large danger of selection bias and strategic answers. In addition, only past pesticide use can be accessed, which encompasses products where market admission may expire. This renders an ex-ante technology assessment, as needed to guide the greenRelease development, challenging.

Complexity, compatibility, and trialability as perceived technology attributes are part of theory on technology adoption (Rogers, 1983) and found to influence adoption decisions in empirical research (Shang et al., 2021). The strength of greenRelease is that the technology can be simply used in existing spraying sequences and does not require larger changes in the farm management. However, adopting the microgel containers to specific crop-product combinations and their validation in field trials is time consuming and costly. Accordingly, only a limited number of pesticides with greenRelease will be developed towards market readiness in the near future. The field validation and communication of the technology should also cover that a product available with greenRelease potentially replaces numerous other pesticides which are not yet available with the technology. In practice, this requires farmers to largely change their spraying sequence. Thereby, the potential use of greenRelease by farmers is increased, but at the expense of more complex farm management changes.

The model FarmDyn assumes a rational, fully informed and profit maximizing farmer. In the model, the decision to adopt the greenRelease technology is solely driven by its costs compared to the ones of current plant protection strategies. However, the adoption and diffusion of technologies are determined by complex behavioral factors (see Dessart et al. (2019) for an overview) and go beyond standard economic assumptions. The results should therefore be understood as the quantification of the economic potential of the technology which influences the adoption and not as a projection of complex adoption decisions.

Finally, the study shows the potential of using bio-economic farm models for the early phase of technology development. Scenarios or sensitivity analysis can contribute valuable insights on economic and environmental implications, even if precise technology characteristics are still largely unknown. In the case of the greenRelease technology, the results indicate the most promising combinations of pesticides groups and crops for technology development from an economic and environmental point of view. However, the study at hand does not fully use the potential of such models as the decision variables are restricted to the technology adoption. Future research could capture complex shifts in labor allocation and cropping activities as well as better account for farm heterogeneity by using a larger farm sample. In the context of future digitalization and automation of farming, modeling adoption decisions can guide further technology development and evaluation. In later stages of market introduction, farm models as part of decision support systems (e.g. Pahmeyer et al., 2021) can help farmers and advisors to select optimal levels of technology adoption.

5. Conclusion

The aim of this study is the assessment of the economic potential and environmental benefit of the greenRelease technology at farm-level to inform further technology development. We find that the economic potential is highest for systemic fungicides in all assessed crops and herbicides in potato cultivation. The former also show a great potential for reducing environmental and health risk, at crop as well as landscape level, and should be the focus of the further technology development. The costs of greenRelease use are low compared to the overall costs of arable farming, making environmental and health benefits key in promoting the technology. In addition, the study illustrates the challenge for new and environmentally friendly technologies to be economically competitive when existing practices do not internalize negative environmental impacts and are thus relatively low priced. This contradicts current policy efforts to lower pesticide use and risk. Policy maker can support the technology development and uptake by research funding, information, and subsidies. In addition, policy measures which restrict the use or increase the costs of pesticides foster the competitiveness of environmentally friendly technologies such as greenRelease.

CRediT authorship contribution statement

T. Kuhn: Conceptualization, Methodology, Investigation, Software, Validation, Writing – original draft. **N. Möhring:** Methodology, Software, Validation, Writing – original draft, Writing – review & editing. **A. Töpel:** Writing – review & editing. **F. Jakob:** Writing – review & editing, Project administration, Funding acquisition. **W. Britz:** Writing – review & editing, Methodology, Supervision, Project administration, Funding acquisition. **S. Bröring:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **A. Pich:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **U. Schwaneberg:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **M. Wustmans:** Conceptualization, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Felix Jakob has patent #EP3261435A1 issued to Assignee. Andrij Pich has patent #EP3261435A1 issued to Assignee. Ulrich Schwaneberg has patent #EP3261435A1 issued to Assignee.

Acknowledgements

This research was done within the Bioeconomy Science Center (BioSC) FocusLabs “Transform2Bio” and “greenRelease”. The scientific activities of the BioSC were financially supported by the Ministry of Culture and Science within the framework of the NRW Strategieprojekt BioSc (No. 313/323-400-00213). The authors thank Dr. Thomas Böcker (LWK NRW) for the support on defining the plant protection strategies.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2022.103454.

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