Agricultural Systems 220 (2024) 104101

Contents lists available at ScienceDirect

Agricultural Systems

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

How does pesticide reduction affect labour time and profitability? A crop production case study

Manika Rödiger [a,*], Alexander Zorn [a], Michael Mielewczik [a], Katja Heitkämper [a], Andreas Roesch [b], Nadja El Benni [a]

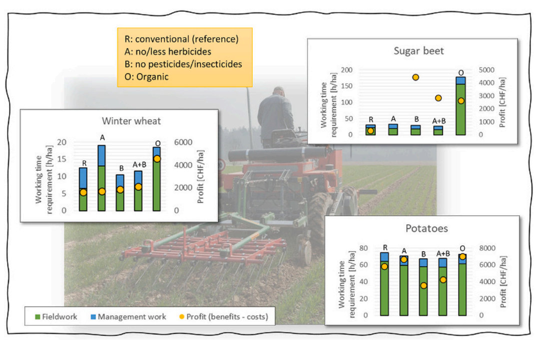
[a] *Agroscope, Sustainability Assessment and Agricultural Management, Tänikon, 8356 Ettenhausen, Switzerland*
[b] *Agroscope, Sustainability Assessment and Agricultural Management, Reckenholzstrasse 191, 8046 Zürich, Switzerland*

HIGHLIGHTS

- Reducing pesticides in crop production can lead to changes in working time requirement and profitability.
- Four pesticide-reduced production schemes were analysed regarding working time requirement and profitability.
- The complete fieldwork and management work were modelled for winter wheat, sugar beet and potatoes.
- For sugar beet and winter wheat, reducing insecticides, fungicides and growth regulators seems beneficial.
- For potatoes, reducing herbicides and organic production seem beneficial, if direct payments are considered.

GRAPHICAL ABSTRACT

Profitability and working time requirements for fieldwork and management work for winter wheat, sugar beet and potatoes produced under five different production schemes.



ARTICLE INFO

Editor: Emma Stephens

Keywords:
Herbicide reduction
Pesticide reduction
Plant protection
Working time requirement
Cost-benefit analysis

ABSTRACT

CONTEXT: National and international agendas are focusing on reducing pesticides due to their detrimental effects on flora, fauna, and human health, which has led to the introduction of agri-environmental programmes aimed at reducing the risk of pesticides. Pesticide reduction in agriculture can have an impact on labour time requirements and profitability.
OBJECTIVE: We used winter wheat, sugar beet, and potatoes as examples to analyse the changes in profitability and working time requirements, including management tasks.
METHODS: For the calculations, we used five different production schemes for each crop: reference; (A) reduction of herbicides; (B) reduction of growth regulators, fungicides, and insecticides; combination of schemes (A) and (B); and organic production. The working time requirements for fieldwork and farm management work were modelled for each scheme and crop. The respective partial costs and benefits of the schemes were calculated for each crop.
RESULTS AND CONCLUSIONS: Based on the model assumptions, scheme (B) appears favourable in terms of working time requirements, and profitability of winter wheat and sugar beet. Scheme (A) offers synergies between the same parameters for potato production. Economic analysis shows that crop production with reduced

* Corresponding author.
E-mail address: manika.roediger@agroscope.admin.ch (M. Rödiger).

https://doi.org/10.1016/j.agsy.2024.104101
Received 12 March 2024; Received in revised form 22 June 2024; Accepted 15 August 2024
Available online 23 August 2024

pesticide use may even experience an increase in financial viability if the yield is not severely jeopardised, and farmers can be compensated through premiums and direct payments.
SIGNIFICANCE: Our results can support policy-making, since the labour time requirement and profitability of pesticide-reduced crop production can affect the success of voluntary agri-environmental programmes for the reduction of the risks from pesticide use in agriculture.

1. Introduction

The consideration of pesticide reduction on national and international political agendas declares the societal aim of environmental preservation and the avoidance of detrimental outcomes regarding human health (Alavanja and Bonner, 2012; Geiger et al., 2010; Hallmann et al., 2014; Stehle and Schulz, 2015). However, a reduction of pesticides in crop farming requires the adaptation of production procedures to counter the potential detrimental effects of weeds and plant pests on crop growth and, ultimately, yield. Plant protection and weed control can include the spraying of plant protection products and herbicides, as well as the mechanical weeding by machines or by hand. There are also possibilities to combat plant pests with natural antagonists. Strategies to minimize pest and weed pressure are also deeply embedded in general long-term cultivation strategies, including crop rotation. Reducing the amount of pesticides and herbicides at a given pest and weed pressure, though, makes it necessary to increase the effort to avoid yield reduction by other efforts, such as the choice of more robust varieties or more mechanical weeding.

The adaptation of the production can lead to different tasks in fieldwork and management work and thereby lead to altered labour times. More labour-intensive production impacts the costs and revenues of crop production (Beckmann and Wesseler, 2003 for integrated pest management). Moreover, the effects on the yield and the gains from agri-environmental payment schemes (e.g. FOAG (Federal Office of Agriculture), 2023) but also from label price premiums may change the economic result of production.

The evidence on how the reduction of pesticides affects the working times required for crop production is inconclusive (Duval et al., 2021 for agroecological farming). Colnenne-David et al. (2023), Busenkell and Berg (2006), and Mack et al. (2023, for root crops and oil seeds) found evidence of an increase in working times, whereas Lechenet et al. (2014) did not find a relationship between pesticide use and labour time. Lundqvist (2000) found that producing organically instead of conventionally increased the workload since weed control required more work. But as Maas et al. (2000) pointed out, there are different findings regarding the effect of organic farming on the working time.

The mentioned studies differed in their approaches. Nonetheless, it can be noted that these studies have either focused on fieldwork and neglected management work, or have reported the sum of working time for all farming activities, or have not at all quantitatively reported the working time required. A detailed and complete view of the effect of pesticide reduction on each task in crop cultivation is, to our knowledge, missing so far.

Regarding the economic impact of pesticide reduction, findings from the literature are conclusive regarding the decreasing costs of synthetic pesticides and fertilisers (Busenkell and Berg, 2006; Lechenet et al., 2014; Rajmis et al., 2022). Busenkell and Berg (2006) found that while marginal return could be slightly reduced on one farm, another farm experienced hardly any difference in marginal return. Rajmis et al. (2022) reported an increase in gross margin from a pesticide reduction through precision agriculture compared to conventional agriculture. Lechenet et al. (2014) concluded from their results that low pesticide use does not necessarily lead to lower economic returns but could even result in an increase in profitability. Further, Mack et al. (2023) results indicated that the average farm income of arable crop farms would increase due to direct payments compensating for yield losses. From a sustainability assessment comparing conventional production with two integrated production techniques differing in strictness on different experimental sites with wheat and maize (Vasileiadis et al., 2017), we resume that the economic sustainability decreases for most sites from the conventional to the strict integrated production sites. Cavan et al. (2023) reported assessments of alternative weed management systems and reported that the economic sustainability increased in only one of three scenarios, while it seems that economic sustainability did not decrease in the other two scenarios, while all scenarios decreased herbicide use. We presume that while costs for pesticides decrease, costs for labour and machinery might increase, with the magnitudes depending on the crop type. Direct payments compensating for yield losses and label or quality premiums can uphold the profitability of crop farming without pesticides.

To gain more insights into the direction and magnitude of the changes resulting from pesticide reduction, we analysed the differences in working time requirement (WTR) for field and management work and outcomes in profitability of four pesticide-reduced production schemes in detail. This paper addresses the following question: What is the effect of a reduced use of pesticides and herbicides with accordingly modified production and management procedures on (i) the WTR for crop cultivation and management and (ii) profitability?

The aim of the present study was to quantify the differences in WTR and profitability between conventional and pesticide-reduced production schemes. The paper contributes to the existing literature by providing a detailed analysis of the effect of pesticide reduction on the WTR, including all tasks in crop production, by analysing the effect on the WTR for management tasks and by further investigating the effects on the profitability of the production. To our knowledge, this study is the first to explicitly include management work related to the production of the respective crops in pesticide reduction analyses quantitatively.

The remainder of the paper provides the reader with a background on the study case, that is, the geographical scope, the specific agri-environmental schemes, and the crops in Section 2, and a description of the data, method, and modelling tools in Section 3. In Section 4, the results on the WTR for fieldwork and management work and on profitability for each crop and agri-environmental scheme are reported and discussed. The paper ends with the conclusions in Section 6.

2. Background

Our case study focuses on Switzerland, which is an interesting case to study due to its already high agri-environmental standards and its ambitious agri-environmental goals, with several failed attempts to further transform the agricultural system (Mann and Kaiser, 2023; Forney, 2016). In, 2017, the Swiss Parliament launched a national strategy to decrease the risk of pesticide use in Swiss agriculture (BR (Bundesrat der Schweizerischen Eidgenossenschaft), 2017). To support the success of the national strategy, direct payments are granted to farmers for the reduced use of herbicides and other pesticides (FOAG (Federal Office of Agriculture), 2022b). In our study, we compared the two agri-environmental schemes, as well as a combination of both, to the Proof of Ecological Performance (PEP) and to organic production. The Proof of Ecological Performance (cross-compliance) is a precondition for the receipt of direct payments by these farms (Jarrett and Moeser, 2013; Forney, 2016). The requirements for each production scheme are as follows:

PEP (reference scheme): Regarding pesticide use, the requirements for PEP include restrictions on pre-emergence herbicides, granules, and insecticides, and it requires the consideration of damage thresholds and weather forecasts as well as untreated control windows for growth regulators in cereals, fungicides in canola, and special permits (FOAG (Federal Office of Agriculture), 2023).

(A): Voluntary direct payment programme to avoid or reduce the use of herbicides, to treat only single plants, or to treat only in the rows so that a maximum 50% of the area is sprayed. For sugar beet, farmers also have the possibility to spray on the whole plot from seeding until the sugar beet plants have four leaves but not afterwards (Agridea, 2022b; FOAG (Federal Office of Agriculture), 2022b). Extra direct payments are 250 Swiss Francs (CHF) per hectare for winter wheat and sugar beet, and 600 CHF for potatoes.

(B): Voluntary direct payment programme to avoid the use of growth regulators, fungicides, and insecticides. Exemptions: certain molluscicides, seed dressing, laminarin-based products, *Bacillus thuringiensis*, and fungicides in potato cultivation (Agridea, 2022b; FOAG (Federal Office of Agriculture), 2022b). Extra direct payments are 400 CHF per hectare for winter wheat, 800 CHF for potatoes, and 1000 CHF for sugar beet.

(A) + (B): Combination of the voluntary direct payment programs (A) and (B)

Organic: No chemical-synthetic plant protection products. However, there is a defined list of mechanical and biotechnical measures that can be applied in organic production, such as copper, bacteria, or fatty acids (Bio Suisse, 2023). Extra direct payments are 1200 CHF per hectare + (A) + (B) (wheat: 1850 CHF per hectare, potatoes: 2600 CHF per hectare, sugar beets: 2450 CHF per hectare).

For the specific amount of pesticide interventions, see Table 1 and Supplementary Tables 3, 4 and 5.

To analyse the effect of a reduction of pesticides on WTR and profitability, we used the example of winter wheat, sugar beet, and potato. These three crops cover a relevant share of the total production area of arable cropping in Switzerland (FOAG (Federal Office of Agriculture), 2022a). In addition, these three crops have the potential to reduce pesticide and herbicide use on a national level. From 2009 to 2018, the highest shares of herbicides, relative to the cultivated area of the crops (without considering the toxicity of the pesticides), were used in sugar beet, maize, and cultivated grasslands (de Baan et al., 2020). Fungicides were mostly used in potatoes and winter wheat, relative to the cultivated area. The major share of insecticides was used in potatoes, again relative to the cultivated area (de Baan et al., 2020). With the choice of winter wheat, sugar beet and potatoes we also wanted to include crops that vary in the required working time for production since pesticide reduction effects different crops differently regarding required labour times (Mack et al., 2023). Other crops, such as maize or rape seed would have been interesting as examples es well, however, we had to limit the choice due to time constraints.

3. Materials and methods

We used a mixed methods approach, triangulating the modelling of WTR and the calculation of profitability with expert workshops and information from the literature.

3.1. Modelling working time requirements

The work on the farm can be categorised into fieldwork, special work, and management work. Typical fieldwork operations are soil preparation, fertilisation, and harvest (Achilles et al., 2018; Bochtis et al., 2019; Schick, 2008). Special work involves repairs or maintenance tasks that are not frequently performed (Moriz, 2007a). Management

Table 1

Differences between production schemes for winter wheat, sugar beet and potato fieldwork. The remaining production tasks are the same for all schemes.

Winter wheat			
Production scheme	Soil preparation	Fertilisation	Pest and weed control
PEP	Chisle, 1 pass	Mineral fertilizer spreader, 3 passes	Sprayer (chemical product), 2 passes
(A)	Plough, 1 pass		Sprayer (chemical product), 1 pass; weeder, 2 passes; manual weeding 5 h ha^{-1}
(B)	Chisle, 1 pass	Mineral fertilizer spreader, 2 passes	Sprayer (chemical product), 1 pass
(A) + (B)	Plough, 1 pass		Weeder, 2 passes
Organic	Plough, 1 pass	Slurry, 1 pass	Weeder 2 passes; manual weeding 8 h ha^{-1}

Sugar beet			
Production scheme	Seedbed preparation	Fertilisation	Pest and weed control
PEP	Power harrow, 1 pass	Mineral fertilizer spreader, 3 passes	Sprayer (chemical product), West 8 passes, East 6 passes
(A)			Band spraying, West 8 passes, East 6 passes
(B)			Sprayer (chemical product), 3 passes
(A) + (B)			Band spraying, 2 passes
Organic	Toothed harrow, 2 passes; power harrow, 1 pass	On intercrop: Slurry, 1 pass; dung, 1 pass	Finger hoe, 3 passes; manual weeding East 180 h ha^{-1}/ West 100 h ha^{-1}

Potatoes				
Production scheme	Seedbed preparation	Planting	Fertilisation	Pest and weed control and haulm stripping
PEP	Power harrow, 2 passes	Automatic potato planter, 1 pass	Mineral fertilizer spreader, 2 passes	Sprayer (chemical product), 13 passes; Row hoe, 2 passes; Slug pellet spreader, 1 pass
(A)				Sprayer (chemical product), 8 passes; Band spraying, 1 pass; Row hoe, 3 passes; Weeder, 2 passes; Slug pellet spreader, 1 pass
(B)				Sprayer (chemical product), 10 passes; Row hoe, 3 passes; Slug pellet spreader, 1 pass
(A) + (B)				Sprayer (chemical product), 8 passes; Band spraying, 1 pass; Row hoe, 3 passes; Weeder, 2 passes; Slug pellet spreader, 1 pass
Organic	Power harrow, 1 pass	Automatic potato planter combined with K fertilisation, 1 pass	On intercrop: Slurry, 1 pass; dung, 1 pass	Sprayer (biological product), 6 passes; Weeder, 2 passes; Combined hoe and dam shaper, 2 passes; flaming haulm, 1 pass

Band spraying: Spraying in rows, hoeing between rows.

work are tasks to lead, administer and control the farm, for example, accounting, making sales contracts, and filling out payment application forms (Moriz, 2007b). A full list of operations that were categorised into fieldwork, management work, and special works can be found in the Supplementary Tables 1 and 2.

The calculation of WTR for the fieldwork of the three selected crops and the respective production schemes was performed with the "PROOF" Model Calculation System (Riegel and Schick, 2005, Schick, 2008 for further description of the model), which was also used by Heitkämper et al. (2023). For model assumptions other than specified in Table 1, we refer to the Supplementary Tables 3 to 11, and to Supplementary fig. 1. The model output is the working time requirement in hours per hectare per growing season for the respective crop. The system boundaries were set at the farmgate, which means that preparation tasks, such as mounting the hoe to the tractor and travel times to and from the field, were considered in the model.

To calculate WTR for farm management work, such as the planning of labour and machinery, making plot lists, or filling out application forms, we used the model set "OffWo" for arable farming (Moriz, 2007a, 2007b; Moriz and Mink, 2010). Main inputs to the model are the annual frequency of operations. The annual frequency of the tasks listed in Table 2 was determined in expert workshops. Further management tasks in the model were also adapted: planning of fertilisation and chemical plant protection, storage control for fertilisers, nutrient balance, acquisition of fertilisers, and plot lists (see Supplementary Table 2). The output of the model is the total WTR for the management tasks and the WTR per hectare. For a further description of the model see Moriz (2007a, 2007b), Moriz and Mink (2010) and the Supplementary figs. 2 and 3, and the Supplementary Tables 12 to 18.

3.2. Production schemes

Based on three expert workshops, the production schemes described in Table 1 were selected and found to represent a Swiss farm. For winter wheat, pesticide reduction was assumed to affect soil preparation, fertilisation, weed control, and chemical plant protection. The seedbed preparation, seeding, and harvest were kept constant among all production schemes. For sugar beet, the four analysed pesticide reduction schemes were assumed to differ for seedbed preparation, fertilisation and weed and pest control from PEP, whereas soil preparation and seeding remained the same in all schemes. In Organic, a false seedbed was assumed to stimulate weeds to germinate, and fertilisation on the intercrop was included, since no fertilisation was assumed during crop growth. In potato production, the production schemes (A), (B) and (A) + (B) were assumed to differ from PEP in the work procedures chemical plant protection, and mechanical weed control. Organic additionally differs in seedbed preparation, fertilisation, planting, and flaming of potato haulm. Again, in Organic, fertilisation on the intercrop was assumed.

For management tasks, less storage and field controls for the schemes with a reduced use of pesticides compared to the reference scheme PEP were assumed to be necessary (see Table 2). Moreover, less record keeping was assumed with a reduced use of pesticides, except for Organic winter wheat and potatoes. In addition, less consultancy was assumed to be necessary if the use of pesticides was forbidden in a scheme. Pesticide acquisition was assumed not necessary for Organic winter wheat and sugar beet. Application form filling was assumed to be the same for all schemes in sugar beet, since sales contracts are made in advance independent of the production scheme. However, the Organic production of winter wheat and potatoes was assumed to require the filling of applications for the Organic label in addition to the direct payment applications.

3.3. Calculation of required working time

We derived data for winter wheat, sugar beet, and potatoes on (i) the number of farms that cultivated the crop, (ii) the total cultivated area of the crop per farm, and (iii) the number of plots of the crop per farm from the Swiss Agricultural Policy Information System (APIS), which contains information on almost all agricultural holdings in Switzerland and provides information at the plot level. We used the dataset of the farming year, 2017. As crop cultivation predominantly takes place in the plain region, we restricted the analysis to farms allocated in the plain region. Further, we ignored very small plots of less than 0.01 ha. Supplementary Table 6 provides the descriptive analysis, including the shares of farms that had 1, 2, 3 or 4 plots of the respective crop. For example, 49.21% of the farms that grew winter wheat had one plot of winter wheat with on average 3.1 ha in size (see Supplementary Table 6). The shares served as weighting coefficients for calculating the average of the WTR for fieldwork and management work for farms with 1 to 4 plots.

$$\text{For winter wheat}: \text{WTR\_av} = 0.4921^{*}\text{WTR}_1 + 0.2523^{*}\text{WTR}_2 + 0.1519^{*}\text{WTR}_3 + 0.1037^{*}\text{WTR}_4$$

$$\text{For sugar beet}: \text{WTR\_av} = 0.5557^{*}\text{WTR}_1 + 0.2726^{*}\text{WTR}_2 + 0.1231^{*}\text{WTR}_3 + 0.0486^{*}\text{WTR}_4$$

$$\text{For potato}: \text{WTR\_av} = 0.6966^{*}\text{WTR}_1 + 0.1920^{*}\text{WTR}_2 + 0.0741^{*}\text{WTR}_3 + 0.0372^{*}\text{WTR}_4$$

The abbreviation WTR_av stands for average working time requirements, WTR with subscripts 1 to 4 being the working time requirements for 1 to 4 plots with corresponding sizes. The equation was used for calculating fieldwork WTR and management WTR.

3.4. Data and methods for economic analysis

The method used for assessing profitability is a cost–benefit analysis

Table 2
Annual frequency of management tasks related to plant protection for five production schemes (Proof of Ecological Performance (PEP), herbicide-free/herbicide-reduced (A), without growth regulators insecticides and fungicides (except for potatoes) (B), a combination of (A) and (B), and Organic).

Task	Winter wheat					Sugar beet					Potato				
	PEP	*(A)*	*(B)*	*(A) + (B)*	*Organic*	*PEP*	*(A)*	*(B)*	*(A) + (B)*	*Organic*	*PEP*	*(A)*	*(B)*	*(A) + (B)*	*Organic*
Field controls	5	4	2	2	2	8	7	5	3	3	12	13	9	9	8
Storage controls pesticides	1	1	1	0	0	1	1	1	1	0	1	1	1	1	1
Record keeping	4	3	1	1	5	6	5	3	3	3	12	11	8	8	10
Application form filling	1	1	1	1	2	1	1	1	1	1	1	1	1	1	2
Consultancy	3	3	1	0	0	3	3	1	2	1	3	3	1	2	1
Purchases pesticides	2	2	1	0	0	West: 1 East: 2	West: 1 East: 2	1	1	0	3	3	3	3	1

(partial costing). In a comparison of production processes that only took into account the positions affected by the adapted production scheme, the profitability (net total after deducting the costs of production from the benefits) of the considered variants was analysed. Changes in cropping practices can have both positive and negative effects on the cost of the production process and the benefits that can be achieved.

A change in cropping strategy primarily affects the costs of inputs, for example, reduced use of pesticides or other chemicals, machinery costs, and labour costs. The underlying work processes were determined during the expert workshops. Information on the prices of the operating resources was obtained from farm management data collections (Agridea, 2022a; Agridea, 2023a). Machine cost data were taken from the cost catalogue (Gazzarin et al., 2022). The methodology used to calculate machine costs is documented in Gazzarin and Lips (2018). This approach includes the allocation of fixed costs and therefore also covers possible investment in new machinery.

Revenues are determined by crop yields, crop prices, and direct payments related to the production process. In terms of yield, changes in quantity, such as reduced yield due to the non-use of pesticides, and quality, such as deductions or label premiums for no use of pesticides, are possible. To calculate revenues, yields were valued using current Swiss prices and quality premiums (Agridea, 2022b; Agridea, 2023b). Furthermore, the specific direct payments for the agri-environmental schemes, as described in Section 2, were considered (Agridea, 2023a; Mack et al., 2023). These direct payments are intended to compensate for the additional costs or lower yields resulting from the reduced use of pesticides.

Furthermore, we calculated how high the yield must be in an alternative scheme to achieve the economic results of the PEP reference process. In what follows, we use the term parity yield for this hypothetical yield. If an alternative production scheme achieves lower (higher) economic efficiency, the yield must increase (decrease) ceteris paribus to reach the level of the reference scheme PEP.

4. Results and discussion

Reducing the use of pesticides in arable farming affects various costs and performance items (Heinrichs et al., 2021). Likely because of the different methodologies used, we find discrepancies between our results and results in the literature, which suggested that the reduction of pesticides would probably lead to an increase in fieldwork labour requirements, even though the magnitude might be small (Busenkell and Berg, 2006; Colnenne-David et al., 2023; Mack et al., 2023; Pimentel et al., 2005).

4.1. Effects of pesticide reduction on working time requirement

Potatoes required the highest total WTR_av of the analysed crops across all schemes, except for Organic sugar beet. The lowest WTR_av was found for winter wheat. Our analysis shows that the magnitude in change of total WTR_av between production schemes clearly varied between crops, confirming the results of Mack et al. (2023).

Comparing between schemes over all crops, Organic production had the highest fieldwork WTR_av, except for potatoes. The low management WTR_av for Organic for all three crops compensated for some but not all additional fieldwork, so that Organic had the highest total WTR_av for winter wheat and sugar beet. This is in contrast to the findings of Heinrichs et al. (2021), which reported that labor requirements are often lower for organic crop production compared to conventional. If no manual weed control was required, the reduction of pesticides usually resulted in a lower WTR_av. Scheme (B) led to a decrease in fieldwork requirements for all crops.

4.1.1. Comparison of working time requirements for fieldwork

For the fieldwork, the findings were mixed, depending on the scheme and the crop. Using no herbicides increased the WTR_av in the case of wheat production when weeds were removed manually (schemes (A) and Organic), but in the case of sugar beet and potato a reduction of herbicides reduced the WTR_av (Scheme (A) $<$ PEP). A strong increase in fieldwork time by manual weeding was also found by Colnenne-David et al. (2023). Mechanical-technological solutions to manual weeding, such as a hoeing robot, and to pests have the potential to reduce both fieldwork WTR and pesticide use by increasing accuracy, efficiency and cost-effectiveness (Balaska et al., 2023; Baltazar et al., 2021). However, the technology is currently expensive and is not fully autonomous, such as in the case of a hoeing robot, which limits its usability (Heitkämper et al., 2023). Also in other cases, the technology still has to be improved (Baltazar et al., 2021). Nonetheless, these technical advances promise improvements for farmers' labour requirement and a decrease in pesticide and herbicide use.

The reduction of WTR_av was not only the result of plant protection activities in the field. This resulted, partly for potatoes and fully for sugar beet, from a reduction of time for harvest and transport (see Supplementary Tables 26 and 28) because of the assumed lower yields. With unchanged yields, there would hardly be any difference between PEP and (A) for sugar beet and potato, based on our production assumptions.

There were several sources for the differences in WTR_av between the schemes (for details on that see Supplementary Tables 24 to 29). For all crops considered, different procedures in soil preparation, seedbed preparation, and fertilisation led to different machines and working widths or different numbers of passes.

4.1.2. Comparison of working time requirements for management work

For the management WTR under typical Swiss conditions, our results clearly showed that a reduction in the use of pesticides led to less plant protection-related WTR in management. This contradicts results such as from Cellier et al. (2018) and Merot and Wery (2017), who found evidence for an increase in management complexity converting to organic and avoiding pesticides. Different to the experimental study of Schwarz et al. (2018), fewer observations and spraying operations were, based on the experts' assessment, assumed in the field, which also reduces the time required to document pesticide applications and agricultural consultancy. The lower management WTR can compensate for some additional hours of work in the total WTR when less amounts of pesticide are used in crop production.

The filling of application forms for direct payments and/or for labels consumed the highest amount of time. The WTR_av for this task increased with a decreasing number of passes with pesticides for winter wheat and potatoes (for detailed figures see Supplementary Tables 25 and 29). For sugar beet production, the application form filling was the same for all schemes (3.5 h ha^{-1}). A high share of management working hours was also necessary for consultancy and for third party controls of the farm. Less consultancy was needed if the use of pesticides was forbidden in a scheme, so that no time was necessary for Organic and (A) + (B) winter wheat production, while 1.9 h ha^{-1} were required for PEP and (A). In potato production, the WTR_av for consultancy was highest for PEP and (A) (3.2 h ha^{-1}) and lowest for (B) and Organic (62 min ha^{-1}, for detailed figures see Supplementary Tables 25, 27, 29).

4.1.3. Sensitivity analysis of fieldwork time requirement

The *number of interventions* for spraying or mechanical plant protection had a large impact on the WTR. Increasing/decreasing the number of interventions for chemical plant protection in winter wheat PEP production and mechanical plant protection in Organic winter wheat (harrow hoe) by 1 increased/decreased the WTR by ±/-50%. The *width of the machinery* also had a large effect on the WTR, even though it was less pronounced than the number of interventions. For mechanical plant protection in Organic winter wheat and sugar beet production, an increase/decrease of the width by 1 m, changed the WTR by −13/+28% in winter wheat and − 21/+41% in sugar beet. Increasing the *number of plots* in chemical plant protection from 1 to 2 of the same size had a smaller effect on the WTR, with a reduction of −12% (see Supplementary Table 19 for full results). Overall, the results showed that the assumed range of yield had a small effect on the WTR_av for harvest and transport (see Supplementary Table 20), and hence also on the total WTR_av.

4.2. Effects of pesticide reduction on profitability

4.2.1. Comparison of schemes' profitability

The results of the cost benefit calculations are shown in separate figures for the crops winter wheat (Fig. 1) sugar beet (Fig. 2) and potatoes (Fig. 3; for detailed figures, see Supplementary Table 21 and Supplementary figs. 4, 5 and 6). For all three crops analysed, there were schemes whose profitability (net total = benefits–costs) was higher than in the reference PEP scheme. For wheat, there were clear incentives to avoid herbicides and other pesticides. For potato, dispensing with herbicides appeared to be economically feasible, while dispensing with insecticides can lead to greater losses. In sugar beet, by contrast, dispensing with herbicides appeared to be economically challenging, while schemes without insecticides and fungicides exceeded the profitability of the reference scheme.

Considering the effects of omitting pesticides on production costs, in organic crop farming, production costs were the highest for all crops (apart from Scheme (A) in winter wheat), whether due to higher seed costs and/or significantly higher labour costs in the case of manual weed control. Higher production costs for sugar beet and potatoes compared to conventional production were also found by Heinrichs et al. (2021). Otherwise, omitting pesticides resulted in lower production costs compared to the conventional reference (PEP), as long as no manual weed control was required, as in wheat (A) with no herbicides. Further, the benefit level can usually be maintained or even improved by dispensing with pesticides. Significant performance losses were expected when omitting selected pesticides on potatoes (schemes (B) and (A) + (B)) and when omitting herbicides on sugar beet in Scheme (A). The yield losses associated with omitting pesticides were mostly compensated for by higher prices and direct payments. Yields and prices are decisive for profitability, and direct payments play a subordinate role. Swiss farmers can compensate for the economic effect of the yield loss for winter wheat in all schemes considered through labelling programs and state support. Thus, for winter wheat in Switzerland, there are both market and political incentives to reduce the use of pesticides in arable farming. The economic results for potatoes and sugar beets are not as clear.

Label programs such as IP-Suisse or Organic Label also allow farmers to differentiate products with reduced pesticide use on the market. This differentiation is particularly mature in Switzerland. The success of the differentiation is evident in the increasing participation in Schemes (B) and Organic (Swissgranum, 2023). In the case of potatoes and sugar beet, price differentiation is not as mature as for wheat. An improvement therein could ultimately have a positive influence on both market volume and prices (cf. Colnenne-David et al., 2023).

In the Organic scheme, profitability was higher in each considered crop. This is in accordance with Tzilivakis et al. (2005) who showed a higher profitability of organic sugar beet production conventional sugar beet production as well. Heinrichs et al. (2021) and Nemes (2009) also reported a higher profitability of organic farming for most crops as well. However, it is possible that in production systems, such as the organic system, costs occur, which cannot clearly be allocated to on crop and one year because they have beneficial effects along the crop rotation, such as cover crops or more diverse crop rotation. Moreover, analysing only one year neglects the longer-term implications of not using pesticides. For example, not using herbicides in several crops in a rotation can lead to increasing problems with weed control over time (Schwarz et al., 2018). Currently, the direct payment system in Switzerland allows farmers to avoid using herbicides in some, but not all, crops on a farm; this enables them to control weeds effectively by using herbicides in subsequent years. Thus far, there has been little experience of the dynamic effects of reducing pesticide use.

Further analysis was carried out regarding the parity yield, and the results are provided Supplementary Table 23. Based on the given price levels and production costs, the parity yields showed a clear and similar development: with decreasing use of pesticides, direct costs mostly decreased, whereas both market prices and direct payments increased. Hence, the yield to obtain the economic result of the reference, PEP, may also decrease. For sugar beet in Schemes (B) and (A) + (B), we recorded very low parity yield levels, even lower than the organic parity yield.

4.2.2. Sensitivity analyses of profitability

The profitability for different yield levels (high and low compared to average) was calculated (Supplementary Table 7 for underlying yield assumptions, Supplementary Table 22 for full results). The resulting effect on profitability was lowest for winter wheat, with an increase/decrease of profitability by 21% to 34% with an outlier for Scheme (A) + (B). For potatoes, PEP exhibited the greatest variation in yield and

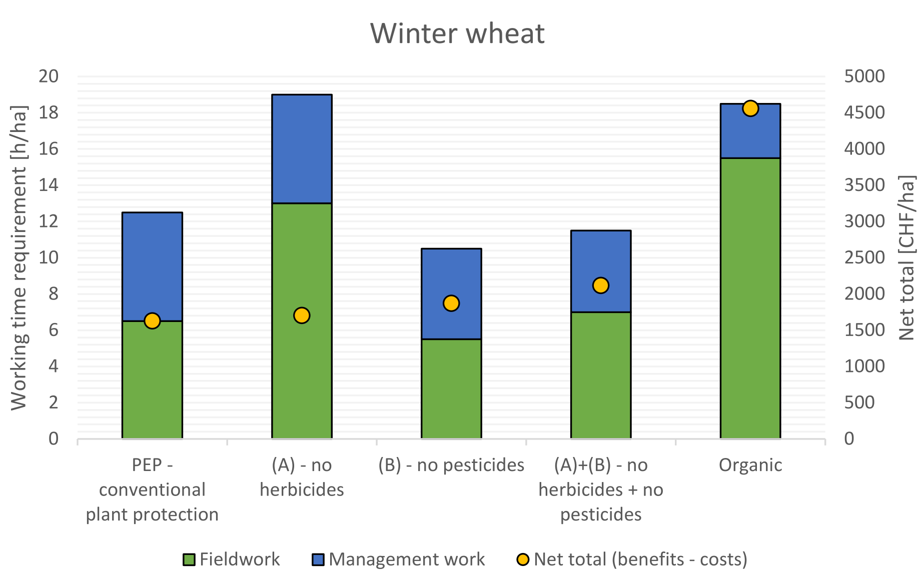


Fig. 1. Profitability (net total) and working time requirement for fieldwork and management for winter wheat production under conventional compared to four pesticide-reduced schemes.

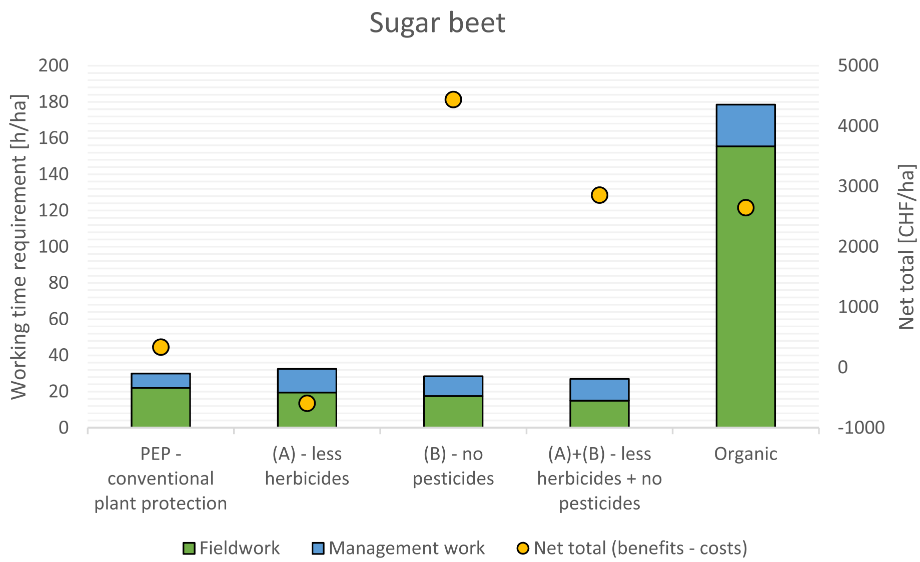


Fig. 2. Profitability (net total) and working time requirement for fieldwork and management for sugar beet production under conventional compared to four pesticide-reduced schemes.

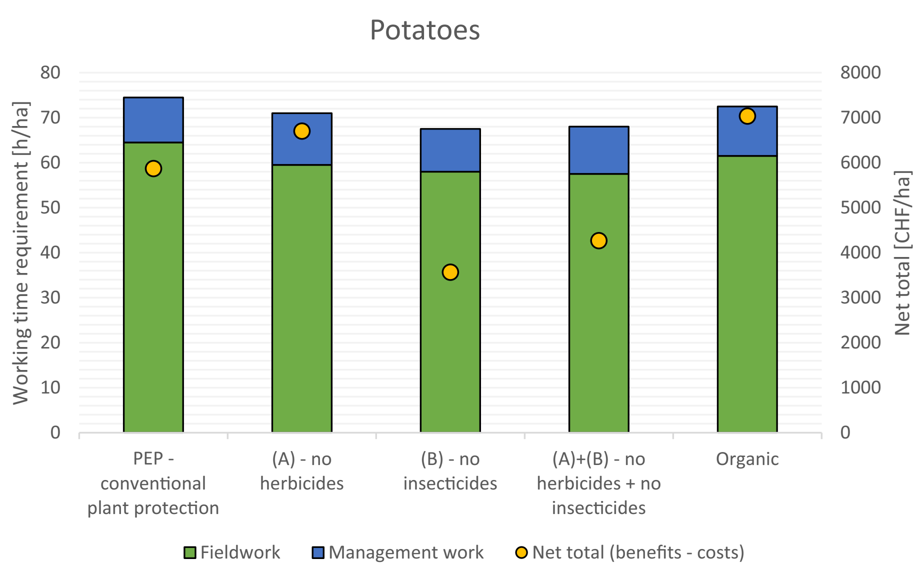


Fig. 3. Profitability (net total) and working time requirement for fieldwork and management for potato production under conventional compared to four pesticide-reduced schemes.

corresponding profitability, with over ±/-100%, and scheme (A) exhibited the lowest profitability variation, with ±/-9%. In the case of sugar beet, different yield levels had only a minor influence on the relative profitability of different schemes, with the exception of organic farming. Here, the yield variation was highest, contributing to the large variation in profitability of this production scheme (+69/−75%). Generally, the extent of the variation in profitability was consistently greater than the underlying variation in yield.

4.3. Limitations of the study and future research

Our study has several limitations. Farms in Switzerland and elsewhere usually cultivate several crops to have crop rotation on the fields. If farmers reduce the use of pesticides and herbicides, they might increase their effort to maintain yields by applying mechanical and agronomical measures, such as including cover crops, intercrops, catch crops, and more complex crop rotations. The total WTR on a farm therefore comprises the production-related working time for each cultivated crop, in addition to the WTR for farm management. Since we have not made assumptions about the crop rotation for a whole farm, the results for crop-related WTR represent only a share of the WTR of a farm in a real-world context. Studying a complete crop rotation or even more complex production systems would enable to consider costs and working time requirement of operations that are done in the overall context of the production but also have an effect on a specific crop. Therefore, in future studies, it would be relevant to include labour time, costs, and benefits for preventive plant protection measures, such as crop rotations and intercrops, and to consider a farm-level view on working time and profitability. Future research could identify farm types and crop rotations based on national databases to analyse effects more system-wise.

The data situation for the evaluation of alternative plant protection measures is difficult due to the great complexity resulting from numerous influencing factors (such as location, crop rotation, weather, variety, and fertilisation) and their interactions. This results in great uncertainty with regard to changes in several factors and the consequences of yield. There are data gaps and great potential to expand the data on alternative measures and their effects on yield, which could be the aim of future research.

Due to the method chosen for working time calculation, our results do not include differences between farms, such as farmer characteristics (e.g. experience, age, interest, tradition) or environmental conditions (e.g. soil, microclimate, weed, and pest burden), and are only very limited between regions. Therefore, we could not analyse the intra-scheme variance. We have addressed this issue with a sensitivity analysis; however, this does not cover all differences between real farms. Moreover, in the future, it will be relevant to calculate the change in required working time with new technologies in agriculture, such as robots or drones.

5. Conclusion

The consideration of pesticide reduction on national and international political agendas declares the societal aim of environmental preservation and the avoidance of detrimental outcomes regarding human health. However, a reduction of pesticides in crop farming requires the adaptation of production procedures to counter the potential detrimental effects of weeds and plant pests on crop growth and, ultimately, yield. Socioeconomic factors are also affected by pesticide reduction adaptations in production. The tasks in fieldwork and management and, relatedly, the time required for crop farming may be of concern. Furthermore, the profitability of crop farming can change. To gain more insights into the direction and magnitude of these changes, we analysed the differences in WTR for field and management work and outcomes in profitability of four pesticide-reduced production schemes in detail. We find that, under current conditions in Switzerland, there are synergies between labour time and profitability for potatoes produced without herbicides and for winter wheat and sugar beet produced without growth regulators, fungicides, and insecticides. However, especially for potatoes and sugar beet, the WTR is also reduced because of a lower yield. Organic production seemed less favourable concerning synergy. However, organic production practices have been used and researched for a relatively long time and have probably been well adapted to counter negative long-term effects on weeds and pests. The system boundaries of our analysis might lead to the negligence of other effects influencing the performance of this farming system. For the other pesticide reduction schemes, there is less experience, and long-term effects have yet to be fully understood.

We conclude that the reduced use of pesticides in crop production does not necessarily lead to an increase in WTR and can increase profitability, based on current Swiss direct payments and price conditions. To make herbicide-free production more attractive, solutions are needed to reduce the amount of fieldwork related to reduced pesticide use. Manual root weed removal substantially increases WTR and thereby affects profitability.

Our results suggest that it is relevant to include management labour time when assessing the impact on labour time and profitability of pesticide reduction schemes. For most of the analysed schemes and crops, management labour time decreased with the reduced use of pesticides, which can compensate for some hours of higher fieldwork time requirements.

Funding

The study was funded by Agroscope internal resources.

Ethics approval

Not applicable.

Consent to participate

Informed consent was given verbally by the experts.

Availability of code

Not applicable.

CRediT authorship contribution statement

Manika Rödiger: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Alexander Zorn:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis. **Michael Mielewczik:** Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Katja Heitkämper:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Andreas Roesch:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Nadja El Benni:** Writing – review & editing, Conceptualization.

Declaration of competing interest

The authors did not receive support from any organisation for the submitted work. The authors have no relevant financial or non-financial interests to disclose.

Data availability

Relevant data are included in the article and supplementary material.

Acknowledgements

We would like to thank Claudia Degen, Hansueli Dierauer, Markus Hochstrasser, Adrian von Niederhäusern and Florian Sandrini for their support with expertise in defining the production schemes.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2024.104101.

References

Achilles, W., Eckel, H., Eurich-Menden, B., Frisch, J., Fritzsche, S., Fröba, N., Funk, M., Gaio, C., Grebe, S., Grimm, E., Grube, J., Hartmann, W., Horlacher, D., Kloepfer, F., Meyer, B., Meyer-Hamme, S., Sauer, N., Schroers, J.O., Schultheiß, U., Wulf, S., 2018. Betriebsplanung Landwirtschaft 2018/19 – KTBL-Datensammlung. In: Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V. (KTBL), 26th edition. Darmstadt.

Agridea, 2022a. REFLEX 2022 - Betriebswirtschaftliche Datensammlung. Lindau, Agridea.

Agridea, 2022b. Faktenblatt Ackerbau – Massnahmenpaket für eine nachhaltigere Landwirtschaft. Lindau, Switzerland.

Agridea, 2023a. Beitragsrechner (V 4.9.7). https://agripedia.ch/focus-ap-pa/wp-content/uploads/sites/22/2023/01/Beitragsrechner-D-V4-9-7.xlsx. Agripedia.

Agridea, 2023b. Deckungsbeiträge 2023 – Getreide, Hackfrüchte, übrige Ackerkulturen, Futterbau, Spezialkulturen, Tierhaltung. Lindau, Switzerland.

Alavanja, M.C.R., Bonner, M.R., 2012. Occupational pesticide exposures and cancer risk: a review. J. Toxicol. Environ. Health Part B 15, 238–263. https://doi.org/10.1080/10937404.2012.632358.

Balaska, V., Adamidou, Z., Vryzas, Z., Gasteratos, A., 2023. Sustainable crop protection via robotics and artificial intelligence solutions. Machines 11, 774. https://doi.org/10.3390/machines11080774.

Baltazar, A.R., Santos, F.N.D., Moreira, A.P., Valente, A., Cunha, J.B., 2021. Smarter robotic sprayer system for precision agriculture. Electronics 10, 2061. https://doi.org/10.3390/electronics10172061.

Beckmann, V., Wesseler, J., 2003. How labour organization may affect technology adoption: an analytical framework analysing the case of integrated pest management. Environ. Dev. Econ. 8, 437–450. https://doi.org/10.1017/S1355770X03000238.

Bio Suisse, 2023. Richtlinien für die Erzeugung, Verarbeitung und den Handel von Knospe-Produkten. Fassung vom 1. Januar 2023. https://www.bio-suisse.ch/de/unser-verband/verbandsintern/richtlinien.html.

Bochtis, D., Sørensen, C.A.G., Kateris, D., 2019. Operations management in agriculture. Academic Press Elsevier, London.

BR (Bundesrat der Schweizerischen Eidgenossenschaft), 2017. Aktionsplan zur Risikoreduktion und nachhaltigen Anwendung von Pflanzenschutzmitteln. Bericht des Bundesrates 06 (09), 2017.

Busenkell, J., Berg, E., 2006. Farm level analysis of agro-environmental measures in arable farming in North Rhine-Westphalia and Rhineland-Palatinate. Berichte über Landwirtschaft 84 (1), 49–72.

Cavan, N., Omon, B., Dubois, S., Toqué, C., Van Inghelandt, B., Queyrel, W., Colbach, N., Angevin, F., 2023. Model-based evaluation in terms of weed management and overall sustainability of cropping systems designed with three different approaches. Agric. Syst. 208, 103637 https://doi.org/10.1016/j.agsy.2023.103637.

Cellier, V., Berthier, A., Colnenne-David, C., Darras, S., Deytieux, V., Savoie, A., Aubertot, J.-N., 2018. Évaluation multicritère de systèmes de culture zéro-pesticides en grande culture et polyculture-élevage (Réseau Rés0Pest). Innovations Agronomiques 70, 273–289.

Colnenne-David, C., Jeuffroy, M.H., Grandeau, G., Doré, T., 2023. Pesticide-free arable cropping systems: performances, learnings, and technical lock-ins from a French long-term field trial. Agron. Sustain. Dev. 43, 81. https://doi.org/10.1007/s13593-023-00931-7.

de Baan, L., Blom, J., Daniel, O., 2020. Pflanzenschutzmittel im Feldbau: Einsatz und Gewässerrisiken von 2009 bis 2018. Agrarforschung Schweiz 11, 162–174. https://doi.org/10.34776/afs11-162g.

Duval, J., Cournut, S., Hostiou, N., 2021. Livestock farmers' working conditions in agroecological farming systems. A review. Agron. Sustain. Dev. 41, 22. https://doi.org/10.1007/s13593-021-00679-y.

FOAG (Federal Office of Agriculture), 2022a. Agrarbericht 2022. Federal Office of Agriculture of the Swiss Confederation, Bern. Online at: https://www.agrarbericht.ch/de/produktion/pflanzliche-produktion/flaechennutzung.

FOAG (Federal Office of Agriculture), 2022b. Beitrag für den Verzicht auf Herbizide im Ackerbau und in Spezialkulturen. Online at. https://www.blw.admin.ch/blw/de/home/instrumente/direktzahlungen/produktionssystembeitraege23/spezialkulturen.html. Date of access: 08.02.2023, date of last update: 26 September 2022.

FOAG (Federal Office of Agriculture), 2023. Ökologischer Leistungsnachweis. Online at. https://www.blw.admin.ch/blw/de/home/instrumente/direktzahlungen/oekologischer-leistungsnachweis.htmlc. Date of access: 08 February 2023, date of last update: 30 January 2023.

Forney, J., 2016. Blind spots in Agri-environmental governance: some reflections and suggestions from Switzerland. Rev. Agric. Food Environ. Stud. 97, 1–13. https://doi.org/10.1007/s41130-016-0017-2.

Gazzarin, C., Lips, M., 2018. Methodische Grundlagen für die Berechnung der Maschinenkosten. Agroscope Sci. 79, 1–32.

Gazzarin, C., Bütler, A., Anken, T., Bravin, E., Hoop, D., Sax, M., Schlatter, M., Zorn, A., 2022. Kostenkatalog 2022 – Richtwerte für die Kosten von Maschinen, Arbeit, Gebäude und Hoftechnik. Agroscope Transf. 448, 1–56.

Geiger, F., Bengtsson, J., Berendse, F., Weisser, W.W., Emmerson, M., Morales, M.B., Ceryngier, P., Liira, J., Tscharntke, T., Winqvist, C., Eggers, S., Bommarco, R., Pärt, T., Bretagnolle, V., Plantegenest, M., Clement, L.W., Dennis, C., Palmer, C., Oñate, J.J., Guerrero, I., Hawro, V., Aavik, T., Thies, C., Flohre, A., Hänke, S., Fischer, C., Goedhart, P.W., Inchausti, P., 2010. Persistent negative effects of pesticides on biodiversity and biological control potential on European farmland. Basic Appl. Ecol. 11 (2), 97–105. https://doi.org/10.1016/j.baae.2009.12.001.

Hallmann, C.A., Foppen, R.P., van Turnhout, C.A., de Kroon, H., Jongejans, E., 2014. Declines in insectivorous birds are associated with high neonicotinoid concentrations. Nature 511, 341–343. https://doi.org/10.1038/nature13531.

Heinrichs, J., Kuhn, T., Pahmeyer, C., Britz, W., 2021. Economic effects of plot sizes and farm-plot distances in organic and conventional farming systems: A farm-level analysis for Germany. Agric. Syst. 187, 102992 https://doi.org/10.1016/j.agsy.2020.102992.

Heitkämper, K., Reissig, L., Bravin, E., Glück, S., Mann, S., 2023. Digital technology adoption for plant protection: assembling the environmental, labour, economic and social pieces of the puzzle. Smart Agric. Technol. 4, 100148 https://doi.org/10.1016/j.atech.2022.100148.

Jarrett, P., Moeser, C., 2013. The Agri-food Situation and Policies in Switzerland. OECD Economics Department Working Papers, 1086. OECD Publishing, Paris.

Lechenet, M., Bretagnolle, V., Bockstaller, C., Boissinot, F., Petit, M.-S., Petit, S., Munier-Jolain, N.M., 2014. Reconciling pesticide reduction with economic and environmental sustainability in arable farming. PLoS One 9 (6), e97922. https://doi.org/10.1371/journal.pone.0097922.

Lundqvist, P., 2000. Ergonomics in organic farming. Proc. Human Fact. Ergonom. Soc. Ann. Meet. 44 (22), 655–657. https://doi.org/10.1177/154193120004402242.

Maas, L., Malvestiti, R., Amaral Gontijo, L., 2000. Work in organic farming: an overview. Ciência Rural 50 (4), e20190458. https://doi.org/10.1590/0103-8478cr20190458.

Mack, G., Finger, R., Ammann, J., El Benni, N., 2023. Modelling policies towards pesticide-free agricultural production systems. Agric. Syst. 207, 103642 https://doi.org/10.1016/j.agsy.2023.103642.

Mann, S., Kaiser, A., 2023. Why is agricultural policy not more environmentally ambitious? Comparing failed attempts in Switzerland. Resourc. Environ. Sustain. 11, 100096 https://doi.org/10.1016/j.resenv.2022.100096.

Merot, A., Wery, J., 2017. Converting to organic viticulture increases cropping system structure and management complexity. Agron. Sustain. Dev. 37, 19. https://doi.org/10.1007/s13593-017-0427-9.

Moriz, C., 2007a. Arbeitszeitbedarf für die Betriebsführung in der Landwirtschaft. Ein kausal-empirischer Ansatz für die Arbeitszeitermittlung in der Milchproduktion, Dissertation ETH Zürich.

Moriz, C., 2007b. Arbeitszeitbedarf für die Betriebsführung in der Landwirtschaft. Ein kausal-empirischer Ansatz für die Arbeitszeitermittlung in der Landwirtschaft. ART Schriftenreihe 6, 1–118.

Moriz, C., Mink, A., 2010. Betriebsführungsarbeiten im Ackerbau. Landtechnik 65 (3), 198–200.

Nemes, N., 2009. Comparative Analysis of Organic and Non-Organic Farming Systems: A Critical Assessment of Farm Profitability. Food and Agricultural Organization of the United Nations, Rome, Italy. Online at: https://openknowledge.fao.org/server/api/core/bitstreams/9d5e4fcf-4e3b-4c21-bf35-96bd6dabcda0/content.

Pimentel, D., Hepperly, P., Hanson, J., Douds, D., Seidel, R., 2005. Environmental, energetic, and economic comparisons of organic and conventional farming systems. BioScience 55 (7), 573–582.

Rajmis, S., Karpinski, I., Pohl, J.P., Herrmann, M., Kehlenbeck, H., 2022. Economic potential of site-specific pesticide application scenarios with direct injection and automatic application assistant in northern Germany. Precis. Agric. 23, 2063–2088. https://doi.org/10.1007/s11119-022-09888-1.

Riegel, M., Schick, M., 2005. The PROOF model calculation system using the example of pig husbandry. In: Krause, M. (Ed.), Increasing Work Efficiency in Agriculture, Horticulture and Forestry XXXI CIOSTA-CIGR V Congress Proceedings, September 19–21. Hohenheim, Germany, pp. 360–367.

Schick, M., 2008. Dynamische Modellierung landwirtschaftlicher Arbeit unter besonderer Berücksichtigung der Arbeitsplanung. Ergonomia-Verlag, Stuttgart.

Schwarz, J., Klocke, B., Wagner, C., Krengel, S., 2018. Untersuchungen zum notwendigen Maß bei der Anwendung von Pflanzenschutzmitteln in Winterweizen in den Jahren 2004 bis 2016. Gesunde Pflanzen 70, 119–127. https://doi.org/10.1007/s10343-018-0422-3.

Stehle, S., Schulz, R., 2015. Agricultural insecticides threaten surface waters at the global scale. Proc. Natl. Acad. Sci. 112 (18), 5750–5755. https://doi.org/10.1073/pnas.1500232112.

Swissgranum, 2023. Produktionsflächen nach Anbauweise. Schweizerische Branchenorganisation Getreide, Ölsaaten und Eiweisspflanzen (Swiss granum), Bern.

Tzilivakis, J., Jaggard, K., Lewis, K.A., May, M., Warner, D.J., 2005. Environmental impact and economic assessment for UK sugar beet production systems. Agric. Ecosyst. Environ. 107 (4), 341–358. https://doi.org/10.1016/j.agee.2004.12.016.

Vasileiadis, V.P., Dachbrodt-Saaydeh, S., Kudsk, P., Colnenne-David, C., Leprince, F., Holb, I.J., Kierzek, R., Furlan, L., Loddo, D., Melander, B., Jørgensen, L.N., Newton, A.C., Toque, C., van Dijk, W., Lefebvre, M., Benezit, M., Sattin, M., 2017. Sustainability of European winter wheat- and maize-based cropping systems: economic, environmental and social ex-post assessment of conventional and IPM-based systems. Crop Prot. 97, 60–69. https://doi.org/10.1016/j.cropro.2016.11.002.