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Digital technology adoption for plant protection: Assembling the environmental, labour, economic and social pieces of the puzzle

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ABSTRACT

The prototype of a hoeing and spot spraying device was used to evaluate the impacts of digital technologies in vegetable production on labour, economic and social issues. These impacts were analysed in a case study conducted on a farm in Switzerland. Working-time requirements were modelled on the basis of time studies conducted during field trials. The results were used in a cost analysis and a comparison with a conventional plant-protection strategy. Furthermore, an in-depth interview with the farm manager revealed the personal, intellectual and social characteristics of successful technology adopters and the impact of applying a new technology to the working process. While one might expect digital technologies to substitute labour with capital, the prototype, in its current form, requires both higher investments and a higher input of labour per hectare. This study shows that the success of new technologies relies on enthusiastic farm managers in addition to public and consumer support, which can be gained by promoting the reduced amount of pesticides applied by these digital technologies.

Introduction

Agricultural economists have considered the history of agriculture over the last 200 years to be a continued substitution of labour by capital [1–4]. It seems that recent trends towards the digitalisation of agriculture continue this substitution process [5, 6]. Simultaneously, the transformation process now also focuses on protecting natural resources [7–9] and changing the job profile of farmers in the direction of being entrepreneurs [10]. Precision agriculture (PA), as defined by the International Society of Precision Agriculture (ISPA) [11], is not just a product but a strategy 'that takes account of temporal and spatial variability to improve sustainability of agricultural production' and can lead to the prudent use of pesticides and thus reduce their negative impacts on the environment and human health. However, farmers' adoption of these new technologies still faces technical challenges, as well as economic and social hurdles [12]. According to de Oca Munguia and Llewellyn [13], research on the determinants of agricultural innovation adoption 'has failed to converge towards a consistent explanation for why farmers choose to adopt new technologies and practices'. Over the last decade, the factors that affect the adoption of digital technologies in farming have received increased attention. Sun et al. [14], who focused on the meat industry, showed the complexity of the digital technology adoption process. They argued that a number of variables and interactions affect the adoption of innovations. In their conceptual paper, they concluded that 'the innovation adoption process should be viewed from a systemic perspective'. In the area of field crop robotics, Lowenberg-DeBoer et al. [15] argued that the field has 'an urgent need for a more systematic study' beyond the focus on changes in variable costs. They argue further that, 'In the shorter term, it will be important for governments to engage with key stakeholders, including farmers, peak bodies, and trade unions, to negotiate and manage the transition to a more automated agriculture. In order to ensure that such discussions are adequately informed, research to quantify the likely impacts of the use of robots in agriculture is urgently required' [15]. This study aims to sharpen the case analysis of the determinants of adoption using a multi-perspective approach.

Pierpaoli et al. [16] identified three categories of drivers that influence the intention to adopt PA: (i) competitive and contingent factors (e.g., farm size, geography, soil quality), (ii) socio-demographic factors (e.g., computer confidence, education) and (iii) financial resources (e.g., income, ownership). Since the case study was conducted on only one farm and thus the competitive and conditional factors as well as the

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Fig. 1. Prototype based on a camera-controlled hoeing machine (left) with added spot-spraying technology for targeted pesticide application (right). Source: Agroscope, R. Total.

financial resources were already given, this study concentrates on the socio-demographic factors. Kuehne et al. [17] developed a framework to explain and predict the adoption of digital technologies called ADOPT (Adoption and Diffusion Outcome Prediction Tool). They name a number of factors that influence adoption, including ‘variables related to economics, risk, environmental outcomes, farmer networks, characteristics of the farm and the farmer, and the ease and convenience of the new practice’ [17]. According to Lowenberg-DeBoer and Erickson’s [18] recent review of studies on the adoption of precision agriculture in different parts of the world, further possible influencing factors that add to the adoption puzzle have been identified in the literature: the use of a crop consultant, the use of computers and the perceived profitability of PA. Jensen et al. [19] addressed the economic profitability of implementing various precision farming (PF) technologies and controlled traffic farming (CTF) on four main crops in Denmark. The authors found that PF and CTF facilitated large savings in the use of herbicides and, therefore, had positive long-term economic effects, which in turn supported technology adoption. In addition to constituting enabling factors for these technologies, the economic effects also impact labour and its organisation on farms. Finally, they can exert an influence on the mindset of the farmer. Annosi et al. [20] focused on owners or managers of small and medium enterprises and their subjective perceptions of the opportunity behind the adoption of technology on the one hand and of the incentives or constraints dictated by the external environment on the other. They also asserted that organisational capabilities embedded in organisational skills and routines influence technology adoption. Bukchin and Kerret [21] identified the influence of hope and self-efficacy on technology adoption, while Chavas and Nauges [22] referred to uncertainty and learning. Reissig et al. [23] analysed the factors that influence administrative burden by using e-government, which describes interactions with administrations by electronic means analogous to e-commerce and e-banking. They stated the importance of knowledge, support and attitude for the adoption of digital technologies. Alvarez and Nuthall [24] described the relationship that exists between computer use and the aims, personality traits and learning styles of dairy farmers. The findings of the previously mentioned studies [21–24] demonstrate a large variety of factors that play a role in technology adoption and were used to compile a list of factors that were tested for validity in a social psychological interview with the farm manager.

To mitigate the undesired impacts of digital innovations on agriculture, social research is beginning to engage with the ‘responsible research and innovation framework (RRI)’ [25–27]. This approach aims for all social stakeholders involved in the entire innovation research and development process to cooperate in order to bring both the process itself and the outcome in line with society’s needs and expectations [28]. This study uses the RRI framework to enable reflection on the human aspects, such as motivation and social behaviour, during the pilot phase of technology adoption. It joins the ranks of research projects striving to raise awareness about the need to cooperate with producers to enable sustainable innovation development [29].

This case study investigates the use of a plant-protection prototype applied to the farming of field-grown lettuce. According to Groher et al. [30], Swiss farmers who produce high-value products, such as vegetable crops, show a higher adoption rate of novel technologies than farmers of arable crops. Lettuce is a widely grown crop in Switzerland. It is planted at low densities and the plants are spaced relatively far apart, which makes this crop suitable for spot spraying and selective hoeing within the rows. Equipped with optical sensor technology, the fundamental properties of the prototype differ from a conventional hoeing machine or spray boom in terms of technical features, such as working width and driving speed, and the handling of the technology, which affects how farmers work with the device. A description of the field trials and detailed results on the pesticide savings achieved with the spot spraying technology of the prototype have been published by Haberey et al. [31]: the smaller the crop coverage, the higher the pesticide savings. During the first application, when the average field surface covered by lettuce was 23%, an average saving of 81% was achieved. During the second treatment, when field coverage averaged 41% of the field, the average savings were 70%. Thus, only 19% and 30% of the standard amounts of pesticides had to be applied during the first and second applications, respectively. Over the lettuce-growing season, the prototype facilitated insecticide savings of 75% compared to the standard treatment.

The current paper assesses economic, labour and social issues related to the adoption of new digital technology from the perspective of innovation and adopter attributes, as proposed by Rogers [32]. This study draws on a farm manager’s positive experiences with a newly developed prototype device. It is assumed that (i) the prototype in its actual state has a high potential for pesticide savings, (ii) the technical features directly influence the work process with regard to labour demand, (iii) the prototype strategy for plant protection becomes cost efficient under specific conditions and, finally, (iv) specific social and psychological determinants have a positive influence on the adoption of a new technology. Identifying influential parameters in the three areas of labour, economics and sociology, as well as determining their effects on the adoption of this new digital device for plant protection, can provide both manufacturers and policy makers with useful information about user needs and acceptance factors, thereby contributing to future successful attempts to introduce a new technology.

Materials and methods

Technical features of the prototype device for plant protection

Within the framework of a project on resource-saving, sustainable plant protection in vegetable growing through camera-controlled plant-protection robots, a prototype for combined spot spraying and hoeing in

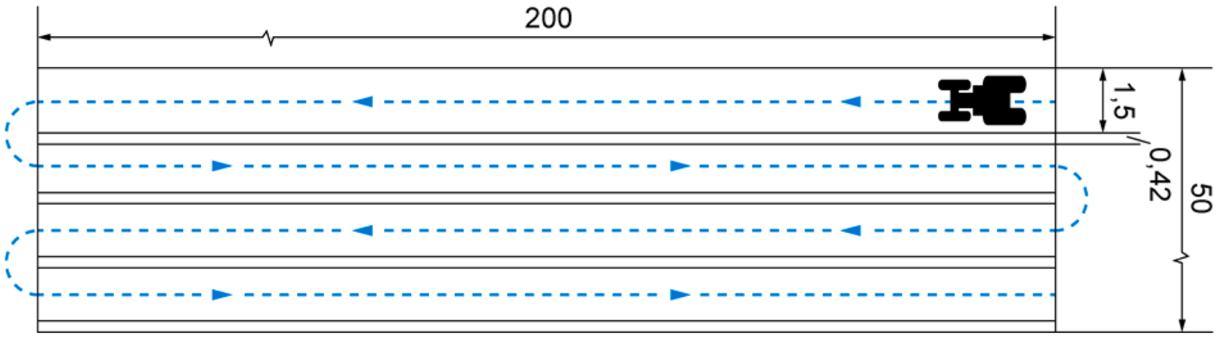

Fig. 2. Diagram of a standardised plot, dimensions for 'prototype' variant [m].

Table 1
Model assumptions for work economics calculations.

	Mechanical Weeder	Prototype
Plot size [ha]	1	
Plot length [m]	200	
Plot width [m]	50	
Working width [m]	3	1.5
Driving distance [m]	3000	5200
No. of turning operations [n]	14	25
Driving speed [km/h]	6.5	1.2

vegetable crops was developed. Machinefabriek Steketee B.V. built the prototype based on an existing camera-controlled hoeing device (IC weeder), which is already in use for mechanical weed control in and between crop rows (Fig. 1). The main components of the tractor-pulled prototype are four tool holders, each with fixed and movable hoeing blades and a solenoid valve block for pesticide application. Each solenoid valve or movable hoeing blade can be activated independently. The hoeing and spraying components of the prototype are controlled by camera-linked software that analyses the images and further sensor readings. Computer software differentiates between crop plants and weeds. Based on these data, the software coordinates the nozzles' on and off settings for spot spraying and activates or deactivates the mobile hoeing blades for mechanical weeding. The machine's working width is 1.5 m, which corresponds roughly to about four rows of lettuce. The prototype also has a side-shift control system that automatically moves the toolholders laterally to keep them above rows [31]. The economic calculations in this study compared the percentage of pesticides applied in the field trials to the percentage applied during standard treatment with a conventional technology (boom sprayer).

Data collection and model calculation of working-time requirements

The labour studies conducted for this paper focused on the comparison of the working-time requirement between the prototype and two conventional devices: (i) a field sprayer for chemical plant protection and (ii) hoeing equipment for mechanical weed control. The latter is similar to the widely used coulter weeding-hoeing (CWH) device with semi-rigid or flexible tines for cultivating between rows.

For the working-time analysis, video recordings of the prototype in operation were made during the three-year field trial phase, which included different vegetable crops and different working methods: (i) only hoeing, (ii) only spot spraying and (iii) combined hoeing and spot spraying (Table A.1). One camera was fixed in the driver's cab. Additionally, a trained person filmed the work process from outside the cabin. The dates for the recordings followed the use of the prototype and depended on the growing stage of the crop and the weather conditions. The video recordings were analysed at the work-element level with MEZA, a specialist software for time studies (DRIGUS Systeme GmbH, Dortmund, Germany). Each work element or workflow segment had a precisely defined beginning and end point with corresponding influencing factors, measured in centiminutes (cmin = 1/100 min; standard method according to [33]) [34]. A time study enabled the analysis of whether the driving speed shown in the display could be achieved over longer distances. For this purpose, the time for the work element 'hoeing' was allocated to the respective distances driven in metres. New work elements were identified, including the 'computer settings on the display' for adjusting the hoeing or spraying settings. The measured data were statistically evaluated and the corresponding arithmetic mean values were entered in a work-element database as planning times for each work element. They were then available to use for modelling the working-time requirements of different work process variants in the 'Proof' model calculation system [35]. Working-time requirements for operations, such as turning procedures or inputting settings on the display, were analysed with the workflow model adapted to camera-controlled hoeing and spot spraying. Workflow models from a previous study [36] were used to model the estimated working-time requirements for hoeing and spraying with conventional equipment without sensor technology. All results refer to a 1-ha plot (Fig. 2), and the field edge is stipulated as the system boundary. The model assumptions are shown in Table 1.

Model assumptions for plant-protection costs analysis

The economic assessment of the prototype device captures a partial budgeting of the plant-protection strategy, which consisted of weed control, fungicide, insecticide and molluscicide applications. For use with the prototype, a crop protection strategy was defined and then compared with a common Swiss strategy for lettuce farming, as outlined in the Plant-protection list of the Agroline Consumer catalogue [37]. No differences were assumed in terms of yield, quality or income between hoeing within and between the plant rows instead of using herbicide and between reducing the amounts of fungicides and insecticides applied owing to the use of the camera-supported spot-spraying technology. The costs of the plant-protection strategies were calculated according to the following equation:

$$PPC = \sum_{i=1}^{n_1} x_P c_P + \sum_{i=1}^{n_2} h_M c_M + \sum_{i=1}^{n_3} h_L c_L$$

PPC = plant-protection costs [CHF]; n1 = number of plant-protection products used; xP = quantity of used plant-protection products [l], [kg]; cP = plant-protection products costs [CHF/l], [CHF/kg]; n2 = number of passes with machines; hM = machine time [h]; cM = machine costs [CHF/h]; n3 = number of passes with labour input; hL = labour time [h]; cL= labour costs [CHF/h]

The standard strategy comprised two herbicide applications (pre- and post-planting) and three combined fungicide and insecticide applications using a common field sprayer (Table A.2). The standard strategy also included one pass of slug pellet spreading with a centrifugal spreader and one pass of mechanical weed control with a CWH device.

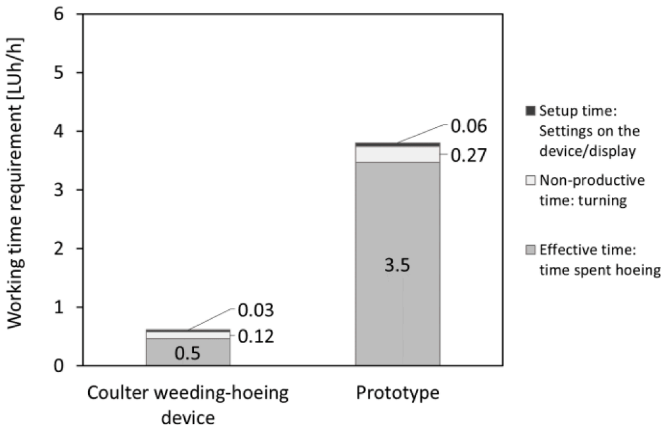

Fig. 3. Comparison of working-time requirements for weed control between a conventional CWH device (working width 3 m, driving speed 6.5 km/h) and the prototype (working width 1.5 m, driving speed 1.2 km/h) taking into account the time types (standardised plot). LUh = Labour unit hours.

Table 2
Working-time requirement for weed control with the prototype at different driving speeds and working widths (standardised plot), LUh = Labour unit hours.

Parameters Driving speeds [km/h] (working width 1.5 m)	Working-time requirement [LUh]
0.5	10.7
1.0	5.5
1.5	3.8
2.0	2.9
Working widths [m] (driving speed 1.5 km/h)	
1.5	3.8
3.0	2.2
4.5	1.5

The prototype strategy comprised two combined fungicide and insecticide applications, using 19% and 30% of the product quantity used in the standard strategy, respectively. A third pass was carried out when the crop covered most of the soil and few pesticide savings could be achieved by using the prototype. Thus, this pass was performed with the field sprayer and 100% of the product quantity of the standard strategy was used. Both strategies included a pass with molluscicides. As the prototype removed weeds in and between rows during spraying, no herbicide passes were necessary. An early pass with the prototype, during which early germinating weeds are controlled, was included in the prototype strategy (Table A.3).

Overall plant protection includes three sub-costs: (i) pesticides, (ii) machinery and equipment and (iii) labour. The model assumptions for the prototype cost calculation are compiled in the appendix (Table A.4). Tractor costs include fuel, repair and maintenance. For the prototype and the conventional variant, the assumption for fuel consumption is the same and amounts to 40 CHF/h. These costs are added to the machinery costs. The worked area was calculated as follows: each pass of, for example, pesticide application was counted as the worked area. If two passes were necessary on a surface of 10 ha, the worked area was recorded as 20 ha. To calculate the hourly machine costs of the prototype as CHF/h, we assumed a worked area of 40 ha per year (a surface of 10 ha with four passes), a depreciation of 10 years and a repair cost factor of 0.9 (90% of the purchase price) over the operational life of 500 ha [38].

For sensitivity analysis, the costs of producing 1 ha of field-grown lettuce using the standard strategy were calculated with the full-cost calculation software ProfiCost [39]. The amount of plant-protection products resulted from the study of Haberey [31]. Area performance was derived from the labour studies (cf. chap. 2.2) and was based on the highest value achieved with the prototype to date: 0.26 hectares per hour. The CWH device can achieve travel speeds of up to 12 km/h depending on the target crop and soil conditions. In this study, an average driving speed of 6.5 km/h and area performance of 0.88 ha/h for the CHW device was assumed in the economic calculations. The purchase price of the prototype was determined in consultation with the importer. Further information, such as the machinery costs of the field sprayer and the hoeing machine, was taken from the Agroscope Machinery Cost Catalogue [38] or obtained from the farm manager. The total cost calculation was performed using the lettuce standards in ProfiCost [39].

Social and psychological factors influencing technology adoption

The themes discussed in the social-psychological interview and the interview guidelines were initially developed based on comparable studies using a deductive approach [20–24]. The literature review (cf. chap. 1) identified the influencing factors that were chosen for discussion during the interview: attitude, skills and experience, support, learning, self-efficacy, initiative, handling risk, handling difficulty and data perception. Usually, in-depth interviews are conducted in person; however, due to the limitations imposed by the COVID-19 pandemic, this interview was conducted online with audio and video in the fourth year of the project (2021) after the practical experiments had already been concluded. The owner of the vegetable farm on which the prototype was successfully tested answered questions about the influencing factors identified in the literature review. The interview was conducted in Swiss German. After the interview, the research team transcribed his statements phonetically into standard German and then coded them via thematic analysis according to Braun and Clarke's [40] coding guidelines. This inductive method enabled the identification and sorting of various statements on the topics discussed. Two researchers coded the statements independently of one another and discussed their respective allocations of the code until a consensus was reached. For this case study, we deliberately chose a case in which the adoption of digital crop protection technology was successful, with the goal of shedding light on the factors that have a positive influence on technology adoption.

Results

Labour aspects: working-time requirements for plant protection

First, the time requirements for the variants prototype and conventional technology with CWH device were compared (Fig. 3). As expected, the main difference was observed in the effective hoeing time, which was influenced primarily by driving speed and working width (cf. chap. 2.2).

The farmer has to spend considerably more time hoeing with the prototype in its current state than with a CWH device. At 3.46 h/ha, the effective time for hoeing was around 7.5 times that of the standard equipment at 0.46 h/ha. Due to the low working width, the non-productive time incurred by turning at the end of a row is nearly twice as high as with the CWH device, but this has only a slight effect on the overall working-time requirement. With the 'prototype' variant, the setup times take account of the fact that, in the study scenario, two workers are present at the start of work: one on the tractor and the other controlling and adjusting the settings of the hoeing blades. However, when considering the total time, the setup time and the additional working time spent on the computer display settings only have a share of 1.6%. Area performance (ha/h) is the multiplicative inverse of the working time requirement per hectare (h/ha), and it varies from crop to crop. The prototype reached a maximum of 0.26 ha/h in the field trials. This value corresponds to a driving speed of 1.2 km/h and is thus quite low compared to 1.64 ha/h or a driving speed of 6.5 km/h with the 'standard' variant. As area performance is a benchmark for labour and economic issues, it was then used in the cost analysis.

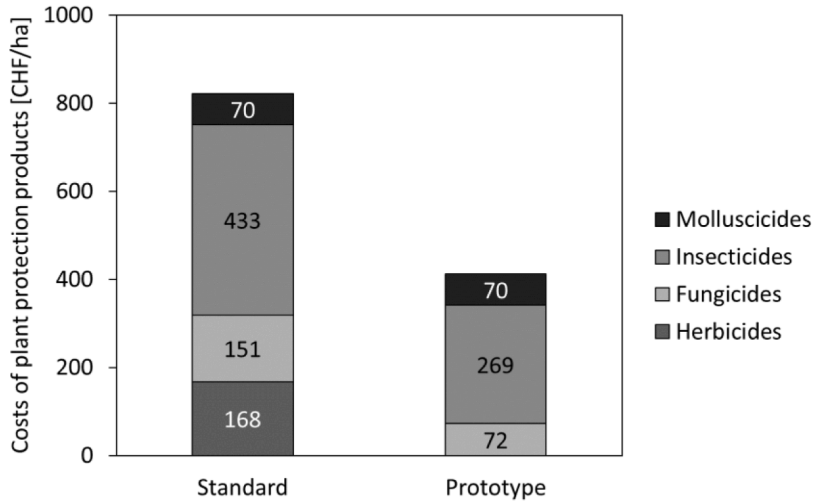

Fig. 4. Plant-protection cost comparison: costs of the pesticides used in the 'standard' and 'prototype' strategy [CHF/ha].

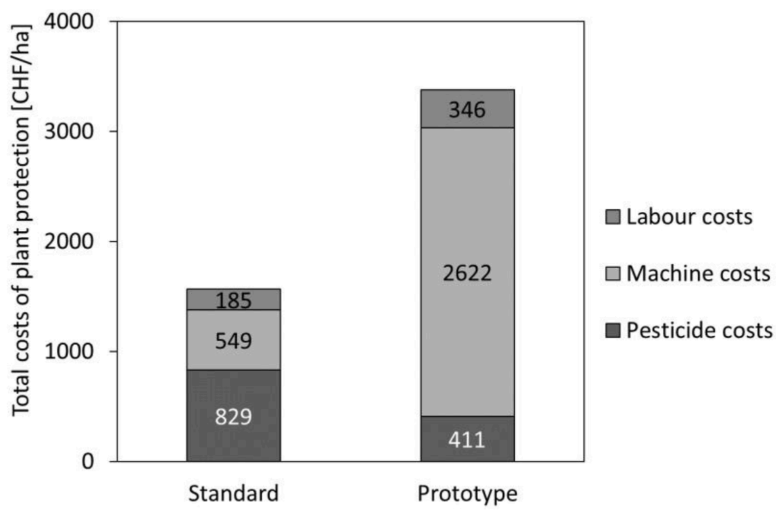

Fig. 5. Plant-protection cost comparison: total costs for the standard and prototype strategies.

Table 3
Influencing factors on plant-protection costs (CHF/ha) for scenarios with the prototype.

Parameters Capacity utilisation [ha]	Plant-protection costs [CHF/ha]
20	4625
40	3379
60	2964
80	2757
Purchase price [CHF]	
135,000	3379
101,250	2874
67,500	2368
Area performance [ha/h]	
0.26	3379
0.88	2834

The influence of driving speed and working width on the working-time requirement/ha is shown in Table 2. By increasing the driving speed from 0.5 to 1.0 km/h, the working-time requirement was reduced by 49%, while an increase from 1 to 2 km/h achieves a reduction of 47%. Equipment breakdowns were not taken into account in this calculation. The increase from 1.5 m to 3 m is the most relevant to Swiss farmers because vegetable producers in this region usually work with bed widths of 1.5 m [41]. An increase from one to two beds in the working width reduces the working-time requirement/ha by 42%. If it is possible to triple the working width, the time-saving potential increases to 61%.

Economic aspects: plant-protection strategy costs

The pesticide costs for one hectare of lettuce in field production are analysed below. The standard strategy was compared with the prototype strategy. As Fig. 4 demonstrates, the prototype strategy has the potential to lower expenditure on plant-protection products by 50% from CHF 822 to CHF 411/ha, because no herbicides and significantly fewer fungicides and insecticides were used.

The total plant-protection costs of the prototype strategy, including pesticides, machinery and labour costs, were CHF 3379/ha, which is 2.1 times higher than the standard strategy, where these costs added to CHF 1563/ha (Fig. 5). Significantly fewer pesticides were applied in the prototype strategy, partly due to the results of mechanical weeding and partly due to targeted spraying. The cost of pesticides had a relative share of only 12%. Nevertheless, the high investment costs of the prototype, which currently stands at CHF 135,000, had a relative share of 78% and could not be compensated for by the lower pesticide costs. As the performance rate of 0.26 ha/h is low, the calculated labour costs of the prototype strategy were also higher than those of the standard

Table 4
Plant-protection costs (CHF/ha) for two different scenarios with the prototype.

Parameters	Scenario 'Prototype now'	'Prototype future'
Capacity utilisation [ha]	40	100
Purchase price [CHF]	135,000	67,500
Area performance [ha/h]	0.26	0.88
Total costs [CHF/ha]	3379	1442

strategy. Still, labour costs only have a share of 10%.

Because the purchasing cost of the prototype is currently expensive, the share of machinery costs is correspondingly high: 78% of the total plant-protection costs in the prototype scenario, as opposed to 35% in the standard scenario. The following factors are the primary influences on plant-protection costs and were assessed in detail in a sensitivity analysis: (i) prototype capacity utilisation [ha/a], (ii) prototype purchase price [CHF] and (iii) prototype area performance [ha/h]. Each of these three factors was modified to calculate the corresponding changes in plant-protection costs (Table 3).

First, the capacity utilisation of the prototype in terms of the annually worked area was considered. The purchase price (CHF 135,000) and the area performance (0.26 ha/h) remained unchanged in this scenario. Assuming a relatively small, worked area of 20 ha per year (a cultivated area of 5 ha with 4 passes), the annual plant-protection costs come to CHF 4625/ha. If the worked area is doubled to 40 ha, the plant-protection costs fall by about 27% to CHF 3379/ha. If the worked area is further doubled, from 40 to 80 ha (e.g., a larger farm or inter-farm collaboration with a cultivated area of 20 ha), the annual plant-protection costs fall by an additional 18% to CHF 2757/ha. In the next adjustment, the prototype purchase price was modified. Economies of scale might contribute to a reduction in purchase price, so starting at the current CHF 135,000, the price was lowered in two stages: first, by one-quarter and, second, by one-half. In each case, machinery costs were reduced by CHF 33,750. The capacity utilisation (40 ha/a) and area performance (0.26 ha/h) remained unchanged in this scenario. A 50% reduction in the purchase price of the prototype reduced the total projected plant-protection costs to fall linearly, by CHF 1011, to 70%. Lastly, the area performance per hour was modified. In this scenario, the plant-protection costs were determined for area performances of 0.26 ha/h (driving speed 1.5 km/h) and 0.88 ha/h (driving speed 6.5 km/h). The latter was the average hoeing speed of a CWH device. The capacity utilisation was 40 ha/a, and the purchase price was 135,000 CHF. The 3.4-fold increase in area performance resulted in a reduction in machine and labour costs, so the total costs for plant

Table 5
Factors and their positive influence on the adoption of digital technologies.

Factor	Positive influence on technology usage
Attitude	Positive attitude towards new technologies
Skills and experience	High technological skills and experience, organisational capabilities
Support	High-quality and close-knit support
Learning	Willingness to learn, readiness for further education
Self-efficacy	Trust to be able to manage the adoption and usage of a new technology
Initiative	Proactivity
Handling risk	Willingness to take risks
Handling difficulty	Ability to handle difficulties
Data perception	Acceptance of sharing data with other actors, e.g. with manufacturers

Table A.1
List of video recordings for time studies (prototype in operation).

Recording date	No. of videos	Vegetable crops	Work processes
03.09.2021	5	Green lettuce/ iceberg / lollo rosso / batavia / oak leaf / romaine	Hoeing
01.09.2021	4	Green lettuce / romaine / endive	Hoeing
25.08.2021	5	Green lettuce / batavia / oak leaf	Preparing hoeing device and computer settings at field edge, hoeing
24.06.2020	4	Celery root / green lettuce / oak leaf / lollo	Hoeing
23.06.2020	2	Celery root / green lettuce	Hoeing
20.05.2020	2	Bok choy	Hoeing
16.05.2020	3	Fennel / bok choy	Turning at field edge
01.10.2019	4	Bok choy / parsley	Preparing hoeing device and computer settings at field edge
11.09.2019	3	Bok choy / parsley	Spot spraying, preparing device for return travel to farm
25.07.2019	6	Fennel/ zucchini / bunching onion / green lettuce	Preparing spot spraying devices, spot spraying and hoeing
18.07.2019	8	Oak leaf	Computer settings, hoeing

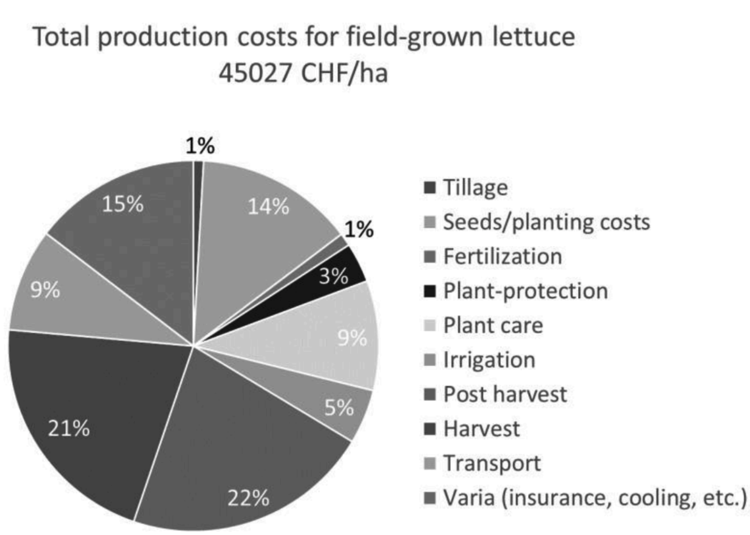

Fig. 6. Total production costs for field-grown lettuce and the relative share of work methods (ProfiCost, 2020 [33]).

Table A.2
Plant-protection strategy 'Standard'.

Pass	Plant-protection product	Registered amount [l/kg*ha]	Price [CHF/kg)]; [CHF/l]
1st	Stomp Aqua (herbicide)	2.0	17.71
2nd	Kerb Flo (herbicide)	3.375	39.20
3rd	Ridomil Gold (fungicide)	2.0	28.50
	Karate Zeon (insecticide)	0.1	130.00
	Movento SC (insecticide)	0.75	104.00
4th	Revus (fungicide)	0.6	78.33
	Dipel DF (insecticide)	0.6	102.00
	Movento SC (insecticide)	0.75	104.00
5th	Revus (fungicide)	0.6	78.33
	Dipel DF (insecticide)	0.6	102.00
	Plenum (insecticide)	0.5	299.00
6th [2]	Generic product (molluscicide)	10.0	7.00

[2]The sixth application was carried out with a centrifugal spreader.
In addition, a mechanical weed control pass was carried out (CWH device). The timing depended on the degree of weed infestation.

Table A.3
Plant-protection strategy 'Prototype'.

Pass	Plant-protection product	Registered amount [l/kg*ha]	Price [CHF/kg]; [CHF/l]	Amount relative to 'Standard' [%]
1st [3]	Ridomil Gold (fungicide)	2.0	28.50	19
	Karate Zeon (insecticide)	0.1	130.00	19
	Movento SC (insecticide)	0.75	104.00	19
2nd [4]	Revus (fungicide)	0.6	78.33	30
	Dipel DF (insecticide)	0.6	102.00	30
	Movento SC (insecticide)	0.75	104.00	30
3rd [5]	Revus (fungicide)	0.6	78.33	100
	Dipel DF (insecticide)	0.6	102.00	100
	Plenum (insecticide)	0.5	299.00	100
4th [6]	Generic product (molluscicide)	10.0	7.00	100

[3]The first application was carried out with the prototype, which removes weeds inter and intra row simultaneously during spraying.
[4]The second application was carried out with the prototype which removes weeds inter and intra row simultaneously during spraying.
[5]The third application was carried out with a standard boom sprayer (as in the standard strategy). At this crop stage, lettuce plants cover most of the soil and limited pesticide savings can be achieved through the use of the prototype.
[6]The fourth application was carried out with a centrifugal spreader.
In the 'Prototype' strategy, an early pass with the prototype removing only weeds was included.

protection decreased by 16%.

To assess the potential for reducing the cost difference between prototype and standard strategies, two scenarios were compared in the following: high-cost 'prototype now' and low-cost 'prototype future' (Table 4). Assuming (i) a capacity utilisation of 40 ha, (ii) a purchase price of CHF 135,000 and (iii) an area performance of 0.26 ha/h, the plant-protection costs of CHF 3379/ha for the 'prototype now' scenario were significantly higher than for the standard strategy, for which the costs were CHF 1563/ha. The 'prototype future' scenario was based on assumptions that are considered realistic and achievable based on current projections. In this future scenario, (i) the prototype was used for the field cultivation of lettuce at 25 ha per year (a utilisation of 100 ha of lettuce), (ii) the purchase price was halved to CHF 67,500 to account for economies of scale and (iii) the area performance was increased to 0.88 ha/h. Given these assumptions, plant-protection costs would come to CHF 1442/ha or 43% of the costs proposed in the current prototype strategy, which is 8% less expensive than even the standard strategy (CHF 1563/ha).

Until now, the study has discussed only crop protection costs in the context of field-grown lettuce production. Overall, the total costs for the production of field-grown lettuce come to around CHF 45,000/ha according to calculations made using ProfiCost (Fig. 6 and Table A.5). The

Table A.4
Model assumptions for machine cost calculation 'Prototype' according to Gazzarin (2021).

Machine type	'Prototype' Hoeing/spot-spraying device	
Area performance [ha/h]	0.26	
Purchase price [CHF]	135,000	
Capacity utilisation per year [ha]	40	
Payback period (years)	10	
Technical life [ha]	500	
Utilisation rate [%]	80	
Residual value (factor)	0.1	
Load level motor [%]	0.6	
Repair and maintenance factor	0.9	
Building requirement [m^3]	25	
Management and risk surcharge [%]	10	
Additional supplements [%]	0	
Cost calculation	[CHF/year]	[CHF/ha]
Amortisation	13,500	
Interest costs	1296	
Building costs	150	
Insurance and fees	150	
Total fix costs	15,096	377
Repair and maintenance	243	
Fuel	—	
Auxiliaries	—	
Total variable costs	243	
Machine rate net (without surcharges) [CHF/ha]	620	
Machine rate incl. surcharges [CHF/ha]	682	
Hourly machine rate [CHF/h]	177	

Table A.5
Model assumptions and total production costs for field-grown lettuce/ha (CHF/ha, conventional technology) calculated with ProfiCost [33].

Activity	Details	Direct costs [CHF/ha]	Labour costs	Machine costs	Aggregated costs
Tillage	plough/harrow	—	87	313	400
Planting costs seed-stock speedy	plant machine, 4920	813	520	6253	
Fertilization	fertiliser applicator, fertiliser	448	20	41	509
Plant-protection	sprayer, centrifugal spreader, pesticides	829	185	358	1372
Plant care	fleece, ridging hiller	908	3252	168	4328
Irrigation	water, pipe	1500	651	—	2151
Post-harvest	package materials	9767	—	—	9767
Harvest	harvest machine, packing	52	8735	789	9575
Transport	truck	—	1017	3049	4066
Varia	insurance, cooling, etc.	1089	165	5353	6607
Total		19,513	14,925	10,589	45,027

use of the prototype generated additional costs of 4%. If, as assumed in the prototype future scenario, the costs can be reduced over time, then the total production costs of the prototype strategy would be comparable to the total production costs of the current standard strategy.

Social and psychological aspects: drivers of adoption

In addition to the cost analysis, this study also placed great importance on the social and psychological factors that drive technology adoption. Statements made by the interviewed farmers are presented in italics. At the beginning of the project, the farm manager had a rather wary ***attitude*** towards the new technology: *'So, I was a bit sceptical about it working, and was then actually pleasantly surprised at how it worked'*. The farm manager was convinced that a positive attitude is essential for the use of new technologies: *'Yes, when you approach it with a negative attitude, then you're wiser to just forget it'*. The farm manager's vision for the future of Swiss vegetable production underlined his positive attitude: *'Four years ago, we were on a hydroponic salad farm in Holland that had nine hectares of greenhouse, everything fully automated as well, and when we saw that (.) Yeah, you've got to say, that's the future in Switzerland as well, exactly'*.

In the interview, the question was raised as to who should be responsible for technological progress in the company. The responsibility for developing the ***skills and experience*** required to adopt digital farm technologies does not necessarily lie with the manager. According to the interviewee, an employee can possess them too: *'Well, 'Junior' copes best with the technology. Again, a different generation to us, and afterwards of course we also have our son-in-law, who works here 20% of the time as an agricultural machinery mechanic'*. However, the farm manager was convinced that if they had the will and enthusiasm, older people could also ***learn*** to use digital technologies. Skill acquisition courses offered by the manufacturer or the sales organisation only made sense to him if people can acquire hands-on experience as well: *'I find it easiest to learn when I can operate it directly'*. Handling the technology, he felt, is *'a question of practice'*. The experience of how one best learns to handle the prototype and thus expands one's skills is something that he passed on to his employees. He did not require manufacturer training for his staff.

Furthermore, the farm manager pointed out that good and accessible ***support*** and direct contact with the company's development department were essential during the pilot phase of adoption. On this vegetable farm, insufficient support led to delays and stress. The farm manager put particular emphasis on the need for close-knit support in the initial stages of using a new technology: *'So, certainly at the beginning, you need support, and there it's important to really have someone behind you who knows exactly what's what, and afterwards you're happy [to have support] from time to time if a special problem comes up'*. For this farm manager, the actual use of the prototype did not lead to increased stress levels; it was a lack of timely support when needed that caused stress.

A further psychological factor is ***risk handling***. In response to the question of whether he was prepared to take risks or would rather avoid them, he stated, '*We've always taken risks.*' The fact that he created a model of a facility he saw ten years ago in Belgium, sought a market for it, and had now been producing on his own facility for six years confirmed not only his willingness to take risks but also his proactivity in taking a pioneering role in the introduction of new technologies. The early use of technologies that were not yet in common use was indicative of a high risk tolerance: *'Er, we had high tunnels relatively early on, when there were hardly any high tunnels at all in Seeland [name of the region where the farm is located]'*. This leads to the next psychological component that influences successful adoption which is the experience of ***self-efficacy***. The term refers to an individual's conviction that they can successfully cope by themselves, even with difficult situations and challenges. The farm manager had been dealing with digital technologies for quite some time now and was confident that they were working. Even when it was a new technology, he felt he would be able to cope with it. However, the introduction of new technology to farms can also cause ***difficulties***. The farm manager stated that it is quite common to make certain farm-specific modality adjustments. Awareness that difficulties are a common part of the adoption process, along with the will to overcome those difficulties, can contribute to a successful technology implementation.

Concerning perceptions about data collection, the farm manager agreed in principle with the collection and transfer of ***data*** within the context of digitalisation. He agreed to pass on his data to support research, since he also benefits: *'Yeah, when data comes to you [researchers], we know what's done with it'*. In terms of data handling, especially production data, the farm manager had two concerns: first, he wanted more information about what happens with the data and how they are interpreted when they wind up with the federal government; second, he felt that the data collection, which requires additional effort from farmers, ought to be remunerated.

The farm manager raised further points concerning the **future promotion of camera-controlled spraying and hoeing devices**: 'Plant-protection isn't approved indefinitely—herbicides and such (.) And then we've got to look for solutions'. Furthermore, 'When the plant-protection thing has come to fruition, where we can do two measures with just one, umm, we've already made huge strides, haven't we?' According to the farm manager, the future **availability of workers** willing to accept the working conditions in an agricultural environment plays an important role in the process of adopting a new technology that has the potential to reduce the physical or timely workload. Finally, to answer the question of how people who have **no enthusiasm for technology** can master digitalisation, the farm manager smiled and recommended the hiring of 'contractors'.

The farm managers' statements allowed us to derive the impact of the previously discussed factors on the adoption of digital technologies and specify in what way these factors have positively influenced the adoption process (Table 5).

Discussion

Assessing new technologies requires a multidisciplinary perspective. Only by assembling the four aspects of environmental, labour, economic and social issues can we create a holistic picture of the adoption process. The results of the present study make this abundantly clear. This study aimed to identify the most important influencing parameters for the adoption of the new camera-controlled plant protection technology. With an average insecticide reduction of 75% over the lettuce-growing season compared to the conventional strategy, the prototype showed high potential for resource savings and a positive impact on the environment. The technical features of working width and driving speed significantly influenced labour demand. The results showed a working-time requirement for plant protection of 3.83 h/ha (prototype) compared to 0.65 h/ha with conventional technology. In contrast, the handling of the new technology had only a marginal effect on the working-time requirement of 0.06 h/ha, which was twice as high as that of conventional technology. This result is attributable to the fact that the corresponding technical and digital settings usually have to be made only at the beginning of the workflow. Nevertheless, this led to a different workflow on the farm, as two people were needed to manage the settings. The prototype's current purchase price (135,000 CHF) accounted for a high share of machine costs, which in turn accounted for 78% of the total costs; unfortunately, this prevented the prototype from being economically viable.

With regard to the use of digital technology, one might distinguish between two types of producers in the future: those who rely on contracting out farm work and those who acquire competence in information technology. The manager of the pilot farm showed his clear entrepreneurial focus when he assessed both types as potentially successful in the course of adopting a new technology. Self-efficacy and a willingness to take risks are traits that promote entrepreneurial thinking in agriculture [21, 42, 43] and, as Janker et al. [10] have found, are closely associated with higher learning capacities. The farm manager in this case is an experienced tech-savvy individual with high digital competence who also had high expectations for his self-efficacy, all of which are qualities whose contribution to successful technology adoption has not yet been corroborated in the literature [14].

Technological and digital competency appeared to play a crucial role on the pilot farm. The farm manager, his son and his son-in-law all possessed these skills. Moreover, it was important to the farm manager that he introduce the employees to the technology himself and that they then use the technology regularly. As mentioned in the interviews, he asserted that these technologies are best learned and applied through direct experience rather than through a theoretical process. This hands-on approach could favour the transfer of smart technologies to practitioners. The interview further revealed that, particularly when a new technology is first introduced, close and high-quality support from the manufacturer or the sales company, as well as thorough instruction for employees, is necessary to ensure trouble-free operation. These results agree with the findings of Fielke et al. [44], who pointed to the importance of agricultural knowledge and extension networks for the successful introduction of digital technologies. Extension services often require data sharing, which, despite evidence of concern about the use of farm data by third parties [45], was not shared by the manager of the pilot farm.

Even with many advancements, the prototype technology is currently in a stage where the farmer must be physically present to operate and supervise the work process. The process of digitalisation not only increases capital requirements but, in its current form, also labour requirements. This raises the question of whether there is any motivation for a farm manager to adopt it. For a technology described in theoretical terms by researchers to be successfully used in practice, major hurdles must usually be overcome. The interview suggests that the farm manager's personality plays a major role in successful adoption. His-positive attitude towards new technological developments, in general, and the prototype for camera-controlled plant protection, in particular, appears to be the most important factor in successful technology adoption. At the same time, his pioneering spirit, his networking with other stakeholders and his personal initiative should be emphasised. These traits and behaviours support the farm manager's belief in the future benefits of the new technology, even if not all of these benefits can be realised at this stage. This optimism suggests that he is aware that in the future, it will be increasingly difficult to find people who are prepared to do physically strenuous work outdoors and in all weather, which he mentioned in the interview. Groher et al. [30] found that, in Switzerland, digital technologies for vegetable crops are already in use to reduce the physical workload. A switch from monotonous physical labour in the fields to monitoring automated operations from a central location represents a decrease in workload, which could lead to higher technology acceptance rates amongst employees. The critical question remains whether it is possible to hire employees with the required technological and digital competencies if there are no qualified persons on the farm. Another reason for the farm manager's motivation stems from the particular growing conditions on the pilot farm. Under certain circumstances, the cultivation conditions for lettuce require an additional mechanical weed control pass due to early weed growth. On the pilot farm, part of the hoeing was performed manually. The farm manager highly values the digitally assisted hoeing capability of the prototype because it contributes to a significant reduction in the physical workload.

From a labour perspective, it would make sense for the prototype to aim to double its current working width, although its low efficiency is not just a result of its lower-than-ideal working width. Sørensen et al. [46] analysed the operation and costs of automated weeding in organic farming scenarios and pointed out the impact of the utilisation rate and the weeding quality. When two complex activities, such as camera-controlled hoeing and camera-controlled application of plant-protection products, are carried out simultaneously, there is an increased susceptibility to breakdown. This has a direct effect on driving speed. However, development should aim for a truly autonomous hoeing robot that does not require human supervision during the process. In a country like Switzerland, which experiences high prices and scarce labour resources, the introduction of robots in crop production takes on a special significance. Only once the technology has developed to a stage where the machine can perform hoeing functions unsupervised will the expected shift in the capital-labour ratio take place. The specific types of commercialized crop robots made available will depend, in part, on market size. In 2016, Schnieper [47] conducted a study on hoeing devices on farms in Switzerland. At that time, digitally assisted hoeing devices were commercially available from four manufacturers. According to the sales companies, 23 to 29 devices were used on farms. The respective share of the four brands was between 3 and 15 units. Highly specialized robots would be commercialized only for relatively large markets and/or high value crops. The ongoing transformation process in agriculture suggests that the industry ought to take steps from automation to autonomy [48]. However, this development is not yet as advanced in vegetable production as it is for arable crops. A general-purpose robot with specialized attachments would probably be the most attractive prospect for a mosaic of niche markets.

Regarding economic considerations, a calculation of the unit prices (e.g., per head of lettuce) might shed further light on the cost-effectiveness of smart technology. Nevertheless, efficiency and cost-effectiveness are not the only incentives for using a new technology. Nowadays, many plant protection products are subject to extensive environmental regulations with respect to drift and run-off. Environmental protection goals are becoming wider ranging and more complex, and it is expected that even stricter regulations will be passed in the future. The incentives for the market launch of the prototype acquire an additional dimension when the consumer also forms part of the equation. Quality Label programmes could also take into account the argument to reduce the use of plant-protection products. The use of this new technology could also prove attractive if the consumer is prepared to pay a premium for production methods with a lower environmental impact or if the state were to develop a scheme that reimburses farmers for the adoption of eco-friendly production methods.

Limitations and future research

The present study considered the adoption process of a new technology based on a case study of a practical vegetable farm. Because each farm's specific situation has a significant influence on observations about technology use, labour, economy and social issues, the transferability of the results will have to be verified based on studies conducted on other farms. Here, an application of the ADOPT framework [17] could be a useful supplement to the qualitative approach in order to assess the adoption process in detail. From a research perspective, the focus of this study was on the technical optimisation and further development of the prototype. With regard to labour and economic aspects, prototype scenarios in organic farming should be further analysed. Due to restrictions on the use of pesticides, further studies on the substitution of manual labour and workload reduction should be prioritised. The higher prices that can be achieved for organic products might also contribute to cost efficiency. In a cost-efficiency analysis, whether conventional or organic, the influence of the new technology on yield and quality should be taken into account. If there is no effect or even an improvement compared to conventionally grown crops, this argument might provide additional incentives for technology adoption. The possibilities for inter-farm use of the prototype by farm collaborations or contractors and related changes in the job profiles of farmers are fertile ground for more research based in Switzerland, which has a high proportion of family farms. As a final limitation, the case study presents solely a successful adoption process; accordingly, the character traits that enabled the process were identified in the statements and attitudes of a single farm manager. Further research on other farms is required to gather more insights into the traits that promote, hinder or prevent the adoption of new technologies than can be gleaned from this case study alone.

Conclusion

The development and adoption of new digital technologies are driven by multiple intersecting factors. In the case of the study's plant-protection prototype, Swiss policy with regard to environmental protection measures that were already implemented or expected to be passed played a decisive role. Vegetable producers are under great pressure due to the ban on effective but environmentally harmful pesticides and the need for suitable alternative production methods. The development of a device that reduces pesticide use is one of several responses to this situation. Beyond environmental policies, the manager of the pilot farm made it clear that finding external labour also poses challenges. Nevertheless, from this difficult starting position, which is shaped by external influences, he is enthusiastic about new technology. Even for enthusiastic farmers, bringing digital technologies to market maturity requires technical development as well as individual farmers having technological skills, enthusiasm and high expectations for self-efficacy. Policymakers should be aware of their responsibility to support farmers in adopting new technologies by providing appropriate financial and advisory measures.

1CHF = 1.0824 US-Dollar (27.01.2022).

Data availability

Data will be made available on request.

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Authorship contribution statement

S.G. conducted the time studies with the support of K.H. (labour), K. H. analysed the results, E.B. (economics) defined the strategies with the help of experts and performed the cost calculations, L.R. (sociology) analysed the literature and conducted the socio psychological interview. K.H. and L.R. wrote the article with contributions from E.B., S.M. (socio economics) and S.G. (preparation of figures) and all authors gave critical feedback on the manuscript.

Appendices

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