Received: 17 October 2022 | Accepted: 11 September 2023

DOI: 10.1111/soru.12456

ORIGINAL ARTICLE

Sociologia Ruralis Journal of the European Society for Rural Sociology

ESRS

Cyborg farmers: Embodied understandings of precision agriculture

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Abstract

Precision agriculture is often seen as disembodied and placeless, promised to either bring about a fourth agricultural revolution or as the start of dystopian rural futures, where farmers and their knowledge will be replaced by machines. A growing body of literature shows more nuanced ways of working with precision agriculture. This illustrates the need to investigate how, and under which conditions, precision agriculture is integrated and internalised by farmers. Based on 25 in-depth interviews with male Dutch crop farmers, contractors, researchers, and ag-tech developers, we develop the concept of the cyborg farmer, who embodies the use of precision technology while maintaining an intimate relationship with agro-ecological context. This approach challenges the mind–body dichotomy in that the cognitive is not understood as primary, as emotions and the materiality of the body are taken seriously. This perspective emphasises the importance of embodied knowledge in how farmers interpret precision agriculture data. Our findings highlight the productive tension between data-driven elements of precision agriculture and the embodied and intuitive understanding of agro-ecological context.

This productive tension consists of the successful integration of different forms of knowledge by the cyborg farmer, where embodied sense-making and precision agriculture data are integrated into the formation of useable knowledge. The cyborg farmer maintains farmer agency and resists the dominance of algorithmic rationality over other forms of knowledge .

KEYWORDS
assemblages, digital agriculture, embodied knowledge, more-than-representational knowledge, new materialism, process-relational perspectives, Agriculture 4.0, precision agriculture

INTRODUCTION

> *As a farmer, you need to enter your land. You need to feel it, to smell it. That will never change. But of course, farms get bigger. Back in the day, you could see all your fields on an evening walk. But today's farmers cannot do that in one evening. So you need a tool to show you what's the matter, so that when I take a walk I know where to go.*
>
> Farmer CF10, an arable farmer in The Netherlands on an 800-ha co-operative farm

To feel the land, to smell the land, these are not the terms you might expect when a farmer describes their use of precision agriculture. On the contrary, precision agriculture is often seen to alienate farmers, where they become office workers, far removed from the field (Gardezi & Stock, 2021). The connection between farmer and land in these scenarios is, figuratively speaking, little more than the fibreglass cable transmitting data between farmer, fields and technology.

Techno-optimists describe the potential of these scenarios as something positive and desirable, seeing precision technologies (the technologies that collectively make up precision agriculture) as the suite of technologies that will bring agriculture into the 21st century, increasing productivity while reducing environmental impacts (Bhakta et al., 2019; Marvin et al., 2022). In these imaginaries, tasks can be taken out of the hands of the farmer, and some (if not all) of the decision-making can be replaced by software and algorithms. Humans might be involved at higher levels of decision-making, but operational activities can be replaced with digital technologies (Wolfert et al., 2017). Decision-support tools, robots, drones and a host of other technologies would take the farmer out of the field and create an autonomous farm (Shamshiri et al., 2018). While this is a vision for the future rather than current reality, these imaginaries do structure the development of technologies and future farm work settings (Daum, 2021; Lajoie-O'Malley et al., 2020).

In rural sociology, a large body of critical work has emerged on these same imaginaries of precision agriculture, taking a more cautious position. These more techno-critical, or dystopic scenarios of precision agriculture, describe the risks of precision agriculture for farmers, farm labourers and rural communities. These risks range from negative effects on labour relations and farmer skills to broader concerns about power relations in the agri-food chain, which shift due to the entry of venture capitalists and software companies (Brooks, 2021; Duncan et al., 2021, 2022; Fraser, 2019; Miles, 2019; Prause, 2021; Rotz et al., 2019a). These authors show the downsides of precision agriculture, especially when the visions of large agricultural corporations, big tech and finance structure the development of precision technologies (Clapp & Ruder, 2020; Duncan et al., 2021, 2022; Miles, 2019). Precision agriculture in its current form is seen as excluding styles of farming other than large-scale mono-cropping and forms of knowledge other than data-driven knowledge (Brooks, 2021; Gardezi & Stock, 2021; Gras & Cáceres, 2020; Miles, 2019).

These concerns are valid and key to understanding the impact of precision agriculture. At the same time, in these concerns, there is often a view of precision technologies as disembodied and placeless tools. An emerging body of work has shown that such dichotomous thinking (i.e., precision agriculture per se excludes certain ways of farming) does not fit with the reality of farming. Instead, agriculture has been characterised as a highly embodied practice in which farmers' corporeal and sensorial experiences and the multiple connections between the farmer and the material and non-human elements in the farm are central (Carolan, 2017; Ditzler & Driessen, 2022; Higgins et al., 2017; Legun & Burch, 2021). Different engagements with precision technology are possible, which can, for example, include partial use and retrofitting of existing equipment (Rose et al., 2022). These studies connect to a broader call for agri-food studies to attend to the lived experience on the farm and the assemblage (and assembling) of the farm in making agriculture work (Carolan, 2016; Darnhofer, 2020). This calls attention to the micro-politics and small interactions on the farm and its materiality rather than to broader, deterministic power structures. Beyond looking at visions and imaginaries of the future, it shows how the technology is experienced here and now and shows the messy and improvisational nature of using precision agriculture.

However, despite an emerging body of work on precision agriculture assemblages (Comi, 2020; Higgins et al., 2017, 2023), detailed studies on how farmers embody precision technologies are still scarce, and this is where this article aims to make a contribution. We will show that precision agriculture can be a further expansion of the embodied farmer, not an element apart from the farmer but part of the whole. Hence, precision agriculture becomes an extension of the farmer, where farmer, precision technologies and agro-ecological context are integrated. This is developed through the concept of the '*cyborg farmer*', coined by Klerkx et al. (2019) and Klerkx (2021), but not yet further developed or explored in detail. This concept is based on a posthumanist understanding of precision agriculture, where the body of the farmer is centred as the site of understanding precision agriculture. This is a novel way to think about how farmers engage with precision agriculture, connecting to approaches that show ways of engaging with precision agriculture that go outside of the aforementioned dominant corporate model imposed by ag-tech companies (Ditzler & Driessen, 2022; Higgins et al., 2017; Legun & Burch, 2021). The question that guides our enquiry is: *How does the embodied use of precision technologies by farmers take shape, and what does this mean for the development of precision agriculture and for the formation of cyborg farmers?*

To answer these questions, we draw upon semi-structured interviews with Dutch crop farmers, contractors, ag-tech companies, advisors and researchers all working with precision agriculture. The respondents were required to have experience in working with precision agriculture.

To further explore this research question, we will provide a theoretical framework introducing the key concepts that supported our analysis. We start with a description of how embodiment has been conceptualised in a broad literature on knowledge, digital technologies and cybernetics. We connect this to a conceptualisation of embodied technology use and link this to agriculture.

The theoretical framework is followed by the methods section, the findings and a discussion and conclusion.

CONCEPTUALISING THE CYBORG FARMER

We seek to unravel how precision agriculture is combined and integrated into the socio-material context of the farm and the mechanisms of how farmers use precision agriculture by connecting this to embodied knowledge.

Embodied knowledge and the role of embodied knowledge in agriculture have ties to a broader movement in rural sociology that seeks to understand the diverse knowledge of farmers. Experiential, traditional, local and tacit knowledge are terms that describe the knowledge that farmers develop over time through the physical act of farming (Burton & Riley, 2018; Carolan, 2008; Higgins et al., 2017; Lundström & Lindblom, 2018). In this article, we use the term embodied knowledge, which stresses the corporeal aspect of knowledge and highlights the more-than-representational nature of this knowledge (Maclaren, 2019; Phillips, 2014). More-than-representational knowledge can be understood as attuned to the lived experience where the representation of this knowledge, such as in this text, is never able to fully represent this knowledge, as this knowledge is based on everyday experience, routines, encounters and embodied experience (Carolan, 2008; Lorimer, 2005).

While other understandings of knowledge forms might also understand knowledge as more-than-representational, embodied knowledge makes explicit the role of the body in knowledge production (Carolan, 2008). This means that we see knowledge as a relational achievement that is produced through the body, meaning that knowledge is produced through the extended self, in an assemblage of human and non-human actors (Brians, 2011; Clark, 2008; Gieser, 2008; Heersmink, 2012). This follows a broader relational-material and process-relational turn in rural sociology (Comi, 2019; Darnhofer, 2020; Roe, 2006).

The more-than-representational approach we engage with understands all knowledge as produced through the body, where the body is central to knowledge production. This assumes the integration of mind, body and broader life-world, where knowledge is not produced in the mind but is an inherent quality of the body situated in the world (Gieser, 2008). The mind should not be seen as a separate or single organ, where knowledge is produced based on inputs, but rather as an element in the production of knowledge, where knowledge is produced through the lived body, which simultaneously experiences, acts in and is aware of the world (Clark, 2008; Cutler & MacKenzie, 2011). The body provides us with access to the world, and tactility and other senses provide this access. We understand and learn about the world through embodied experiences (Hansen, 2006). This points us to the non-dichotomous nature of the cyborg farmer, where mind and body are on intimate terms, and the boundaries between the human and non-human are porous (Darnhofer, 2020).

The extension of the body through technology is integral to the formation of the cyborg farmer. In rural sociology, there has been limited attention to the potential of technologies and tools in embodied knowledge production, as the emphasis is usually on landscapes, countryside and nature (Maclaren, 2019; Phillips, 2014; Roe, 2006). An exception is Carolan (2007, 2008) who emphasises the role of technologies in shaping the body and how technology leads to particular ways of knowing the world. This is, for example, linked to the use of the tractor by farmers, which provides a unique kinaesthetic experience and viewpoint, placing the farmer inside the field and allowing them to see and feel the land through the tractor (Carolan, 2008). A further example of embodiment of technology is provided by Merleau-Ponty (2002), who described the blind man's stick, which: 'ceased to be an object for him, and is no longer perceived for itself; its point has become an area of sensitivity, extending the scope and active radius of touch, and providing a parallel to sight' (Merleau-Ponty, 2002, p. 165). The body is born anew through every interaction with technology, as it is chimeric in nature, forming a new whole through human–technology interaction. Humans and technology have long been intertwined, where it is difficult to tease out where the human starts and the technology ends (if one can do so at all; Heersmink, 2012). The knowledge available to us is co-determined by the technologies we use, which are integrated with our bodies (Heersmink, 2012).

Krzywoszynska (2016), who describes care in vineyard growing, helps understand what embodiment and embodied knowledge look like in agriculture. It is a knowledge developed in the agro-ecological context of the farm, developed and shaped through lived experience. To understand embodied knowledge is to understand the impact of taste, smell, feelings, sounds and views in agriculture on the production of knowledge. This embodied knowledge determines which branch is pruned in a vineyard (Krzywoszynska, 2016) and allows people to form a connection to the countryside (Carolan, 2008). We would stress that integral to this formation of embodied knowledge are also the technologies (whether a specific shape for pruning, secateurs or tractors) that mediate the interactions between farmers and the agro-ecological context. These encounters between technology, humans and environment form the farm and inform the embodied knowledge of farmers.

This understanding of how knowledge and technology are intertwined is essential to our understanding of digital technologies. Lundström and Lindblom (2018) have shown how farmers make sense of decision support systems by connecting the data and information afforded by measurement and modelling technology to their existing embodied knowledge. We take this a step further, where we do not see technology merely contributing to knowledge production. Instead, an integration of human and technology, a cyborg, constructs and informs embodied knowledge (Heersmink, 2012). In our view, this perspective synergises with the recent interest in relational approaches in rural sociology. The embodiment perspective expands on the relational approach by providing an understanding of the body as an unstable assemblage, formed through the relations in which it enters with other objects and technologies. The body itself is an assemblage in a constant state of becoming (Brians, 2011; Currier, 2003), entering into relations with its broader agro-ecological context and with other human and non-human actors and assemblages.

This follows broader posthumanist approaches, which have set out the intertwined nature of humans and technology, where these collectives are hybrids or cyborgs of nature and technology (Bear & Holloway, 2019; Finstad et al., 2021; Haraway, 2006). The collective of human and non-human actors active in farming shapes how we understand the cyborg farmer, developed out of humans and technology (in our case precision agriculture), and shows the relationships between humans and the farming environment (Klerkx et al., 2019). Bear and Holloway (2019) and Finstad et al. (2021) explored similar developments between farmers, cows and milk robots, highlighting the more-than-human entanglements that develop. They use the term hybrids to explore how human and non-human actors are part of co-constitutive relationships, existing through their relation to one another. As Søraa and Vik (2021) show, this hybrid is a cyborg, existing through its connections to other actors, through human and non-human animals and through technology.

The cyborg farmer is an embodied collective of human and non-human actors, conceptualised through the body, where the physical presence of the farmer matters. The farmer becomes a cyborg through the extension and augmentation with technology but remains present and embodied in an agro-ecological space. Precision technologies are mediated by the cyborg farmer, which in turn augment and aid the farmer in understanding their fields and crops. Precision agriculture opens up these new spaces, for example, through new spatial dimensions provided by drones and augmented reality, new tactile and motorial dimensions provided by automation and robots and cognitive dimensions triggered by artificial intelligence (Comi, 2020; Klauser & Pauschinger, 2021; Klerkx, 2021; Klerkx et al., 2019). This integration between farmers and precision agriculture, and the implications of this integration, has so far mainly been on a conceptual level, where the cyborg farmer is a potential development. In the rest of this article, we set out to show that cyborg farmers are already a reality and that it is the farmer using precision technologies in an embodied way.

METHODOLOGY

The initial aim of this research was to understand how precision technologies are used and adapted by Dutch crop farmers. In researching this, we based ourselves on the work of Higgins et al. (2017) who show how the adoption and use of precision technologies is ordered by commercial-technological and biophysical factors. Our aim was to understand how farmers adapt precision technologies, how they adapt their farm to precision technologies and how they use these technologies. We opted to use semi-structured interviews with farmers and other actors in the precision agriculture industry to study this. The question list is provided in Annex I in the Supporting Information.

It was later, while analysing the data, that we realised the relevance of farmers' sensory experiences in how they understand precision agriculture. These embodied experiences are by nature more than representational, which are challenging to capture through representational methods like interviews (Maclaren, 2019). These experiences can also not be fully captured in a codified account (Carolan, 2008). Nevertheless, this does not mean that it is impossible to describe the more-than-representational embodied experience of farmers but rather that this account is but a partial representation of the more-than-representational (Maclaren, 2019; Sutherland, 2021). As Carolan (2008, p. 412) describes 'we cannot literally feel in these pages what respondents truly experienced in their lived experience. But this does not mean that we cannot at least get a taste of their world through their words'.

Respondents were selected through a purposive sampling strategy combined with snowball sampling. We opted for this approach in order to select respondents who had experience with the use of precision agriculture, which is still relatively new to Dutch farms. The interviews were held with crop farmers (some of whom also did precision agriculture contracting work on the side; CF, 14 respondents), contractors (CON, two respondents) agronomic advisors and researchers (RES; five respondents) and people working in the ag-tech industry (IND; four respondents), for a total of 25 interviews. Separate question lists were used for people working in the industry and for researchers (see Annex I in the Supporting Information). Including broader actors than just farmers allowed us to determine the potential for integrating farmers' knowledge with precision agriculture. The interviews took place from November 2018 to February 2019 and took place on the farm and at the workplace if possible, except for five interviews that took place by phone.

The farmers involved in this research varied in their use of precision technologies, their farm size and their farming operation. Details about the farmers are provided in Annex II in the Supporting Information. Farmers were all male and between the ages of 30 and 60. Our sample included more young farmers than is typical for the population of Dutch crop farmers, considering the statistic that 70% of farm owners are over 50 (Berkhout et al., 2022).

The use of precision agriculture varied between farmers, who to varying degrees used GPS (Global Positioning System) for controlled traffic farming, variable rate applications of inputs, soil and crop scans and satellite and drone imaging. Farm sizes ranged from about 40 ha to approximately 800 ha, which captures the range of crop and arable farms in The Netherlands quite well, although farmers in this research generally have larger than average farms. The farms spanned the different biophysical contexts and crops grown in The Netherlands, including flowers, grains and root crops. Most farmers grow a relatively standard rotation of potatoes, sugar beets and grains.

Two aspects where our sample differs from the general population of crop farmers are correlated, which means that larger farms are, on average, operated by younger farm managers (Berkhout et al., 2022). We speculate that this is related with the use of precision agriculture. Extensive use of precision technologies requires capital investments, made possible by having a larger farm. This does not explain why our sample is all male. We did not select for this characteristic, but respondents who replied to our requests for interview were all male. We also asked during the interview whether other people on the farm (e.g., wives, employees, etc.) were involved with the use of precision agriculture, but this was typically not the case. A more in-depth exploration of gender in relation to precision agriculture is outside the scope of this article.

Participants in the research were interviewed using a semi-structured interview guide. Interviews took between 30 and 90 min. Audio recordings from interviews were transcribed using a clean verbatim style in NVIVO 12. Transcription and data analysis were done in the native language (Dutch). Quotes used in the article are translated from Dutch by the first author. Throughout the research and fieldwork, inductive coding was used to form a broad categorisation of the incoming data. Following the fieldwork, the framework that we set out in the theoretical background was used to develop a list of codes. This set of codes was used to code all transcripts and formed the main part of our analysis. Both lists of codes are presented in Annex III in the Supporting Information.

INTEGRATING AND VALIDATING PRECISION AGRICULTURE WITH EMBODIED KNOWLEDGE

In this section, we show how Dutch crop farmers integrate precision agriculture with their existing embodied knowledge. Precision agriculture consists of multiple technologies, some of which are sensor technologies. These sensor technologies can augment the farmer, as they form an addition to the existing senses of the farmer. Now the farmer can also see through different forms of vision, mediated by technology, which augments and aids the farmer in understanding their fields and crops. Sensor technologies become an extension of the vision of farmers, allowing them to know their fields in new ways and to help them understand what is happening in their soils and crops. It allows farmers to see things that are not visible to the naked eye and to integrate this with their knowledge, as a crop farmer (CF5) describes:

> So you can see by eye whether something is wrong with the crop. But once you realise that a certain spot is not as green as the rest, well you are already too late because you only see a 10% difference by eye. With cameras, we can look much deeper and far better. You can anticipate [issues such as nutrient deficiencies, diseases, etc.]

Precision technologies allow farmers to see and perceive things in new ways, extending the farmer and the farmer's eye. At the same time, farmers connect this to their existing knowledge of the field, as the data often say very little without connecting it to their historic embodied knowledge of being in the field. During one of the interviews, the interviewer had the opportunity to look at the soil and harvest maps of one of the fields. Generally, precision agriculture data are presented to the farmer in terms of different maps of the field, where the field is divided into zones with different values for certain parameters (i.e., pH, soil conductivity and biomass). Farmer CF12 highlighted several aspects that were visible to him (but not to the interviewer) in the field maps:

> So you can recognise some things in the map, like this spot is a wet spot where they had to dig a pipe through the land. [Visible as a line in the field that had lower yields and that stood out in the soil maps]. [...] So you also get moisture, yield and dry mass. Look, you even get to see the temperature of the grain. So that's really great. [...] And it's funny to see that because you can see that there is another wheat grown in the outer edge, which we harvested later. And what you can also see in the data, here we harvested first, and then we had some dinner, so when we returned to harvesting, we got a different temperature.

These interpretations of precision agriculture data may not always relate to farm yields or operations, but they shed light on an important aspect of precision agriculture. As the maps remained meaningless for the interviewer while being very revealing for the farmer, we realised that simply having data is insufficient. Understanding the reasoning behind differences in data is crucial. Farmers' first-hand experiences on the land are invaluable in comprehending the meaning of the data. As the farmer describes, this is an embodied knowledge that develops over time, where previous actions in the field are used to make sense of the data that is presented.

This embodied knowledge develops in relation to precision technologies. We present a quote of farmer CF4, who uses NDVI (Normalized Difference Vegetation Index) values (which show biomass and increases in biomass over time) of his fields to decide where to go for the evening walk and relates this to the fact of spreading fertiliser. NDVI values can show reduced growth, but the underlying cause (e.g., disease, nutrient and moisture deficiencies) can only be identified by seeing the crop itself.

> That remains important, but over the years, that has changed. I now go through all the parcels by NDVI values. That means I already know where I need to go in the field, like, here I see something and there I see something else and the rest doesn't interest me as much. Related to that, I also always spread fertiliser myself
>
> Interviewer: Why is that?
>
> Because with spreading fertiliser I can take 30 ha at a time, you go 10 km an hour so it goes fast. And with the height you have, you can see every bit of the field. So you can look around to see what you see, to visualise it for yourself.

The evening walk, influenced by NDVI values and the spreading of fertiliser, is related in embodied knowledge formation. In a way reminiscent of Carolan (2008), the fertiliser spreader provides the farmer with height and speed to see every corner of the field in a limited amount of time. NDVI values direct the sight of the farmers to certain spots, where seeing the crops and the causes of poor growth can be understood. The importance of sight, to see what the data actually say is stressed by CF4. The wish of the farmer is not to sit in his office and to collect and interpret data on his own. Rather, the farmer explains that to understand the data is to walk to the field and combine the various forms of data with the physical experience of being in the field.

This is important to the farmer as the various forms of data do not provide the rich experience of the physical sensory experience in the field (seeing and feeling the soil, crops, weather, etc.). The farmer might look at the land and dig the soil to see what is going on in order to understand what the data are saying. As CF11 indicates, the feeling for it, the feeling for which spots are wet or dry, why they are this way and to go and look (and dig the soil) at these spots is important to validate the data:

> CF11: Well it's not like you reduce the feeling for the soil. For sure you don't. No, no, no.
>
> Interviewer: That also has to stay?
>
> CF11: Yes, yes! It's not like, I do not see how it would work if I sit here in the kitchen and I send the tractor into the land and that's that. I do not see how that would work. Because you have certain spots that you know when you prepare the land, it could be a wet spot, you don't see that in the computer.
>
> Interviewer: You don't think that that could come?
>
> CF11: No, I don't think so. Because you'll always have to come out and see how dry it is, and you see a bunch of things. You can see that with the decision support tool for Phytophtora, which works well as a supporting tool. [...]. But you still have to go and take a look, you have to use your farmers' wisdom.

These quotes highlight the embodied knowledge of farmers in connection to precision agriculture. Farmers go to the land in response to the data they receive, to see the plants, dig the soil and get a general feel for how their crops are looking. However, data are not just interpreted on the spot but are also connected to farmers' wisdom as CF11 states. This wisdom is broader than the single experience of going into the field but involves the repeated experience of farming the same fields over a number of years. The recurring embodied experiences of being in the land, getting to know the land and its wet spots, its dry spots, which spots are growing better and why, develop over the years. Farmer CF2 and farmer CF7 describe how their historically developed embodied experience plays a role in decision-making:

> You know exactly where the risks are through experience. But you still have to go to those places to see what's the matter. [...] With Phytophthora, for example, you know that there are some sure spots [places that have recurring infections) and some spots where it could also be [present]. (CF2)
>
> I am not someone who blindly follows the numbers, but I use my own knowledge and insights. And maybe I'm wrong, but I have been farming for 22 seasons now. So I think I can sense which way it goes and connect the dots. I understand what happens and why. (CF7)

Farmers choose to follow this more-than-representational, embodied knowledge over blindly trusting precision technologies. Decision-making, even if based on precision agriculture data, takes place in the field. Precision agriculture does not mean the farmer can sit back and decide at a distance but rather means that they enter the field and start with a look at the crops to see how they are performing. This is connected to experiences built over years of varying environmental conditions. Crops, weather and moisture are compared to previous embodied experiences of years past. These embodied experiences make precision agriculture data concrete and allow for decisions to be made. This is also recognised by people in the industry, as voiced by IND6 who describes the need to provide advice based on this embodied approach, by taking an auger to dig a soil pit:

> I have had words with some advisory services, who described that they still needed 5 years of extra research [in order to make sense of and provide advice on precision agriculture data]. And I said: 'Well, take an auger and take the farmer into the field'.

The experiences and practices above indicate a certain approach of engaging with precision technologies in an embodied way. To take an auger and to enter the field, to dig a soil pit and see the state of the soil and to experience it. This is how farmers work with precision technologies and how advisors can connect to the needs of farmers in using precision technologies.

The use of this embodied knowledge is to an extent also in tension with the data-driven nature of precision agriculture. There exists an approach to precision agriculture that seeks to highlight the need to base decisions on data and to remove the 'feeling' for it. For RES2, for example, the embodied aspect of using precision agriculture goes counter to a purely data-driven form of reasoning:

> So you learn to see your crops and soils in a different way. You learn to count the numbers and to base your decision-making on those numbers. And that is a different mentality than waking up in the morning and deciding how you'll farm that day. I exaggerate a bit, but that is what you will often see in practice.

This view, of transforming farming purely into a number of data streams, is in tension with making precision agriculture work in an embodied way. Those espousing this data-driven approach indicate that one learns to see the farm in another way. It is about counting the numbers, about data that decide how farming gets done. This approach is not unique to any particular group, as farmers and people in industry and research also describe this. This is illustrated when farmer CF14 describes his need for algorithms in deciding how to use variable rate application:

> We bought a lot of [precision technologies], and I have created prescription maps, even for others. So I know how to work with the technology, that is not the problem. Our problem is rather the agronomic underpinnings. You have a soil scan, organic matter levels, and you want to do something, but which algorithms to use? And then I play it by ear, but that is not scientifically proven.

We describe this to show that there is a tension between embodied experiences and the drive to make agriculture data-driven. A purely data-driven approach would eliminate the potential to 'play it by ear' and to do 'unscientific' farming. Embodiment, and 'the feeling for it', is not necessarily trusted. Farmers are working with precision technologies in an embodied way, but there is a balance, where some of them do seek to codify decision-making and to base their decisions more on data. There is a tension between data-driven, algorithmic farm management styles and more embodied farm management styles. At the same time, there are people in the ag-tech industry, like IND2 who emphasise the need to make technology work with the feeling for it that farmers possess:

> Yes, and farmers find that [being able to see how a decision is made] is important right? Because you can make a closed-off decision, but that is not what they want. They want to keep the feeling for it. To retain the insight, it's very important to preserve that, the insight. [...] Because in the end the basis is agronomy and that remains. We only deliver a tool that can aid the farmer. But it does not make a bad farmer into a good farmer. It can only help bring a good farmer further.

Despite the desire for a data-driven approach, there is the realisation that embodied knowledge is essential in making precision agriculture work. Farmers want to retain autonomy over decision-making and want to be able to see what decisions are based on. Precision agriculture cannot be a black box if farmers want to integrate it with their embodied knowledge, as they need to understand how decisions are made and need to be able to link the underlying data and information to their own embodied understanding of their farm. There is no way to get around the embodied knowledge that is needed in agriculture, as farmer CF2 also sets out when we discussed the future use of precision technologies on his farm:

> Farmer: So we want a live dashboard, right in the canteen.
>
> Interviewer: 'Spray now!?' [the conversation before had been on the potential for precision technologies to make decisions about spraying]
>
> Farmer: No, not like that. Rather, something is the matter and what are we going to do? Who decides when to spray? Not the computer.

And after the interviewer asked whether he would trust a computer with these decisions, the same farmer describes:

> Well, yes, but you would need to provide the computer with a lot of input. I would have to be connected to a plug and you'd have to implant my employees with a chip. So the computer can read their minds and see what they think, and translate that to tasks. It will not be a black box.

To this farmer, precision technologies will ultimately not make the decisions without the input of him and his employees. The embodied experience is central, and in this somewhat futuristic scenario becomes integrated with precision agriculture. The technology itself becomes embodied, implanted in the farmer and farm workers in order to understand the embodied experience of the people working in the field. Even a vision of fully data-driven algorithmic farming needs the embodied experience of the people working in the field.

THE CYBORG FARMER—MIND, BODY AND TOOL ON INTIMATE TERMS

We provide a discussion of our empirically grounded account of cyborg farmers as embodied with precision agriculture. This is the farmer who connects data interpretation to the multi-sensory experience of being in the field. Knowledge develops through the body, extended through technologies and situated in a broader space/environment. This conceptualisation responds to questions on how precision agriculture is changing farms, farmers and farm work and how knowledge is mobilised (Klerkx, 2021; Klerkx et al., 2019; Prause, 2021; Rotz et al., 2019b).

By providing empirical underpinning of the concept of the cyborg farmer, we highlight how precision agriculture only functions as a collective of farmers' knowledge, precision technologies and agro-ecological context. Precision agriculture (through satellite data, drone shots and soil maps) allows for new ways of seeing the land and provides an extension to farmers' knowledge. This extension is reminiscent of the ideas of Klauser and Pauschinger (2021) who describe how drones open up the air as a new dimension in agriculture ('volumetric agriculture') and connect to ideas on emerging forms of 'augmented agriculture' (Klerkx, 2021) in which technology enhances human senses. Precision technologies allow for an extension of the body, providing new dimensions to farming and associated knowledge.

With our findings, we confirm the earlier work of Legun et al. (2022) and Lundström and Lindblom (2018), who show the importance of farmers' knowledge in relation to autonomous robots on farms and for decision support systems, respectively. In our case, the use of embodied knowledge can be recognised in how farmers interpret data. The data that is provided through precision agriculture is calibrated with embodied knowledge by the farmer entering the field, walking through the field where the senses are used to make sense of the data. This centres the farmers' body as the site of knowledge production while linking to the materiality of precision agriculture and agro-ecological space. The farmers' bodies and senses link the data-driven elements of precision agriculture with an embodied understanding of agro-ecological context (Currier, 2003). Embodiment thinking has been developing in the margins of rural sociology (Carolan, 2007, 2008; Krzywoszynska, 2016; Maclaren, 2018). As our research shows, this approach can provide an exciting way to link embodiment thinking to a relational account of technology use. This provides a way to go beyond mind–body dichotomies (Darnhofer, 2020), in which the cognitive is not understood as primary, as emotions and the materiality of the body are taken seriously, that is, the farmer is understood as a being who thinks and senses. Our research shows the importance of the material body situated in agro-ecological space as a focal point for understanding, theorising and critiquing digital technologies (Brians, 2011; Krzywoszynska, 2016).

As we showed in our results, there is tension between the data-driven elements of precision agriculture and the embodied and intuitive understanding of agro-ecological context. At the start of the century, Tsouvalis et al. (2000) wrote about the tension between knowledge cultures in precision agriculture. While farmers use precision agriculture data to a far greater extent, similar issues still exist, and there are similarities in how farmers mobilise knowledge in order to make sense of data. To understand data is to link back to situated and embodied experiences (Tsouvalis et al., 2000).

In response to research on precision agriculture that has emphasised harmful conflicts between knowledge cultures (see, Bell et al., 2015; Carolan, 2017; Miles, 2019), we set out how the tension between knowledge cultures is productive. We see this tension as productive because farmers are situated between these different knowledge cultures and take elements from different forms of knowledge to come to decisions. The cyborg farmer bridges the gap between a data-driven knowledge culture in precision agriculture and the farmers' embodied understanding of agro-ecological context.

Our results show that the cyborg farmer develops when data from precision agriculture is integrated with the embodied experience in the field. Farmers make decisions after the two forms of knowledge have been re-calibrated with one another. This shows the potential for agency in precision-agriculture decision-making, confirming the findings of other authors who highlight farmer agency in the use of precision technologies (Higgins et al., 2017, 2023; Legun & Burch, 2021). This agency of farmers ensures that precision agriculture does not come to dominate the knowledge that farmers use. They keep a diversity of knowledge, of which precision agriculture is one. This nuances authors who describe the potential of precision agriculture as an algorithmic lock-in or as a domination of algorithmic rationality over other forms of knowledge (Carolan, 2020b; Gardezi & Stock, 2021; Miles, 2019).

There are different approaches to this integration of knowledges. Some of the farmers in our results highlight the limitations of precision agriculture and base their decisions to a larger extent on experience and intuition. Others are looking for ways to farm 'algorithmically' and to base their decisions on a far more data-driven approach. There is a spectrum between the two approaches, a scale of possibilities between data-driven and intuitive farming.

In a sense, the cyborg farmer is also a play on the virtual farmer described by van der Ploeg (2003). The cyborg farmer is a persistence of the local art of farming in the face of the virtual farmer constructed by the expert, sensor and data-driven knowledge system embedded in precision agriculture. This goes against farms without farmers that can be run through algorithms and digital technologies, as the cyborg farmer presents the potential to resist these futures, where the embodied knowledge of farmers and farm workers has a key role to play in the development of precision agriculture.

Our findings suggest that there may be different sorts of cyborg farmers, that is, farmers who use embodied knowledge in the use of precision agriculture in different ways and with different intensities. Conversely, human observation, experimentation and calibration by the farmer can counteract possible inaccuracies or 'precision traps' within precision farming (Visser et al., 2021) and connect existing farming practices with new possibilities afforded by precision agriculture (echoing Rose et al., 2022). What our findings add to this earlier work is that the different ways of engaging with precision technologies and the intensity of being a cyborg farmer could lead to what has been coined as 'digital farming styles' (Klerkx et al., 2019). As our findings suggest, these may range from a rather light engagement and embodiment of digital technologies to a heavy engagement and embodiment, which may include several forms of wearables (e.g., sensor gloves, exoskeletons and augmented reality glasses) and digital twins. This could provide a new avenue in a long tradition of farming styles research in rural sociology (e.g., van der Ploeg, 1994, 2012; Vanclay et al., 2006)

PRACTICAL IMPLICATIONS FOR PRECISION TECHNOLOGY DEVELOPMENT

Not all precision technologies are equally suited to the needs of farmers, with some authors wondering whether some of these technologies were ever intended for farmers at all (Duncan et al., 2021, 2022). Venture capital and agricultural technology firms developing technologies that have no use to farmers are well known in the literature (Fairbairn et al., 2022). In the development of precision technologies, it will be worthwhile to focus on the potential of embodied technology use. Multiple scholars have already stressed the need for responsible innovation approaches or more radical emancipatory innovation processes (Bronson, 2018, 2019; Eastwood et al., 2019; Fraser, 2021; Rose & Chilvers, 2018). An approach that is focused on embodied learning would fit well with these responsible and emancipatory innovation processes but would need to better emphasise the inclusion of embodied knowledge. In this, we can learn from innovation approaches that have sought to include different, often Indigenous knowledge in innovation processes (Peddi et al., 2022; Sayarer et al., 2019; Verran et al., 2007). These approaches would support the development of technologies that can function within the diverse biophysical contexts of farms and farmers. In this, our findings support Ditzler & Driessen (2022), who have called for a broader mindset in the development of digital agriculture technologies (in their case, robots for so-called pixel cropping[1]) so that these can be used in a wider variety of farming systems. They emphasise the presence of the farmer in the field as essential to embodied knowledge production for pixel cropping, something that we recognised in our research involving (much more conventional) crop farmers.

For advice and extension providers, connecting precision agriculture to the embodied knowledge of farmers can help advisors and farmers in understanding and using these technologies. Research has shown the importance of tactile and embodied spaces to learning processes (Cooreman et al., 2020; Cowan et al., 2015; Klerkx, 2021), and this can be explored further in future research. Learning about precision agriculture can be as simple as entering the field together with the farmer and connecting the data inputs from precision agriculture to sensory experiences in the field. This would allow for the integration of precision technologies with embodied knowledge, providing avenues for advisors and farmers to improve their understanding of both their soils and crops and of precision agriculture.

CONCLUDING REMARKS AND FURTHER RESEARCH

The cyborg farmer is the farmer with agency, using precision technologies in an embodied way, balancing between knowledge cultures. The cyborg farmer is not an active form of resistance against current capitalist agricultural systems, but neither is it the wholesale acceptance of its dominant forms of knowledge. Cyborg farmers are neither luddites disavowing technology nor are they completely bound to a high-tech farm that is built on precision agriculture.

Instead, the cyborg is the in-between, the farmer who makes precision technologies work on their specific farm, accepting certain elements while resisting others. It is following certain recommendations by a decision support tool while ignoring others because it makes more sense to follow intuition. It is the interpretation of data with embodied senses while sharpening embodied knowledge with this same data. The cyborg farm is a balance between agro-ecological context, precision technologies and farmers' embodied knowledge.

Considering this conclusion, it will be important to involve the embodied aspect of precision agriculture in research, technology development and advice and extension. This would allow farmers to further integrate the finesse, control and adaptability precision agriculture has to offer with their bodily and sensory affordances. Further research can help identify essential elements of precision agriculture that help develop embodied knowledge and enable the cyborg farmer.

Our interviews represented accounts of the practices of farmers but did not show all the precise mechanisms that farmers use in integrating precision agriculture and embodied knowledge. This was limited due to our use of an interview-based approach. While this does give insight into the practices and engagements of farmers with precision technologies and how these relate to the embodiment, this did not allow for getting the detailed insights and logitudinal analysis needed for describing mechanisms of embodiment.

We follow other authors in arguing that future studies on this topic need to integrate different ethnographic and technographic methodologies in understanding embodiment in precision farming, such as work shadowing, focus groups, deep mapping, mapping and photo elicitation, video data analysis and technographies (Cooreman et al., 2020; Krzywoszynska, 2016; Sutherland, 2021; Vellema et al., 2011). Further in-depth accounts on the formation of this embodied knowledge creation can help investigate in more detail the range of cyborg farmers and explore 'digital farming styles'.

AUTHOR CONTRIBUTIONS

Daniel van der Velden: Conceptualisation; methodology; investigation; writing—original draft preparation; writing—review and editing. **Laurens Klerkx**: Conceptualisation; methodology; writing—review and editing. **Joost Dessein**: Writing—review and editing. **Lies Debruyne**: Writing—review and editing.

ACKNOWLEDGEMENTS

We wish to acknowledge the people who generously gave their time and shared their experiences in the interviews. We also wish to acknowledge the two reviewers who provided insightful comments on an earlier draft of this article.

CONFLICT OF INTEREST STATEMENT

The authors have no relevant financial or non-financial interests to disclose.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy and ethical restrictions.

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ENDNOTE

[1] **ENDNOTE** Pixelcropping: An open field farming method in which different food and service crops are planted together in a grid made up of small (0.25–2.25 m^2) crop patches ('pixels'; Ditzler & Driessen, 2022).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: van der Velden, D., Klerkx, L., Dessein, J. & Debruyne, L. (2023) Cyborg farmers: Embodied understandings of precision agriculture. *Sociologia Ruralis*, 1–19. https://doi.org/10.1111/soru.12456