

Precision Technologies for Agriculture: Digital Farming, Gene-Edited Crops, and the Politics of Sustainability

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Abstract

This article analyzes the rise of precision technologies for agriculture—specifically digital farming and plant genome editing—and their implications for the politics of environmental sustainability in the agrifood sector. We map out opposing views in the emerging debate over the environmental aspects of these technologies: while proponents see them as vital tools for environmental sustainability, critics view them as antithetical to their own agroecological vision of sustainable agriculture. We argue that key insights from the broader literature on the social effects of technological change—in particular, technological lock-in, the double-edged nature of technology, and uneven power relations—help to explain the political dynamics of this debate. Our analysis highlights the divergent perspectives regarding how these technologies interact with environmental problems, as well as the risks and opportunities they present. Yet, as we argue in the article, developments so far suggest that these dynamics are not always straightforward in practice.

Precision technologies for agriculture are changing the face of modern farming, with important implications for debates about sustainability in the sector. Advances in digital technologies, including wireless communication, data analytics, and data-driven genome editing, are increasingly being applied to agriculture in a variety of ways on the premise that they offer more precision in decision-making and practice. Digital farming (also known as “smart” or “digital” agriculture) connects farm equipment to software platforms that track on-farm data and enable analyses of soil and climate conditions in specific location in order to provide farmers with advice regarding seed choice and more precise application of pesticides and fertilizers. Agricultural genome editing utilizes big data generated from computer-assisted genomic mapping to

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determine edits to the DNA of living organisms that promise a more precise way to modify a plant's genetic code to express new traits that can improve crop performance.

There is an emerging scholarly literature on the social consequences of the rise of digital farming that focuses in particular on questions of data ownership and farmer autonomy (Bronson and Knezevic 2016; Carbonell 2016; Carolan 2018; Rotz et al. 2019). A separate emerging literature explores the social aspects of gene editing, with a focus on ethical questions (Bartkowski et al. 2018; Helliwell et al. 2019). What has been missing from these academic literatures is a systematic analysis of the *environmental* implications of these new technologies, not just as separate technological trajectories but as intertwined technologies that are part of a new precision technology "system" for agriculture. The lack of scholarly attention to the environmental dimensions of these technologies is puzzling, especially given that advocates have in fact been trumpeting their environmental benefits as one of the main rationales for their adoption (e.g., Bayer 2018a, 2018b; Corteva 2019), and civil society organizations have forced a public debate on the issue by pushing back against the corporate claims (Cotter and Perls 2018; ETC Group and Heinrich Boll Foundation 2018; Mooney 2018). How this debate unfolds is important because it has enormous consequences for the future of global agriculture and associated governance frameworks, which are tightly linked to environmental outcomes. For this reason, it is important for scholars of global environmental politics (GEP) to take note of and understand this emerging debate. At the same time, the implications of technological innovation for the environment have been relatively neglected in GEP scholarship, not just with respect to specific technologies like the ones examined in this article, but also with respect to the role of technology in shaping broader debates over sustainability (Reynolds and Nicholson, this issue).

This article seeks to answer two questions. First, how has the debate over the environmental implications of precision technologies for agriculture unfolded thus far? Second, how do understandings of technology's role in society more broadly help us to understand the political dynamics of this debate? In answering these questions, we advance two arguments. First, our analysis shows that the two divergent positions have emerged regarding the environmental implications of precision technologies. On one side, proponents promote what they see as the environmental benefits of these technologies, in particular with respect to climate change, chemical use, and resource efficiency. On the other side, critics see these technologies as antithetical to their own agroecological vision of sustainable agriculture because they are predicated on continued agrochemical use, present safety risks, and concentrate corporate power that reinforces an industrial agricultural model. These contrary interpretations perceive the environmental impacts in deeply opposing ways and advocate for very different technological systems to promote agricultural sustainability. Yet at the same time, the picture is complex, as some actors are seeking to utilize precision technologies to achieve the kind of agricultural system transformation advocated by critics. The outcome

of this debate matters immensely for the development of potential regulatory frameworks that govern these technologies.

Second, we argue that key insights from the broader literature on the social effects of technological change help us to understand and interpret the dynamics of this debate. First, technological “lock-in” (Arthur 1989; Carrillo-Hermosilla 2006)—whereby dominant technological systems establish path dependence for subsequent technological innovations—contributes to political dynamics that pit competing technological systems against one another. In this case, the strong lock-in of the dominant industrial agricultural model enables proponents to hail precision technologies as the next logical innovation for agriculture, while it encourages critics to call for a complete transformation of the agricultural production system to one based on agroecology. Second, the double-edged nature of technology—that is, tensions between optimism and the unintended consequences that typically accompany technological innovation (Tenner 1997)—also fosters clashing positions. The widely divergent views in the precision technology debate reflect the extreme ends of this optimism–skepticism dynamic, as proponents focus on the potential for new technologies to solve immediate environmental problems, while critics voice concerns over the risk of introducing new environmental problems associated with those technologies. Third, the literature analyzing the ways in which access to and control of technological innovations can both concentrate power and create new avenues for agency over those technologies (Jasanoff 2016; Winner 1986) sheds further light on the emerging complexities in the debate. Proponents have largely focused on the potential for transformative openings of precision technologies, while critics have mainly focused on concentrating tendencies. But as we show, recent developments suggest that these dynamics are not always straightforward.

The Nuts and Bolts (or Bits and Bytes) of Precision Technologies for Agriculture

Digital farming and genome editing are key technological pillars of modern-day precision agriculture. Although on the surface, these technologies appear quite different from one another, and have different histories, in their current iterations they not only share connections to computational advances and big data analytics but have also become increasingly enmeshed with one another. Precision-based technologies, like many previous transformations of agricultural technologies over the past one hundred years, have been the offshoots of broader technological advancements. The combustion engine and the development of the automobile, for example, were instrumental to the rise of the tractor; advances in our understanding of genetics gave rise to modern plant breeding technologies, such as hybrid seeds; the rise of modern chemistry gave rise to synthetic pesticides and fertilizers; and advances in biotechnology gave rise to genetically modified (GM) seeds. Similarly, the development of digital technologies and the rise of big data analytics are having a major influence on

the development of new agricultural technologies. These data-driven precision technologies are dubbed by some as “Agriculture 4.0,” reflecting the impact on agriculture of what is commonly referred to as the fourth industrial revolution, characterized by the rise of digital technologies (Rose and Chilvers 2018).

Digital Farming

Precision agriculture—making decisions regarding input use based on the unique conditions at a smaller scale within fields—dates back nearly a century, although the data-driven digital version of it emerged in the 1980s and 1990s (Hellerstein et al. 2019). Early tools for digital farming, such as global positioning systems (GPS), yield monitor mapping, and variable-rate application of agrochemicals, remain the most popular (Balafoutis et al. 2017). Technologies have proliferated in recent years to include remote sensing, sophisticated updates to variable-rate technologies, robotics and autosteer machinery, and unmanned aerial vehicles (Kamilaris et al. 2017). Over the past decade, the decreasing cost of digital technology and advances in computing and robotics have made digital farming more affordable and accessible (Weersink et al. 2018). Developers are also currently working on how to use artificial intelligence to enhance data analytics and drive robotic equipment (Wolfert et al. 2017).

Adoption of digital farming technologies is increasing on large commodity crop farms, particularly in industrialized country settings, where there is a tendency toward fewer but larger farms (Balafoutis et al. 2017). In the United States, the use of variable-rate technology rose from 23 percent of corn planted acres in 2010 to 45 percent in 2016 (Hellerstein et al. 2019). Furthermore, adoption rates on US corn farms over 2,900 acres are double those of smaller farms (Schimmelpfennig 2016). Similarly, 97 percent of Canadian farms over ten thousand acres use GPS technology, compared with 21 percent of farms under 500 acres (Statistics Canada 2017). By sector, grain and oilseed farms have the highest digital farming technology adoption levels in Canada, where 63 percent use GPS technology (Statistics Canada 2017).

High-tech data analytics, modeling, and visualization platforms interface with tractors and drones outfitted with sensors and satellite internet connections, which enable the collection of soil (composition, moisture) and weather data (Kamilaris et al. 2017). Digital farming technologies that are currently available can pair site-specific data with big data analytics to assist in decisions for farm management and stewardship, such as which seeds to plant and the amount of fertilizer and pesticide to apply within different areas of a single field (Wolfert et al. 2017). This level of precision contrasts with the uniform monoculture practices that have dominated since the introduction of hybrid seeds and agrochemicals one hundred years ago (Weersink et al. 2018).

The growing power of big data shapes these technologies in important ways. Farmers today have access to unprecedented volumes of information—

from the display screens in their tractors to the farm management apps on their cell phones. The information on which digital farming relies feeds into farmer decision-making at the same time that it is being harvested and analyzed by corporations developing the technology (Pham and Stack 2018; Wolfert et al. 2017). This large volume of data is invaluable to firms not only to refine their digital farming technologies but also to develop new seeds and agrochemicals (Bronson and Knezevic 2016; Carolan 2016).

Start-up firms have been active innovators in digital farming, although they operate in a context of an increasingly concentrated and financialized global food economy. The recent wave of mergers in the agricultural input sector—namely, Bayer-Monsanto, Dow-DuPont, and ChemChina-Syngenta—are attributed in part to technological innovations and joining expertise in seeds and agrochemicals (Clapp 2018). These same firms are actively seeking to position themselves as leaders in digital farming, by developing their own technology or buying other companies. For instance, BASF, Nutrien Ag Solutions, and John Deere, prominent seed and chemical, fertilizer, and farm machinery firms, each independently launched digital farming platforms in recent years (Pham and Stack 2018). Many of these larger firms are keen to acquire one of the more than 1,600 start-ups active in this space (Day 2019). Before being recently purchased by Bayer, Monsanto bought the Climate Corporation—a digital agriculture start-up that has since acquired smaller start-ups, 640 Labs and VitalFields—in part to acquire data (Bronson and Knezevic 2016). In addition to mergers and acquisitions, industry lines are blurred with partnerships across sectors. John Deere, for example, forged linkages with Syngenta, Dow, Dupont, Monsanto, and BASF, prior to the recent consolidation in the sector (Mooney 2018).

Although the rise of data collection and analytics is transforming the politics of agriculture, governance is currently fragmented and ambiguous. Data collection and access for digital farming is primarily regulated by user agreements made by the developers that farmers are required to sign (Carbonell 2016; Rotz et al. 2019). In response, some farmers are advocating for the right to own their data and to repair their own farm equipment (Carolan 2018). In the absence of legislation, various actors have proposed codes of conduct or certification schemes. For example, the American Farm Bureau Federation's Ag Data Transparent certification scheme requires that "contracts clearly outline the farmer's ownership of the data they generate, as well as how companies are using it, securing it, and sharing it with authorized third-parties" (Ag Data 2019).

Crop Genome Editing

The growth in computational capacity and big data generation has given rise to more precise methods of plant breeding, in particular, genome editing and other data-informed plant breeding technologies (Weersink et al. 2018). Digital genome sequencing, developed over the past decade, has vastly reduced the cost

and time involved in mapping the DNA of plants and other organisms. Digital methods for genome sequencing generate vast amounts of data regarding genome sequences, which in turn assist in plant breeding to design seeds for specific field conditions or desirable traits.

Data-driven gene-editing technologies, such as clustered regularly interspaced short palindromic repeats sequences and associated enzymes (CRISPR-Cas9) and transcription activator-like effector nucleases (TALEN), have transformed plant breeding over the past decade. These new technologies essentially act like molecular scissors that enable edits at specific locations in an organism's DNA. With these techniques, it is possible to identify which precise genes are responsible for which traits and to turn them on or off depending on the desired effect (Zhang et al. 2018). For instance, traits that make plants ripen quickly can be edited away to extend a crop's shelf life, and varieties that have more resistance to pests or harsh weather can have those traits enhanced. The DNA repairs itself where it was edited, and the new traits are passed on to offspring (Bartkowski et al. 2018). Unlike earlier forms of agricultural biotechnology, which inserted new genetic material from other organisms or species randomly into plant genomes to test for expressions of desired traits, gene-editing technology can target multiple precise edits to the genome without the insertion of foreign DNA.

Gene-editing research is now taking place to edit plants to improve resistance to drought or pests and to enhance nutritional quality; however, a considerable amount of research also focuses on making crops resistant to herbicides, mirroring the aims of earlier agricultural biotechnology (Zhang et al. 2018). Some gene-edited crops are already on the market in the United States, including a soybean that claims a healthier quality oil and herbicide-tolerant canola (Jaffe 2019). Gene-editing technology also enables *gene drives*, which are still in the proof-of-concept phase. The idea is to alter an organism's genes in a way that ensures that all of its offspring take on the edited traits, enabling a rapid spread of engineered genes through normal reproductive channels. Research is under way to investigate potential applications to control agricultural weeds using these techniques (ETC Group and Heinrich Boll Foundation 2018; Neve 2018).

CRISPR, the dominant gene-editing technology, was first developed in university contexts (Brinegar et al. 2017). Berkeley and the Broad Institute of MIT and Harvard both own patent rights to CRISPR, which spawned several university-linked start-ups. Calyxt, for example, a US start-up cofounded by a genetics professor, developed one of the first commercially released gene-edited soybeans (Nickel 2018). In this context, many of the same large companies leading in digital farming aim to position themselves as leaders in gene editing. They have established research programs, acquired licenses to CRISPR technology, and applied for patent protection on varieties that incorporate multiple complex edits to address herbicide-resistant weeds and improve herbicide resistance in crops (Brinegar et al. 2017; Cotter and Perls 2018). Bayer, Syngenta, and Corteva (a spin-off of the Dow–DuPont merger) are all investing in gene-editing

technologies for plant breeding. For instance, before being purchased by Bayer, Monsanto invested US\$ 100 million in the gene-editing start-up Pairwise Plants (Nickel 2018), and a recent study indicated that Corteva currently holds the largest number of CRISPR patents and applications globally (Houldsworth 2018).

The regulatory environment for gene editing varies in different parts of the world. Because gene editing does not necessarily rely on the insertion of DNA from other species, the United States and Canada have given indication that they will not strictly regulate the process. In the European Union (EU), on the other hand, gene editing faces the same type of regulation as do earlier agricultural biotechnologies (Callaway 2018a). In addition to uncertain regulatory landscapes, it is difficult to access information about the various gene-edited crops that have been researched, tested, and brought to market (Jaffe 2019). There is currently no international regulatory framework to govern the use of gene drive technology. In 2018, however, the parties to the United Nations Convention on Biological Diversity adopted a decision that calls for risk assessment and prior informed consent of affected communities before gene drive organisms are released into the environment (Callaway 2018b).

Sustainability Through Precision? Mapping the Contours of the Debate

Strongly opposing lines of argumentation characterize the environmental politics of precision technologies for agriculture. Proponents highlight their potential to improve environmental sustainability as a key selling point. Bayer, for example, explicitly promotes these technologies as delivering more environmentally sound farming practices. As president of the Crop Science division of Bayer, Liam Condon, notes, “digital tools have shaped many industries, and we are just scratching the surface on what it means for agriculture. Through the power of new digital tools and data analytics, we can help increase farmer productivity and sustainability” (quoted in Bayer 2018a). Similarly, Corteva’s promotional video *Who Was the First Farmer?* voices over an animation of a farmer in a large internet-connected tractor complete with drones flying overhead: “Our natural resources are declining and our planet’s climate is changing, so farming needs to change too. And it has, with smarter tools, sustainable practices, and ever higher yields” (Corteva 2019).

The complementarity between digital farming and gene editing is in part what offers environmental promise for its promoters. Although they operate at different levels—with gene editing focused on the design of inputs, such as seeds, and digital farming focused on assisting decisions at the farm level—these technologies are increasingly interlinked. Data collection regarding the performance of certain crop varieties in specific environmental conditions, for example, can inform the design of new gene-edited plant varieties for optimal performance. Gene-edited crops, in turn, can be recommended to farmers via their farm management software applications (Halewood et al. 2018). Bayer and Corteva make the interface between the various technologies a key part

of their business strategies (Corteva 2019; Reiter 2019). A recent investor hand-out from Bayer, for example, features a Venn diagram that shows its “tailored solutions” for sustainable agriculture in the middle of overlapping circles representing its expertise in seeds and traits, digital agriculture, and crop protection chemicals (Condon 2018).

Analysis of corporate documents and scientific studies on these technologies revealed three key arguments that proponents make regarding the contribution of these technologies to sustainability. First, proponents argue that these technologies are “climate smart” because they can be deployed in ways that improve crop performance in more hostile climatic conditions, while also mitigating carbon emissions (Balafoutis et al. 2017). Digital farming, for example, enables decision-making regarding seeds and chemical use based on soil conditions and weather patterns to maximize yield. In addition, the technology facilitates no-till agriculture, which advocates argue sequesters carbon. It also supports more judicious fertilizer application, reducing carbon emissions and pollution from runoff. Likewise, crops can be gene-edited for traits that withstand harsh climatic conditions and resist diseases that might resurge with climate change. Moreover, gene editing for durability can minimize food waste and associated carbon emissions.

Second, advocates argue that precision technologies for agriculture can reduce toxins from agrochemical use as well as the associated problem of herbicide resistance in weeds. In particular, variable-rate technologies allow much more precise chemical applications, often at lower rates than conventional practices. Advocates add that plants can be edited to fix their own nitrogen in order to decrease synthetic fertilizer use (Weersink et al. 2018). Furthermore, although not yet on the market, there is significant research into the ways in which weed problems can be addressed with gene editing. For example, herbicide-resistant weeds can be resensitized to multiple kinds of agrochemicals, enabling farmers to better control weeds. Researchers have also explored the possibility of using gene drives for autoextinction of pests and weeds, obviating the need for toxic chemicals (Neve 2018).

Third, proponents make the case that precision technologies bring greater efficiency and productivity to farming, which reduces pressure on natural resources and benefits farmer incomes, supporting both environmental and economic sustainability goals (e.g., Bayer 2018b). For example, they stress that crops edited for greater yield, combined with variable-rate technologies that maximize output within different areas in a field, can increase production per unit of land and reduce the need for land clearing. In other words, by increasing the efficiency of production on lands that are already under cultivation, these technologies can spare forested areas, which they argue protects biodiversity (Weersink et al. 2018).

Critics of these technologies push back against the advocates’ claims. Many civil society organizations, for example, express deep skepticism about the implications of digital farming and gene editing for the environment

(e.g., Cotter and Perls 2018; ETC Group and Heinrich Boll Foundation 2018; Morena 2018). First, and perhaps most prominent among these critiques, is the broad concern that just a handful of powerful companies control vast amounts of agricultural data associated with both digital farming and gene editing, raising important privacy concerns, especially for data collected from farmers' fields. Critics warn that the concentration of plant genome data in the hands of the few large seed companies will favor an agricultural research agenda within an industrial agricultural model that is likely to continue to cause environmental harm. They argue that any benefits from these technologies, if realized, are unlikely to reach the majority of the world's farmers (Filardi and Prato 2018; Mooney 2018). These groups call for limits on corporate concentration to rein in this power (Mooney 2018). A growing number of scholarly studies raise similar concerns regarding data ownership and control associated with precision technologies in agriculture (Bronson 2019; Carbonell 2016; Carolan 2018; Pham and Stack 2018).

Second, critics predict that precision technologies will result in a host of specific environmental consequences. For example, they point out that a large proportion of corporate-sponsored gene-editing research is focused on making crops resistant to herbicides such as glyphosate, which is likely to result in more, not less, herbicide use (Cotter and Perls 2018; Mooney 2018). They also question the safety of gene editing and point to scientific research that warns of off-target changes that may occur in gene-edited organisms, the consequences of which we do not yet fully understand (Cotter and Perls 2018; ETC Group and Heinrich Boll Foundation 2018). The risks are even greater for gene drives. If released into the wild, these organisms could threaten biodiversity because they are designed to wipe out specific traits (ETC Group and Heinrich Boll Foundation 2018). For these reasons, many critics call for much tighter regulation of gene editing and a moratorium on gene drives.

Alongside their critiques of precision technologies, critics frequently promote agroecology as an alternative technological system that in their view delivers better environmental and social results (e.g., ETC Group and Heinrich Boll Foundation 2018; Mooney 2018; Morena 2018). They promote this alternative technological system because it eliminates synthetic agrochemical use and minimizes risk by relying on traditional plant breeding rather than genetic modification. It also sequesters carbon in the soil, reduces carbon emissions, and supports biodiversity (Vanloqueren and Baret 2009). And because agroecology does not require expensive agricultural inputs that are controlled by concentrated agribusiness, it is ultimately more affordable for farmers, thus supporting agricultural livelihoods in a more equitable way.

These critiques focus on the ways in which precision technologies are being shaped by corporate interests and how their application is being rolled out in practice, although their views with respect to the potential for these technologies more broadly are mixed. Critics are deeply skeptical of the need for genome editing, which reflects their earlier rejection of the need for traditional agricultural

biotechnology. But at the same time, critics have shown more openness to the utility of some digital technologies, provided that control of their development is in the hand of farmers themselves (Rotz et al. 2019).

This emerging debate over precision technologies for agriculture, summarized in Table 1, illustrates deep divisions, with proponents and critics frequently appearing to talk past one another, as each side has a very different interpretation of how the same technologies will affect environmental outcomes. Which narrative will ultimately dominate in public discourse matters enormously for shaping understandings of the environmental consequences of these technologies and their potential role in more environmentally sustainable food production. How these debates play out also matters for struggles over emerging policy and governance frameworks that establish the rules under which these technologies must operate.

A Technology Lens Deepens Insight into the Politics of the Debate

As outlined, the debate over the environmental implications of precision technologies for agriculture is highly relevant for GEP scholars. The field of GEP has increasingly recognized the importance of food systems to broader debates about environmental sustainability on a global scale, noting the polarized nature

Table 1
The Emerging Debate over Precision Technologies for Agriculture

<i>Aspect of the Debate</i>	<i>Proponents</i>	<i>Critics</i>
Environmental impact	Optimism about benefits: <ul style="list-style-type: none"> • “Climate smart” (e.g., facilitates no-till agriculture) • Reduces agrochemical use • Improves resource efficiency and farmer profitability 	Skepticism and a focus on costs: <ul style="list-style-type: none"> • Reinforces energy use of the industrial agricultural system (e.g., machinery) • Perpetuates agrochemical use • Threatens biodiversity
Corporate involvement	Large corporations necessary to drive innovation for improved sustainability	Corporate concentration and control shapes technology in ways that undermine sustainability
Agricultural system	Embedded in and extension of the industrial agricultural system	Advocates transformation to new system based on agroecology

of debates over what constitutes sustainability in food systems (Clapp and Scott 2018). Yet, GEP literature lags behind other fields in analyzing the unique features of technology's role in the politics of sustainability (Nicholson and Reynolds, this issue). We suggest that insights from the broader literature on the social dynamics associated with technological change can enrich our understanding of the complex politics of these debates. As we discuss in the following pages, greater consideration of the dynamics of technological lock-in, the double-edged nature of technology, and power associated with novel technologies provides useful insights into the political contours of these debates.

Technological Lock-In

Key dynamics identified in the broader literature about technological lock-in—whereby technological systems develop along established pathways from which it is difficult and costly to deviate—are reflected in current debates over precision technologies for agriculture. Technological lock-in typically occurs when powerful social forces drive technological development in certain directions. These social forces are often the result of earlier events—technological, political, and psychological—that cement the societal dominance of certain technological systems over others (McKinnon 2019). This temporal nature of the process means that lock-in can become self-reinforcing over time and can ultimately crowd out other potential technological systems that might offer more benefits over the long run (Arthur 1989). In instances of lock-in, the cost of not adopting a new technology that fits into a dominant technological system can often be higher than the benefits of actually using that technology, even if there are better ways to resolve the problem (McKinnon 2019). In such situations, potential adopters typically make decisions about the costs of adopting (or not adopting) novel technologies in the short term, even in cases when the benefits of switching to a different system may be higher over the long term. This dynamic tends to give the momentum in debates regarding novel technology adoption to those voices that reinforce the dominant technological system while weakening the influence of those promoting alternative systems (Vanloqueren and Baret 2009).

The lens of technological lock-in helps shed light on the ways in which the structural context of the dominant agricultural system shapes the political dynamics surrounding current versus possible alternative systems in the debate over precision technologies. The current industrial model rose to dominance through historical patterns of progressive adoption of industrial agricultural technologies that established new path dependencies. The development of hybrid seeds in the 1920 and 1930s and the monoculture planting practices that accompanied them, for example, encouraged monocrop agriculture and the adoption of tractors to replace horses. When monocropping resulted in new vulnerabilities to insects and weeds in crop systems, the response was the adoption of agrochemical sprays to control those pests. Subsequently, agricultural biotechnology emerged as a means by which to address high levels of agrochemical

use, by engineering crops to be resistant to pests or resistant to what were thought to be relatively benign herbicides, such as glyphosate (Sassenrath et al. 2008).

Although advocates promote precision technologies as part of a more sustainable trajectory, they are deeply enmeshed with elements of the established industrial agricultural system. Most of the corporate research into gene editing and variable-rate spraying equipment, for example, is focused on the use of these technologies in conjunction with herbicides—specifically glyphosate—which have already been locked into dominant agricultural practices. New precision technologies are also deeply enmeshed in the dominance of digital technology systems in society more broadly. The prevalence of and familiarity with digital technologies in society for nonfarming activities, such as for obtaining news and weather forecasts or social media, work to lock-in digital farming adoption by farmers. As farmers sign on to these new digitally linked farming technologies, their entrenchment in the industrial agriculture system to which most of those technologies are tethered only deepens. And as farmers become increasingly reliant on and skilled in the use of digital technologies to guide their farming decisions, lock-in becomes self-reinforcing, because farmers lose the ability to evaluate trade-offs and make decisions in the absence of digital assistance as well as the ability to repair their own digital equipment and machinery (Carolan 2018; Rotz et al. 2019).

Lock-in helps to explain why proponents have kept their discourse focused on the immediate benefits of adoption within the dominant industrial agriculture frame, because it is so entrenched. Critics, by contrast, typically stress the longer-term benefits of competing agricultural models, such as agroecological farming systems, alongside their more specific critiques of the technologies. The debate, in other words, pits two competing technological systems against one another in very stark ways: the locked-in industrial agricultural model versus calls for a complete transformation toward agroecology. As Vanloqueren and Baret (2009) argue, however, alternative visions for sustainable agriculture, such as agroecology, have been underrepresented in broader public debates, in large part due to these tendencies toward technological lock-in, which makes garnering support for major transformative change difficult, despite its longer-term benefits.

Double-Edged Nature of Technology

The literature on the social impact of technological innovation highlights tensions between optimism about the possibilities of novel technologies to solve problems and the risks of unintended consequences associated with them (Jasanoff 2016; MacKenzie and Wajcman 1999). This double-edged nature of technological innovations creates opportunities for opposing perspectives regarding the potential impact of recently introduced technologies. In some cases, unintended effects associated with new technological innovations are minor and can be easily addressed with tweaks to existing technologies that are subsequently introduced. In other cases, however, the side effects can be equally

vexing and as difficult to solve as the original problem. Tenner (1997) refers to this latter category as “revenge effects.” Political debates about technological innovation often reflect this dual role of technology, although more often than not, optimism about the latest technological innovations overshadows pessimism about potential unintended consequences (Winner 1986).

An appreciation of the doubled-edged nature of technology helps to make sense of these debates by showing how each side utilizes the ambiguities associated with the impact of a novel technology to make its case about the technology’s likely impact. The pattern of optimism over the ability of new technologies to address the unintended effects of earlier technologies is common throughout the history of agricultural innovations (Sassenrath et al. 2008) and remains relevant to the latest technological developments, including precision technologies. Proponents of gene editing, for example, advertise its ability to address the problem of herbicide-resistant “superweeds,” many of which emerged after the introduction of GM herbicide-tolerant crops, which led to a massive increase in herbicide application. Proponents stress that crops can now be genetically edited to make them resistant to a cocktail of chemical sprays that weeds likely cannot survive, at least in the immediate future (Neve 2018).

Critics, meanwhile, focus on the likely consequences of such an approach, warning that the effects of gene editing could morph into full-blown revenge effects. They point out that editing plants for resistance to multiple herbicides could have the effect over time of simply multiplying the problem of superweeds, making them resistant to a host of chemicals. Critics also warn that gene editing results in unintended molecular changes in plants on other parts of the genome that were not intentionally altered, leading to unexpected outcomes that we have yet to fully understand. CRISPR, for example, can cause extensive deletions and rearrangements of DNA that could introduce food toxins or allergens (Cotter and Perls 2018). These double-edged dynamics also play out with respect to digital farming technologies. Proponents exude optimism by advertising these technologies as being “climate smart” because they enable no-till cultivation and more efficient agrochemical use. Critics, however, draw attention to the energy use required not only to run the machinery for drilling seeds and spraying chemicals but also for the cloud servers that host the data and software platforms on which these systems rely (Longo and York 2016; Mooney 2018). Digital farming technologies also rely on minerals and mining that are integral to the equipment, and the potential e-waste dimensions of these technologies, which, when they become outmoded, are largely ignored by proponents (Baldé et al. 2017).

There is a tendency for optimistic scenarios focused on immediate problems to overshadow potential longer-term negative consequences in public debates over precision technologies for agriculture. When the EU, for example, made the decision in 2018 to regulate gene-edited crops under the same law that governs agricultural biotechnology, proponents expressed their dismay. They accused critics of putting a chill on the advancement of science (Callaway

2018a), which fit the already established pattern of advocates portraying gene editing scientists as “heroes” (Lander 2016).

Novel Technologies and the Distribution of Power

The relationship between power dynamics and environmental outcomes is central to the field of GE, with scholars highlighting the role of material resources and of discursive framing employed by different actors seeking to shape environmental governance regimes. Corporate actors in particular have been able to amass considerable power to influence such outcomes (e.g., Falkner 2008; Levy and Newell 2005). These insights can be enriched by a deeper appreciation for the complex ways in which the design and roll-out of technologies interface with power relationships in society. Societal forces, for example, matter for understanding which actors have control over technological design, while technology itself also shapes the social context (Jasanoff 2016; Winner 1986). When corporations are the key actors controlling the direction of technological development, they tend to make decisions based on their own self-interests, which can enhance their power (Just et al. 1979; Winner 1986). For example, past technological innovations like agricultural biotechnology benefited from intellectual property protection and required huge upfront investments such that large agribusinesses had a competitive advantage in shaping their technological design to prioritize corporate interests (Wield et al. 2010). At the same time, however, regulation can work to ensure that technological innovation is more widely accessible and can be modified by its users for their own purposes, which could result in a more equitable distribution of power (Jasanoff 2016).

The complex relationship between technology and power is important in unpacking political dynamics surrounding precision technologies for agriculture. Corporate actors have used their economic power to control the direction of the technology’s utility for farming and to shape the narrative to focus only on its positive aspects, such as environmental benefits, and to ignore its externalities, in order to increase adoption rates among users (Bronson 2019; Carbonell 2016). These firms also direct research for technological improvement only to its most profitable components, rather than toward other potentially more sustainable agricultural models that do not rely on purchased inputs, such as agrochemicals and modified seeds. In line with the arguments of critics, these strategies enable corporate actors to develop the technologies in ways that secure their access to and use of the data on which these technologies and their future development rely (Morena 2018).

However, there are some differences between the power dimensions of novel precision technologies for agriculture and earlier innovations in the sector. The lower initial costs due to improved computing capacity offer a potential opportunity to open up development to a wider range of actors. As we explained earlier, digital farming start-ups are proliferating across the globe, including in less industrialized contexts, with an explicit intention to democratize access to

data and technology (Day 2019). Start-ups are also key players in gene editing. Unlike the large corporate players, these smaller firms tend to focus more on improving nutritional qualities rather than on herbicide resistance. Large agribusiness firms must obtain licenses from the universities and start-ups that developed genomic technologies like CRISPR to be able to utilize in them their research programs (Brinegar et al. 2017). The development of these novel technologies thus far suggests there is at least potential for a more open playing field, even if large corporate players still dominate (Bartkowski et al. 2018).

Although these trends indicate the possibility of disrupting historical patterns of control in agricultural technology, it is important to recall that initial phases of research into hybrid seeds and agricultural biotechnology were also characterized by a high number of start-up firms, which were eventually acquired by the big players as mergers and acquisitions continued apace from the 1970s to the early 2000s (Howard 2016). Indeed, in many cases, the start-ups in digital farming and gene editing welcome being purchased by a big player, as the case of the Climate Corporation's purchase by Monsanto illustrates. Moreover, start-ups often must design their technologies to interface with already established platforms and practices. For example, the Climate Corporation (now part of Bayer) has established compatibility partnerships with fifty other software platforms around the world (Bayer 2018c). While this interoperability can open spaces for new kinds of applications to emerge, it still ultimately benefits the owner of the central software platform.

While both start-ups and corporate agribusiness may share a focus on developing technologies that prioritize their own profits, albeit in different ways and with different underlying aims, some emerging civil society and activist initiatives take advantage of lower barriers to entry at this early stage to develop alternative technological platforms. This development is most relevant to digital farming, as gene editing is less practical at the farm and civil society level (Bartkowski et al. 2018). Thus far, resistance movements focus on challenging corporate control over data and machinery, which have important implications for sustainability because they can shape the ways in which these technologies are ultimately utilized in farmers' fields. Initiatives like Open Ag Data Alliance, FarmLogs, and farmOS provide alternative, low-cost open source software, with data ownership and sharing platforms currently operating outside of the control of the corporate giants (Carbonell 2016; Rotz et al. 2019; Wolfert et al. 2017). Farm Hack, for example, links up farmers from around the world through an online platform to share experiences with building and repairing farm technologies and software. Other types of initiatives include farmer organization involvement in broader Right-to-Repair movements, which push back against corporate control over repairs to digital technologies (Carolan 2018).

A technology lens helps to clarify the complex power dimensions in the rise of digital farming and gene editing. Critics argue that corporate dominance over the development, design, and application of these technologies and databases will likely prioritize profit-oriented aims over others. While these priorities

could coincide with some marginal environmental gains within an industrial agriculture paradigm, they also have the potential to result in vexing side effects and to undermine farmer autonomy. If power remains more decentralized within the private sector, with start-ups retaining a strong role, however, the outcomes could be different. Start-ups have the potential to take precision technologies for agriculture in new directions. Thus far, they tend to work on specific applications that are more geared toward the needs of their users and are less likely to require farmers to surrender autonomy. Still, the presence of start-ups does not necessarily ensure an even power distribution or a focus on farmers rather than corporate interests. Civil society and farmer movements that experiment with digital farming technologies are likely to remain more open and democratic in terms of their approach, but even these initiatives do not guarantee justice (Carolan 2018). Presently, there are possibilities for more equitable power dynamics to support precision agriculture practices that prioritize the environment. It is essential to understand these complex dynamics if governance initiatives are to act on and protect these opportunities.

Conclusions

As our analysis shows, the advent of precision technologies for agriculture has sparked a fierce debate over their environmental implications. This debate is important for the broader politics of efforts to promote more sustainable food systems on a global scale. Proponents of these technologies claim that they bring environmental benefits in terms of addressing climate change, reducing toxins, and improving resource efficiency in ways that benefit farmers. Critics, on the other hand, argue against these claims, making the case that these technologies require stricter regulatory control because they can result in vexing environmental side effects and further concentrate power in the hands of corporate actors in ways that undermine farmer autonomy. Instead, critics advocate for an entirely different technological system based on agroecological principles, to achieve the goal of sustainable agriculture.

These debates over precision technologies for agriculture will no doubt play a role in shaping potential policy and governance frameworks going forward. We suggest that insights from the broader literature on technological innovation help to enrich GEP analysis of these debates. In particular, concepts such as technological lock-in and the double-edged nature of technology help to explain the rationale behind different arguments about precision technologies and why the two sides of the debate have become entrenched in such opposite positions. Technological lock-in contributes to the clash between two different technological systems—the dominant industrial agriculture model versus agroecology—while also tending to favor the dominant system. Technological optimism and the specter of unintended consequences also encourage polarization between perspectives, because they enable proponents to prioritize efforts to address immediate concerns, such as excessive herbicide spraying, while ignoring critics'

warnings about the longer-term risks associated with continued reliance on herbicides and the prospect of creating more superweeds. The distribution of power associated with new technologies also helps to provide a more nuanced understanding of the debate, as the extent to which societal forces shape access to and control over technologies interacts in complex ways with the extent to which technological design itself shapes social forces. Although large agribusiness players continue to seek dominance in the development and design of precision technologies for agriculture to secure their profits and control, start-up companies, some of which have more explicitly social and environmental aims, are taking advantage of the current low barriers to entry in the development of some aspects of these technologies. Meanwhile, civil society initiatives have also emerged, especially with respect to digital farming, to create alternative networks that could direct these technologies toward equity and sustainability goals.

Policy and governance arrangements regarding precision technologies for agriculture are as of yet sparse and fragmented. As Jasanoff (2016) stresses, public policy can guide and direct technological design in ways that can result in more equitable and sustainable outcomes. As we have argued in this article, it is important to understand the dynamics underlying political debates around the environmental impacts of these novel technologies, as these matter for the ways in which public policy ultimately guides, or does not guide, the design of these technologies.

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