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Diversity in agricultural technology adoption: How are automatic milking systems used and to what end?

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Abstract Adoption of technology in agriculture can significantly reorganize production and relationships amongst humans, animals, technology, and the natural environment. However, the adoption of agricultural technology is not homogenous, and diversity in integration leads to a diversity of outcomes and impacts. In this study, we examine the adoption of automated milking systems (AMS) in small and midsize dairy farms in the US Midwest, the Netherlands, and Denmark. In contrast to technological determinism, we find significant variation amongst adopters in the implementation of AMS and corresponding variation in outcomes. Adopters have significant discretion in determining the use of AMS, which leads to a diversity of possible outcomes for family and non-family labor, human–cow relationships, animal welfare, the environment, and financial resiliency. Adoption and implementation are shaped by both structural factors, such as debt load and labor market variation, and by farmers' individual personality traits and values, such as a willingness (or not) to release control to technology. Rather than uniform adoption and impacts of technology, we highlight the importance of context, the co-constitution of technology and users, and the diversity of technology adoption and its associated impacts.

Keywords Technology · Environment · Labor · Animal welfare · Dairy farming · Animal studies

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Introduction

In this paper we examine technology adoption, specifically the adoption of automated milking systems (AMS) by small and mid-sized dairy farms. The adoption of AMS dramatically changes the operations and organization of dairy farms, reshaping relationships amongst farmers, employees, technology, animals, and the environment. We argue that the implications of AMS are, however, not experienced uniformly. Instead, there is significant variation amongst adopters in the use and implementation of AMS, with corresponding variation in outcomes. In this study, we begin to explore the variation of implications of AMS adoption for farm labor relations, human–cow relationships, the environment, and farm structural change using interviews with AMS adopters in both Europe and the United States (US) Midwest. We highlight how variation among AMS adopters, especially variation in personality traits and values, can result in very different AMS applications and outcomes related to "cow freedom," labor flexibility, and farmer quality-of-life. This study answers calls raised by Bingham (1996) and others (for example, Kline and Pinch 1996) to move beyond technological determinism and to recognize the importance of context and variation in technological adoption.

In 1992, the Dutch company Lely introduced the first milking robot. Since then, the adoption of AMS has increased, with AMS on over 2400 farms worldwide by 2008 (Reinemann 2008). Most farms using AMS are in The Netherlands, Germany, and Denmark; however, adoption is growing in the United Kingdom, Canada, and the US.

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While the vast majority of contemporary dairy farms use milking machines, AMS are differentiated by the use of sophisticated robotic technology. AMS use a robotic arm to attach and detach the milking system to a cow's udder without human assistance and can result in a 20–30 % reduction in total farm labor-hours (De Koning and Rodenburg 2004; Heikkila et al. 2010). The technology allows cows to voluntarily approach the robot to be milked individually, when they desire, and at any time of day. One robot unit is sufficient to milk 60–70 cows and can increase milk production per cow by 6–35 % due to increased milking frequency (De Koning and Rodenburg 2004). In addition to the installation of the robot, AMS require reshaping dairy production systems, including new animal housing, feed, labor, routines, and relationships to integrate the new technology into the farm system (Meskens et al. 2001). Farmers have significant discretion in how they integrate and implement these changes, which can lead to significant variation in outcomes.

While a broad literature has focused on factors influencing technology adoption as well as the consequences of technology adoption for agricultural production, we extend this literature by uncovering the implications of variation in adoption and implementation. Adoption-diffusion (see Rogers 2003) and farm-structure models (see Napier and Tucker 2001) have demonstrated the importance of social networks and farm structure, respectively, in explaining technology adoption. Treadmill of Technology (see Cochrane 1958) theory emphasizes the detrimental effects of technology adoption for farm income and farm consolidation, while others have examined impacts on labor relations (Friedland et al. 1981; Friedland 2001; Pfeffer 1992) and animal welfare (Fraser 2005; Hurnik 1988). Building on these literatures and a growing science and technology studies (STS) literature that rejects technological determinism, we recognize the importance of context and the co-constitution of technology and users. We examine the impacts of AMS on farmers, employees, cows, and the environment and their relationships, exposing significant variation in the form of AMS use that leads to significant variation in outcomes. Specifically, we find that an individual farmer's desire for control, value of personal relationships, and priorities to maximize profitability were the strongest determinants of AMS implementation that result in specific outcomes (Fig. 1). For instance, adopters who are uncomfortable with sacrificing control to the AMS may implement the technology in forced-flow or structured milking routines that limit the realization of "cow freedom" and labor flexibility associated with AMS. Our findings also suggest that variation in the use of AMS data shapes relationships with technology and cows, pre-existing environmental and animal welfare norms may lead to diverse implementation of feeding with diverse environmental intensity, and variation of capital investment and debt load have significant implications for organization of production and farm resilience. This variation of outcomes suggests the need for further research exploring the specific causal mechanisms by which diversity of robotic technology use leads to diverse implications for individual farms, humans, and cows, as well as larger structural changes in the agrifood industry.

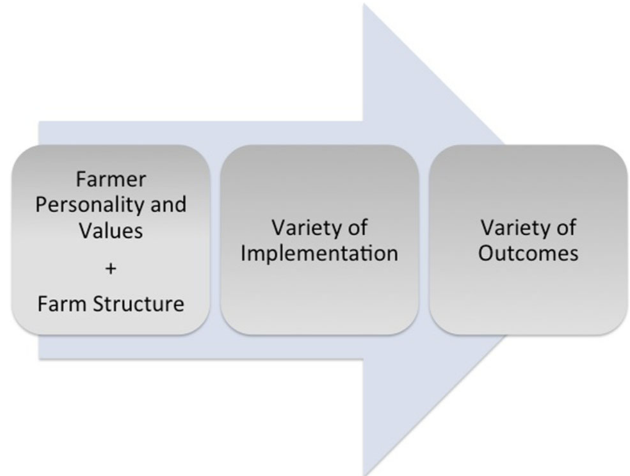

Fig. 1 Conceptual diagram

Understanding technology in agriculture: beyond diffusion and determinism

The adoption of agricultural technologies has long been a focus of the sociology of agriculture. Many studies focus on who adopts a certain technology and why. "Diffusion of innovation" studies (see Rogers 2003) have emphasized the importance of social networks and the transfer of innovations amongst network members. From this theoretical perspective, communication through social networks is the key driver of technology adoption as individuals transfer knowledge and information to others (Fliegel and Van Es 1983; Saltiel et al. 1994). Later farm structure models extended diffusion of innovation studies to incorporate farm structure variables such as debt, farm size, and family structure into explanations of technology adoption (Abd-Ella et al. 1981; Sommers and Napier 1993; Napier and Tucker 2001).

New explanations of technology adoption such as the 'learning selection' model focus on the collaborative relationships between technology developers and end-users who then become 'promoters' of the new technology. A select group of end-users work with technology developers to create and test the new technology, later playing "a key role in the dissemination of the information and adoption of the technology by a larger user group" (Sassenrath et al. 2008, p. 287). This mirrors diffusion of innovation theories in its emphasis on social networks as a key mode of technology transfer, while also exploring the role of technology designers and developers in the adoption of new technologies. The 'pull' model of technology adoption emphasizes the role of problem-solving in driving technology adoption (Hagel et al. 2010). This perspective offers a more macro-structural understanding of technology adoption that moves beyond a focus on individual and/or farm features.

Beyond explanations of reasons for technology adoption, scholars have attempted to examine the impacts of technology on labor relations, farm structure, working conditions, and animal welfare. The classic Agricultural Economic theory of the Treadmill of Technology (Cochrane 1958) examines the impact of technology in agriculture with a focus on larger structural results and increasing farm consolidation. Cochrane (1958) and colleagues (Levins and Cochrane 1996) argue that "farmers constantly try to improve their incomes by adopting new technologies. 'Early adopters' make profits for a short while because of their lower unit production cost. As more farmers adopt the technology, however, production goes up, prices go down, and profits are no longer possible even with the lower production costs" (550). Other farmers are forced to adopt technology to compete, but the majority of farmers will be "lost in the price squeeze and leave room for their more successful neighbors to expand" (550). The Treadmill of Technology emphasizes the detrimental impact that technology adoption can have on farm income and the ways in which it encourages farm consolidation as farmers use technology to replace labor and increase production (Levins and Cochrane 1996).

Technology is often used to displace or replace agricultural labor, both non-family and family labor (Pfeffer 1992), and technology adoption can significantly alter the farm labor market (Bauer 1969) and vice versa (White et al. 2005). Technology can displace labor and increase the burden on remaining laborers as they struggle to maintain high levels of production (Dexter 1977; Pfeffer 1992). Conversely, perceived labor shortages can often provide motivation to adopt new technology (White et al. 2005). This reciprocal relationship between labor and technology is cyclical: labor shortages and/or desire to displace and control labor lead to the development of new technologies, those new technologies in turn reshape labor relations and often increase demands on remaining workers (Friedland et al. 1981; Wells 1996).

Technology adoption in agriculture can also have impacts on farm animals and the environment. The impact of technology on animal welfare and animal living conditions is contested in the literature, but can dramatically alter the relationships amongst animals, humans, and technology. Technology and automation can serve to reduce contact between animals and humans and many argue that this leads to animal neglect. Porcher and Schmitt (2012) argue that livestock animals should be understood as "workers" and that technology can increase work demands on animals in the same way as it does for human workers. Porcher (2006) also argues that the important connections between human work conditions and animal living conditions have been excluded from the literature that focuses either exclusively on human labor relations or animal welfare. Increasing pressures for animal productivity mirror increased pressures for worker productivity (Fraser 2005; Porcher 2006) and technology can reshape the "life, health, and comfort sustaining needs" of animals (Hurnik 1988, p. 105). Also, central to conceptions of animal welfare, technology can impact animal longevity (ibid). Technology adoption in agriculture also has tremendous impacts on the environment, and can result in an increase in the extent and speed of "withdrawals" of raw materials as well as the "additions" of waste and pollutants (Gould et al. 2004). For example, the application of fertilizer in cropping systems has resulted in extensive water pollution and eutrophication from runoff (Correll 1998; Hart et al. 2004). In animal agriculture, intensification has resulted in significant pollution problems, in particular, increasing herd size and industrialization is associated with increased antibiotic use rates (Witte 1998; Sawant et al. 2005) and groundwater (He et al. 2004) and land contamination from manure (Peacock et al. 2001).

While these literatures on the adoption and impact of agricultural technologies offer insight into the role of technology within agricultural systems, other scholars have called for a focus on context in understanding the role of technology. As quoted in Glenna et al. (2011, p. 215): "what is often overlooked is that 'the meaning, consequences, and transformative potential of any particular technology depend upon how that technology is deployed, by whom and for what purposes…' " (Schurman 2003, p. 19). Bingham (1996) argues for a need to avoid technological determinism that "assumes and reproduces a stable and matter-of-fact distinction between the material/technical and the social such that changes in the former are supposed somehow to 'impact' on the latter" (635). Instead, we must recognize that technology and society are co-constituted and that there is no one "impact" of technology, but rather technology and social actors have different roles and relationships in different contexts. Technology is shaped by, as well as shapes, end-users (Pinch and Bijker 1984; Pinch and Oushoorn 2005). Building on this call for specificity and recognition of co-constitution of the social and technology, we move beyond a study of who adopts AMS and why, and instead focus our examination on the range of variation in AMS implementation and how this leads to diverse outcomes for farmers, laborers, cows, and the environment.

Background: automatic milking systems

AMS, also called robotic milking systems, nearly completely eliminate the need for human labor during milking by allowing cows to voluntarily enter a milking pen where a robotic arm attaches to a cow's udder without human assistance. AMS offer a technology to both replace wage labor and provide more flexibility to family labor. Studies show that AMS replace human labor in the milking parlor and account for an average 30 % reduction in labor-hours (Heikkila et al. 2010). AMS have been heavily marketed to small and midsize dairy farms (<500 cows) as a strategy to avoid or reduce the need to hire non-family labor and to increase productivity without increasing labor (Rotz et al. 2003). Manufacturers, researchers, and industry publications have touted AMS as a new tool to support the sustainability of small and midsize dairy farms. They contend that the new technology offers a way for dairy farmers to sidestep the pressures to "get big or get out" and to avoid increasing the role of non-family labor (Hernandez 2012; Zellmer 2012). In Europe and the US, the majority of AMS are used on small and midsize farms (Hyde and Engel 2002; Rotz et al. 2003; Reinemann 2008). Despite high costs, AMS are increasingly popular for lifestyle and labor-saving benefits. Lifestyle benefits, including more time for family and recreation, are the primary motivations for adopting AMS (Haan et al. 2012).

There are few economic studies of AMS, but initial reports indicate lower profitability for farms with AMS compared to conventional systems, particularly in the years immediately following adoption (Heikkila et al. 2010). Although there is variation by model and manufacturer, AMS average between $175,000–$250,000 per robot for base models (Hyde and Engel 2002). Since most farms need multiple robots and likely need revisions to existing structures or new structures built to accommodate robots, typical capital investment ranges between one-half to several million US dollars. Maintenance costs vary by model and brand—and maintenance habits—but monthly service estimates from sales representatives range from $400–$1200. Estimates place the capital costs of AMS between 150 and 260 % higher than a conventional milking system for the same herd size and level of production (Reinemann 1999). To offset these costs, agricultural economists recommend actions focused on increasing dairy production (Heikkila et al. 2010).

A small body of research has examined the role of AMS in reshaping relationships amongst farmers, workers, cows, and technology. In an empirical study of the implications of AMS on daily workplace routines and the role of the stockperson, Butler and colleagues report that farmers found more flexibility in their labor, but not an overall decrease in labor: "In practice, farmers found their work routines changed rather than lessened" (Butler et al. 2012, p. 1). Although there was a general increase in flexibility of labor, farmers did report an increased burden of data analysis. Most found the amount of data available overwhelming and used it in only a very limited manner. In summary, AMS significantly altered the role and identity of the farmer, providing labor flexibility but also increasing the need to analyze and respond to data and changing their relationship to their cows.

Holloway et al. (2014a) argue that the adoption of AMS results in changes in what it means to 'be bovine'. Building on literature recognizing that users and technology are co-constituted, the authors argue that this also applies to non-human animals: dairy cows. Using Foucault's (Foucault 1978) concept of biopower, the authors argue that rather than the emancipatory potential of AMS for dairy cows, AMS operate within disciplinary productivist agricultural systems to recapture particular aspects of bovine life. "Far from simply granting cows their freedom, then, cows are re-enclosed by a set of power relations with this particular technology" (Holloway et al. 2014a, p. 139). In addition, AMS require a renegotiation of ethical relationships amongst cows and farmers (Holloway et al. 2014b). The nature of the human-technology interaction is "contingent and complex" (1) and not uniform and that diversity of these interactions results in a diversity of ethical relations amongst farmers, technologies, and cows. Stuart et al. (2013) also found that while AMS likely offers animal welfare benefits, dairy cows remain coerced, casting doubt on the notion of 'total cow freedom.'

Despite identified issues, studies show that in many ways AMS have lived up to marketing promises: farmers and researchers report significant lifestyle benefits (Meijering et al. 2004), higher production (Hogeveen et al. 2001), and better animal health (Hamann 2002) and welfare (Stuart et al. 2013) as a result of adopting AMS. However, relatively few studies have been conducted and many questions remain, especially regarding the variability among AMS users and potential impacts. The findings of this study indicated that dairy farmers use AMS in very different ways. This suggested that outcomes related to profitability, lifestyle, labor, animal welfare, and the environment may vary substantially. While we did not quantitatively measure outcomes in this study, we examined the various ways AMS are used and how this variation might result in alternative outcomes. This empirical work addresses calls to move beyond diffusion of innovation and determinist frameworks that may limit our understanding of technology and its impacts.

Methods

This study relies on interviews conducted with thirty-five AMS adopters in The Netherlands, Denmark, and the Midwestern US. The Netherlands and Denmark were selected for study because of their early and widespread adoption of AMS and because of their reliance on pasture-based dairy production. Pasture-based and confinement systems represent the maximum variation in dairy production systems, allowing us to analyze the effects of technology investment across diverse production systems. Fifteen of the interviews were conducted in The Netherlands and five in Denmark. The other 15 interviews were with US farmers: seven Wisconsin farmers, three Iowa farmers, two Indiana farmers, and three Michigan farmers. While relatively few dairy farmers in the US use AMS, AMS adoption rates are steadily growing. Estimates in the US indicate that adoption has grown from 12 farms with AMS in 2003 to 200 farms in 2011 (personal communication, D. Reinneman September 29, 2011). Adoption rates are especially growing in the Upper Midwest, where an estimated 100 farms have adopted AMS (personal communication, D. Reinneman September 29, 2011).

In the spring of 2011, we conducted the interviews with 20 dairy farmers using AMS in The Netherlands and Denmark. These farms had used AMS from 7 to 14 years and had small to medium sized operations ranging from 68 to 220 cows. All of the farmers selected managed "pasture-based" dairy operations, allowing cows seasonal access to pasture, with variation in the extent of pasture access. Pasture-based systems represent the traditional dairy operation in both The Netherlands and Denmark. Other university researchers who had previously worked with dairy farmers using AMS provided us with contact information. On-farm interviews took place in diverse locations in each country.

In the summer and fall of 2011, we conducted interviews with 15 dairy farmers using AMS in the Upper Midwest region of the US. Only 2 farmers were using AMS with a seasonal access to pasture and all others were using AMS within confinement operations (no access to pasture, grain fed indoors), although 9 used seasonal pasture for young or non-milking cows. We included both pasture-based and confinement; however, confinement operations are much more common in the US. Farmers were identified through university extension agents, university researchers, and AMS user groups. Farm size ranged from 53 to 240 cows and farmers had been using AMS from as little as 2 months to 11 years.

Interviews were based on an interview guide that focused on the adoption of AMS; relationships among animals, people, and technology; factors influencing operation design; and perceptions regarding impacts to people, animals, and the environment. A translator was used for interviews in The Netherlands when needed. All interviews were recorded whenever possible and later transcribed. Using NVivo software, we analyzed interviews to explore how and why operations were changed and to identify relationships and possible outcomes. Both authors coded interviews for key foci: motivations for adoption and impacts of adoption, using iterative grounded coding to identify themes and subthemes.

Designing and using automatic milking systems

In the following sections, we first discuss the diversity of AMS implementation followed by the possible associated impacts. Decisions about how to design and use AMS must first be understood within the context of the conventions in which farms operate. Farmers in the US and the EU were required to adhere to specific rules and regulations when creating their AMS; however, none appeared to be the leading determinants of decisions. Some differences between the EU and the US were identified that should be noted. For example, when designing their facilities, farmers in the EU faced much more specific and stringent environmental regulations regarding the management of manure. In addition, EU dairy farmers are subject to a quota system that limits the number of cows on each farm. EU farmers also explained that public expectations to maintain traditional dairy systems, involving grazing and extensive personal contact with the herd, was an influential factor but that creating an operation that worked well for them remained the priority. US dairy farmers did not face the same level of regulatory or social pressures compared to European farmers.

To create an AMS, dairy farmers needed to redesign their operations. First, in most cases AMS involved significant changes in barn design. While most dairies have a barn, a holding area (where cows wait to be milked), and a milking parlor; AMS require only a barn. Most farmers interviewed decided to adopt AMS when they did because they felt it was time to replace their parlor and/or barn. AMS adoption typically required moderate to significant changes in farm facilities and in most cases the construction of a new barn. Barns must have specific stations for the robots to be installed and open areas to accommodate new patterns of cow movement and 24-h access to the robots. It is also common for farmers to build an office attached to the barn for the computers linked to the robots. Farmers often worked with AMS sales representatives or consultants to design their new facilities.

A key decision in creating an AMS is the layout of cow movement, typically determined by a series of automatic gates. Automatic gates are installed in the barn to allow or

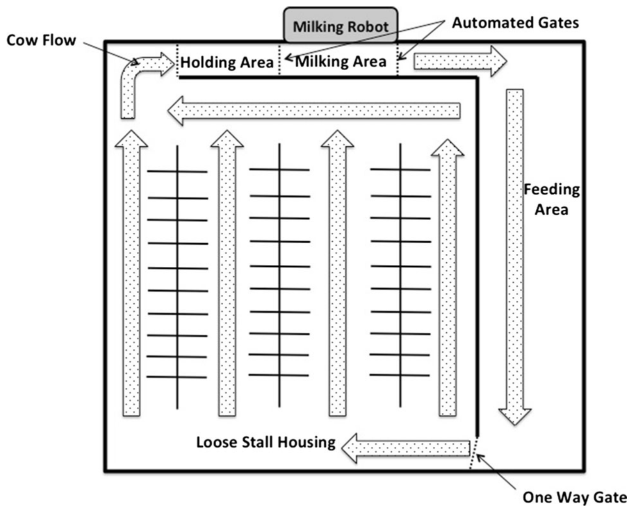

Fig. 2 Sample forced flow design

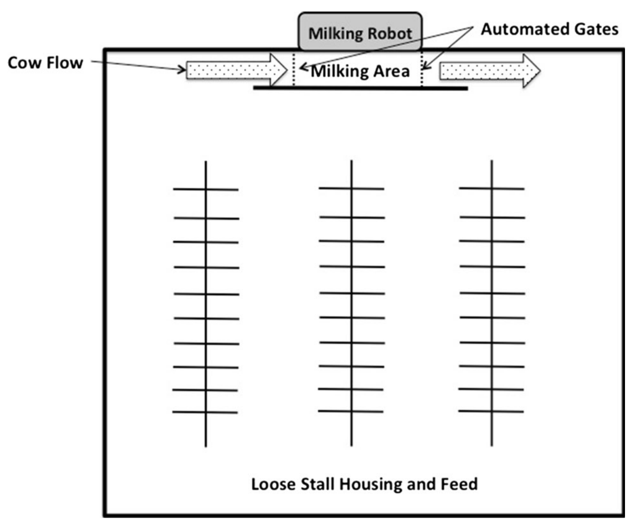

Fig. 3 Sample free flow design

deny access to the robot, other parts of the barn, or pasture. Each cow wears an identification chip in her collar and is recognized when milked or when approaching the gates. A major decision each farmer has to make is where to place the robots in the barn and where to place the gates in order to maximize visitation to the robots. Most farmers who use robots and allow access to pasture do not want cows to leave the barn until they are milked. These farmers have to decide whether to place the gates at the robot, at the barn exit, or in both locations.

When designing their systems, farmers also have to decide if it will be a "forced flow" or "free flow" design. Forced flow is when cows can only access the feeding and sleeping area of the barn (or the pasture) after they go through the robot (see Fig. 2). As they approach the robot, there is an automatic gate leading into a holding area and they cannot leave the holding area without going through the robot to be milked. In contrast, free flow does not use one-way gates to drive traffic (see Fig. 3). All EU farmers, except for one, had free flow designs. In contrast, most American farmers were initially uncomfortable with a free-flow approach and many early AMS-adopters used forced flow. American farmers who adopted AMS more recently tended to opt for free-flow designs. Choice of design seemed associated with notions of control and how comfortable farmers were with "letting the cows go."

Farmers differed greatly in how they designed their AMS regarding both spatial and temporal factors. Most farmers allowed "total freedom" temporally for their cows, with 24-h access to the robots. As one Dutch farmer explained: "they are free to roam back and forth to the robot and the only requirement of the cow is that she goes through the robot at least once a day." This type of "free-choice" system was the dominant one observed. However, a few farmers designed a more controlled system. One Dutch pasture-based farmer sent all of his cows to the robot together twice each day, causing a large back up and forcing cows to wait for several hours. This farmer explained that he likes to have more control over his cows, to ensure they are milked at least twice a day. He did not trust the system to operate on its own. Several American farmers used forced-flow systems that held cows between gates until they were milked. They also argued that this would ensure that cows made it to the robot. These variations resulted in different relationships and outcomes for humans and cows.

Another important decision AMS adopters make when designing their system is what type and how much feed to use. To encourage milking, cows are fed high concentration feed at the robot; therefore most cows attempt to visit the robot as much as possible. Each farmer determines how frequently cows can visit the robot before they will be rejected and turned away at the gate and this number is programmed into the robot's computer. Most farmers set this number at 5–6 visits, to maximize milking frequency without causing cows unnecessary stress. At the robot, a particular amount of highly concentrated feed is distributed to each cow. Farmers can use the computers to set this amount to be the same for all cows or individually tailored for each cow identified by the robot. This additional feed makes it more challenging to determine how much feed to supply in the barn. The selection of feed types and amounts is important to keep the cows interested in approaching the robot as well as to keep cows at healthy weights to ensure sufficient milk production.

AMS creation required rethinking and changing human labor on the farms. Less labor is required, as the robot now does the milking. For example, instead of 2–3 people milking cows 2–3 times each day, it is possible for one person to monitor the computer data and check on cows as needed. Upon adopting AMS, computers become a central part of the dairy operation and workers must know how to run the computers. Farmers can use the data to make sure their cows are healthy and producing milk. Using the identification chips and monitors located at the robot, the computer provides data on weight, number of visits to the robot, conductivity (tests for signs of infection), milk production, and activity (more movement indicates cows are in heat and ready for insemination). The software also can create a list of cows that need attention based on identifying data outside the normal range. While the use of the AMS data varied, all of the farmers interviewed stated they only used a portion of the data available to them. Some farmers check the data on their computer twice a day and others up to six times each day. The use of AMS data was largely related to existing levels of computer skills and ability to adapt to the new software.

In both the EU and in the US, several farmers decided to switch from pasture-based operations to total confinement or to significantly limit access to pasture when adopting AMS. Farmers interviewed also reported that many farmers that they knew of had abandoned pasture-grazing upon AMS adoption. The vast majority of American dairy farms are confinement operations (NASS 2010), while in The Netherlands and Denmark the majority are managed as seasonal grazing systems (Dobson 1998; Haumann and Wattiaux 1999). Despite this contrast, most American and European adopters shared a common perception that grazing was incompatible with AMS. In both in the EU and the US, AMS manufacturers had told farmers that the system would work better under confinement because milking frequency would be higher. While some European farmers followed this advice and reduced access to pasture, others refused to switch because it went against their personal beliefs about how cows should be cared for or what a dairy farm should look like. In the US, pasture-based systems are less common, but some farmers also refused to convert to confinement based on beliefs that pasture is better for the cows and represents a different way of life for the farmer. These farmers shared concerns that more farmers would be converting to confinement due to AMS adoption, resulting in negative animal welfare and environmental impacts.

Exploring outcomes of automatic milking systems

Labor flexibility

Our findings confirm a number of previous studies (Meijering et al. 2004; Meskens and Mathijs 2002) that find quality of life improvements, particularly flexibility in work schedule and less time spent milking, to be a primary benefit realized. Most all adopters cited increased control over their own labor and free time as his/her primary reason for pursuing AMS and the primary benefit. Farmers could sleep in and spend more time with their families. One farmer said, “I didn’t want to be married to the cows anymore. I wanted to do it for the kids, to have time for them.” Many farmers shared how their new flexible schedules allowed them to sleep in later in the morning and attend more family and social events. One Dutch farmer shared: “I think our kids like [AMS] very much because we have to go with them to music lessons and more activities and there was no problem for milking times. We are very flexible so we can do the job before or afterwards.”

Increased labor flexibility also allowed adopters to reallocate farm tasks among family members and to include younger generations in farm management. One Dutch farmer explained that with AMS his teenage children can now participate more in running the dairy whereas “with the conventional system it was not possible because of the intense labor.” The attraction of quality of life improvements was also identified as key to intergenerational transfer of the farm. One farmer said “you may have children that are interested in [dairy farming], but don’t want to commit to that life…. If you put in the robots they may say ‘Yeah, I want to continue on dairying because of the flexibility that it allows.’” Another reported that he had many more choices and started some hobbies that he wasn’t able to do with the old system. This increased control over their own labor is a significant contrast to conventional milking systems in which milking was rigidly scheduled and required several hours of demanding physical labor. For farmers willing to “trust” AMS and minimize their time tied to the barn, these quality of life improvements were significant enough that farmers were willing to adopt AMS despite concerns about financial benefits and reorganizing production.

While most farmers using AMS designed a “free-choice” system that allowed for these quality of life benefits, this was not the case for all farmers. As explained above, a few farmers designed a more controlled system, and these farmers experienced less labor flexibility and fewer “quality of life” benefits from AMS. For example, the Dutch farmer who sent all of his cows to the robot together twice each day was still resigned to the traditional milking schedule and did not experience more flexibility in his lifestyle. Another farmer explained: “It took me a long time to trust [the robot]. It was like a new baby and I wanted to make sure it was breathing, so I slept on the couch [in the barn] for 54 nights.” Farmers who use free-flow designs made disparaging comments about farmers who forced robot visitation. They perceived these farmers as struggling with "just letting the robots do it." They felt that these "controlling" farmers were not using AMS correctly to obtain the lifestyle benefits. To them this "incorrect usage" of the technology constrained the freedom that should come from AMS as portrayed by their manufacturers (Holloway et al. 2014a).

In addition, over time, using AMS data remained challenging for some farmers. If major problems with AMS arise, the computer calls the farmer on their cellular phone so that they can address the issue. While most farmers stated they enjoyed the new freedom associated with AMS, some stated that they remained anxious because they could be called by the computer at any moment. Calls ranged from once per week to once per month and typically resulted in trips to the barn to address the issue brought to attention. Most farmers used AMS to enhance free choice and flexibility for farmers and cows, however, a few had issues with trust and control that caused them to maintain forced visitations or oversight and did not experience the labor flexibility typical of AMS adopters. The degree of lifestyle benefits, therefore depends on how AMS are used.

Non-family labor

Avoiding the employment of non-family labor was cited as one of the farmers' central reasons for adopting AMS. As one Michigan dairy farmer said: "I'd rather pay a loan than pay a worker." Despite diverse labor markets, the ability of robotic technology to replace non-family labor and avoid the concerns of hiring and managing labor was a motivation shared by most all adopters interviewed. One Dutch farmer shared his rationale for purchasing robots: "for a long time when we were smaller it was difficult to find the right employee, so then we said it is just a choice: an employee or a robot…and we chose robots." Another shared that he "wants to do it by himself,… and [AMS] is perfectly doable with one person." AMS allow farmers the possibility to increase milk production without hiring employees, an appealing prospect to farmers who do not enjoy managing employees and whose identity as independent is undermined by employing wage labor (Mooney 1986).

Dairy milking is dirty and physically taxing work, and farmers spoke of difficulty finding qualified employees willing to work for an affordable wage. Along with avoiding the challenges of hiring and managing employees, AMS helped farmers avoid the financial cost of hired labor. One Dutch farmer shared: "the labor was quite expensive for the employees to do the milking" and "the robot itself was a new investment, but now he saves on the labor costs." One Michigan dairy farmer worried about the effect of robots on his relationship with neighbors because neighbors believe that "they are taking away good paying jobs." Another farmer said: "we have the robots because [of] the high salary" that they would have to pay to find "decent" employees and that "the robot was very expensive, but it is also expensive to pay a worker." These narratives support findings by Dijkhuizen et al. (1997) that AMS save on average $200/cow in labor costs and by Wauters and Mathijs (2004) that the reduction in labor-hours from AMS often resulted in laying off non-family workers.

In many cases, reduced labor meant laying-off low-wage workers from Mexico in the US and from Eastern Europe in the EU. Some farmers shared that they wanted to avoid working with foreign laborers whom they were not sure they could rely upon or trust. In the US, other dairy farmers have reported installing AMS specifically to avoid the difficulty of hiring immigrant labor and dealing with immigration concerns (Rivers 2012; Tumulty 2012). Farmers that had bad experiences with foreign labor were especially driven to avoid hired labor in the future, while some farmers maintained very positive relationships with foreign laborers.

On fewer farms, the number of workers did not change, but types of workers did. As one farmer explained: "with having the robots, when you are hiring help they have to be comfortable with the software, the computers…so you need someone with a wider skill set." Workers without these skills were often laid-off, while new skilled workers were hired or retrained if possible. Some farmers explained that these new workers are more costly to employ, but felt that the change in their labor force was essential to ensure that their AMS would run smoothly. Widespread AMS adoption could have significant impacts on rural labor forces: as one American dairy farmer stated: "I think [AMS] are great, but they are obviously going to eliminate peoples' jobs." Our findings support work illustrating that technology is used to displace or replace agricultural labor, both non-family and family labor and may alter the labor market (Pfeffer 1992).

While in almost all cases AMS adoption resulted in labor changes, the replacement of labor varied amongst farms. In many cases, robots simply replaced family labor, freeing up time for other activities, but in other cases non-family laborers were laid off due to AMS adoption. In most cases this meant the loss of one or two laborers, typically immigrants from Eastern Europe (EU) or Mexico (US) or local youth. However, in other cases farmers decided to keep their current workers and retrain them to use AMS. Farmers who put an extra effort into keeping workers during their transition to AMS expressed a strong personal relationship with these employees that seemed to provide motivation for their retention.

Dairy cows

As touted by AMS manufacturers, AMS can provide "free choice" to dairy cows. Instead of being herded several times a day, standing for up to 3 h each time in the holding pen, and being corralled into milking stalls; cows in most AMS are self-directed. Farmers only intervene when they feel it necessary. If a cow has not been milked in a certain time period, the farmer will notice this in their data and "fetch" the cow and bring her to the robot. Many farmers explained how they no longer needed to herd or chase cows for milking, and as a result, the cows no longer walked away from them when they approach. Instead, cows approached humans entering the barn, seemingly curious about the visitor. As one Dutch farmer explained: "the cows will follow you around… they know they aren't going to be chased and it is really fun to watch them interact with people." Due to AMS, many cows and farmers had new and less confrontational relationships. All of the adopters interviewed agreed that relationships with their cows were more positive and that the cows were more relaxed, although the level of force and coercion in the relationship varied depending on implementation.

The amount of time farmers spent with their cows varied among AMS users. The majority of farmers interviewed reported they did not spend less time with their cows after AMS adoption, they just spend that time differently. Instead of spending 4 h a day milking cows, they spend several hours inspecting and observing the cows or fixing things around the barn. Many farmers shared that they felt more in touch with their cows with AMS and are able to detect problems a cow might be having easier and earlier than before. Several farmers spoke of making more eye contact with the cows. However, some farmers did use AMS to allow more travel and to be away from the farm more often. These farmers would then rely more on others to step in if a problem arose, often others who had little knowledge about their herd. While they represented the minority, in a few cases the behaviour of these farmers support public concerns in the EU that AMS will result in herd neglect. This outcome is likely dependent on how attached the farmer is to their herd and how much they feel they can "let go" of their operation. As with decisions regarding free or forced-flow systems, these largely depend on each farmer's personality traits and animal welfare values.

Farmers reported that relationships amongst cows changed when using AMS. Many farmers noticed that their herd's social behavior changed. They shifted from spending time in large groups to spending more time alone or in smaller groups. Cows are moved around in small groups of 3–5 cows, rather than being in larger groups or all together as when herded in mass for traditional milking. Farmers attributed new behaviors to individual milking, although many stated that certain small groups of cows went to the robot together. Farmers claimed that cows had their own social dynamics and rhythms and the system allows them to have their personalized schedules. Many respondents also shared that this flexibility allows "lower ranking" submissive cows to avoid "higher-ranking" dominant cows that may "bully them." Overall, farmers reported that interactions were more positive and less hostile with fewer acts of aggression in the herd.

However, farms demonstrated different degrees of "cow freedom." The farmers that forced cows to visit the robot at certain times each day meant that cows did not experience the free-choice touted by AMS sales representatives. These cows continued to be herded together to stand in confined spaces for many hours waiting to be milked. While the majority of AMS allowed cows to choose when and how often to be milked, most systems used coercion to maintain a balanced milking frequency for the herd. The high-energy food pellets released at the robot during milking represent a "treat" that is "like candy" to the cows. Because of the treat, some cows will attempt to be milked many times a day. To keep cows moving through the robot after milk flow has subsided, a device called "the tickler" delivers a mild electric shock. Some farmers interviewed said that they did not use "the tickler" at all and others turned it off after the first few months of use. Other studies have also identified that these coercion techniques do bring claims of "cow freedom" into question (Holloway et al. 2014a; Stuart et al. 2013).

Those farmers who maintained forced-flow, a rigid milking schedule using herding, more frequent "fetching" of cows, and the "tickler" did not experience the improved relationships with their cows reported by other AMS adopters. Instead, those few farmers who continued to rely on more conventional coercion techniques reported little, if any, change in how they viewed and related to cows. Cows continued to spend many hours in holding pens and experience force and stress in their relationships with farmers. Here we find that multiple outcomes can emerge: the extent that farmers released control and utilized coercion devices determined the extent of "free choice" for cows to move about and do as they wished.

Most of the respondents shared a perception that AMS improve animal welfare, although they had diverse experiences with disease. Many farmers claimed that with AMS cows lived longer, were less stressed, and had fewer incidents of disease. One farmer described his understanding of how AMS improve animal and udder health, "it is less intensive for the cows [to be milked more often]… and they have better udder and overall health." While data from studies remains inconclusive (Meijering et al. 2004), many farmers felt that their cows had less mastitis (teat

Table 1 Summary of variation

	Personality and values	Variety of implementation	Mediating factors	Variety of outcomes
Layout	Comfort with lack of control Animal welfare values	Free flow/forced flow Placement of robots in barn	Number of visits to robot Animals herded or not	Amount of cow freedom to determine milking routine Amount of cow social freedom Extent of force in relationship between cows and humans How much time is spent with cows Whether the cow is seen as a "whole animal"
Labor	Relationships with workers	Extent of non-family labor	Labor market Existing debt	Relationship with labor market Level of skill required for workers Resilience
Data	Computer skills	How often data is checked Which data is used How much "error" is tolerated from robot	Number of visits to robot	How much time is spent with the cows Whether the cow is seen as a "whole animal" Extent of force in relationship between cows and humans Young people more involved in computer
Animals	Animal welfare values Environmental values	How much feed is given How many visits to the robot are preferred Use of the "tickler"		Level of production Amount of cow freedom to determine milking routine New cow social groups Disease and lameness rates Bullying level among cows Extent of force in relationship between cows and humans
Organization of production	Existing debt Financing options Animal welfare values Environmental values	Debt in acquisition	Pasture or confinement Increase herd size or not	Level of production Resilience Environmental intensity Animal health and welfare

infection) with AMS. However, in a few cases rates of infection increased right after AMS adoption and in rare cases disease emerged after several years of use. Some farmers claimed that their overall veterinary bills have gone down due to AMS, while others stated they remained the same or increased. Different AMS, depending on design and maintenance practices, had more or less trouble with bacteria getting into the system. Much is still unknown about these impacts and research continues to examine what aspects of design and use result in different health outcomes for AMS dairy herds.

Conversion to confinement from pasture after AMS adoption has important animal welfare implications. Pasture-based farmers interviewed agreed that pasture is better for cows. One participant explained: "I think they are a lot healthier, not just physically but mentally as well." Farmers argued that hoof and leg lesions, in particular, were much less common when cows were on pasture. The potential animal health benefits of grazing, while debated within the veterinary literature, include reduced incidence of inflammation and lameness (Hernandez-Mendo et al. 2007; Krohn and Munksgaard 1993; Phillips 1990), reduced mastitis infections (Goldberg et al. 1992; Washburn et al. 2002), and reduced teat and skin injuries (Regula et al. 2004). Based on this evidence, farmers who decided to convert to confinement after or upon AMS adoption are likely negatively impacting animal welfare in their operations.

Reorganizing production and environmental intensity

The high capital cost of AMS in many cases led to significant reorganization of production and possible associated increases in environmental intensity. Most farmers that have purchased AMS have made significant changes to their production including increasing the purchase of feed from off-farm sources, reduced use of grazing, and one-half of adopters interviewed have increased herd size, all with the ultimate goal of increasing production to offset capital investment. “If you’re going to spend all the money on robots, it is best to get the best value out of it,” one US farmer stated. The best way to get that value, he and others argued, was to increase production. About half of the farmers in our study had increased their herd size to maximize production. As one EU farmer explained: “before the robot there used to be less cows and they would produce less milk, so now there are more cows and they are producing much more milk.” A Dutch farmer explained: “you have to grow bigger before you can have some money from the robots, so we had to grow and that is why we’re having more cows.” However in many EU cases, growth was restricted due to the dairy quota system. Farm sizes in the EU are likely to increase after the quota system ends in 2015. Some Dutch farmers have already purchased additional robots to accommodate their plans to expand their herd size in 2015.

Across diverse production systems in Europe and the Midwest, many adopters of AMS increased herd size to offset the capital investment, despite AMS’s promise of increased milk production without the need to increase herd size. Increasing herd size may result in a number of environmental problems associated with higher livestock stocking density, including increased antibiotic use rates (Sawant et al. 2005) and increased microbial resistance (Witte 1998), and a higher risk of groundwater (He et al. 2004) and land contamination from manure (Peacock et al. 2001). A large trend to increase herd size, therefore, could result in local and regional environmental degradation.

Both increased purchase of feed from off-farm sources and reduction in the use of grazing were common following adoption. Both of these changes can substantially increase the environmental impact of dairy production. Robotic milking systems require a high calorie feed to be served at the robot during milking to: (1) boost milk production and (2) provide an incentive to encourage visitations to the milking robot. More visitations equates to higher production per cow and per robot, which serves the ultimate goal of increasing production to maximize the value of the capital investment. Adopters emphasized the increased importance of purchased feeds to boost production and maximize the utility of the robot. Increased purchase of off-farm feed may significantly increase the carbon footprint of dairy production by shipping grain-based feed across distances as well as increasing the proportion of commercial grain in cattle’s diet (Phetteplace et al. 2001; de Klein and Ledgard 2005). In addition, this encourages the metabolic rift in agriculture as described by Marx (Foster 1999): while on farm feed production recycles nutrients, reducing fertilizer application as well as manure storage and pollution risks, a greater reliance on off-farm sources creates a rift in this closed-loop system and increases risks of environmental degradation.

Financial benefits and economic resilience

Robotic milking systems require a large capital investment, typically funded through private lending institutions in the US and a combination of private lending and public grants in the EU. Most adopters were ambivalent at best about whether there are any financial benefits to AMS to offset the capital costs. When asked directly if he believed there were any cost savings or financial benefits from having robots, one farmer put it bluntly: “No, it is more expensive.” Others also believed that it was actually more expensive than conventional milking: “No, I hoped [operating costs] would be the same, but it is not a cheap way to do it.” While some farmers believed that AMS was actually a net cost, most were actually unsure of the financial impacts of the new technology or believed that the net effect was neutral:

> I think there are no financial benefits. There are a lot of calculations, and I have calculated a lot myself, and I have come to the conclusion that they are about the same cost price per unit of milk…a few articles in ag newspapers said it is about 1–2 cents higher…but I think it is the same cost price, but it isn’t lower.

Other adopters were also unsure of an overall financial assessment: “it is very hard to determine if it is a [financial] benefit or not because there are several factors…so it is very hard to prove whether there are financial benefits or not.” One said that “financial benefits are not very certain because there are…the costs of electricity, water, and maintenance” to balance with the loan payments and labor savings. Most adopters claimed that they were unsure of the net financial effects of robotic milking systems or had not made the calculations to evaluate the costs and savings of the new technology. This perceived lack of financial benefits of AMS echo the findings of economic studies that find either little, if any, financial improvement on farms that adopt AMS (Hyde and Engel 2002; Rotz et al. 2003).

Pressure to increase production to compensate for the high cost of AMS and possible reduced resilience resulting from debt was a central concern for many adopters. Many US adopters, in particular, spoke of the increased stress and pressure from debt acquired to purchase robots and their maintenance costs. One farmer already planned to exit the industry to escape this mounting pressure: “Their price of maintenance is super high. One of our friends just quit who opened up about a month before us because the cost is too high… he just couldn’t keep the numbers going, and we are probably next. I think within 6 months, I don’t think we will be running anymore because we just can't afford it." Many others shared the same concern about the cost of loans and unexpectedly high maintenance costs of the new technology. One US adopter said he wished he'd known more about the increased costs of: "the loan, along with the maintenance, which is more expensive than I thought it would be." Many farmers with AMS strongly felt the pressures of increased debt and capital costs.

In some cases, the high capital cost of AMS adoption may undermine the future resiliency of dairy farms. One US family who had purchased an automatic milking system just before the 2009 record drop in milk prices regretted taking on the increased debt and costs: "when we got the robots 2 ½ years ago, was just when the price of milk really bottomed out…The biggest challenge was the milk price, because we still had to pay that loan each month, even without a milk check." This need to service the capital investment in technology may lead to reduced resiliency amongst AMS adopters, although the small number of AMS adopters and the short time since the entry of AMS in the US makes systematic analysis of farm-exit rates impossible. However, previous studies have demonstrated that heavy debt loads reduce the ability of farmers to control management decisions and increases the vulnerability of family farms to consolidation or farm-exit (Jackson-Smith 1999), particularly during times of commodity and input price instability such as the 1980s farm crisis (Harl 1991). The farm-level effects of increased industrialization, consolidation, and farm-exit led to widespread structural changes in the organization of agricultural production and rural communities during the 1980s. The volatility of agricultural commodity and input prices (Sarris and Hallam 2006) makes this potential reduced resiliency problematic for the sustainability of individual farms and the longevity of small-scale agricultural production.

Despite general trends, we also found variability in the financial impacts of AMS adoption. Many EU farmers and a few US farmers were able to reduce debt load through the use of public grants for capital investment. Adopters also varied significantly in their pre-existing levels of debt before adoption and in the total amount of capital they invested in AMS. Those farmers with less acquired debt did not feel the same pressures to increase productivity and maintained a higher degree of perceived financial resilience. These lower-debt farms were less likely to have increased their herd size or limited access to pasture, and were less concerned about the effects of debt on their farms' longevity. In addition, European dairy farmers will be substantially tested when government imposed milk quotas end in 2015. While it is difficult to assess variations in farm resiliency, flexibility in farm funding may play a role, as well as arrangements with milk cooperatives and niche markets (e.g., pasture-based or organic milk).

Conclusion

While a growing body of research has examined AMS, much is still to be learned especially regarding the possible impacts of increasing AMS adoption. This paper begins to explore the range of AMS uses and potential impacts. Our analysis reveals that different designs and applications of AMS can result in diverse outcomes. We find that decisions regarding spatial and temporal factors and decisions to increase milk production led to different results. We also find that farmers' individual values, goals, and personality traits have great influence over AMS design, practices, and associated impacts. While more research is needed to examine the extent of these impacts, our analysis suggests a range of different outcomes regarding farm resilience, animal welfare, labor, and the environment. Therefore, we contend that any studies which suggest a universal AMS with universal uses and impacts would be shortsighted. Technology adoption, practice, and impacts are far from universal. Our study of AMS reinforces the notion that technology and society are truly co-constituted and that there is no one "impact" of technology (Pinch and Bijker 1984; Pinch and Oushoorn 2005) and that further research is needed to uncover the causal mechanisms linking diverse implementation to diverse impacts.

Comparing US and EU farms in our study revealed that in many cases individual values and priorities shaped AMS creation, maintenance, and associated outcomes much more than rules and norms associated with each setting. While government regulations, production standards, and cultural norms do shape design and management choices, in this case our analysis illustrates that individual values and personality traits had a significant impact on how relationships were configured and the associated outcomes for people, animals, and the environment. The cultural setting and regulatory context for dairy production in the EU and the US differed; however, we found many similarities in design and changes made for AMS adoption.

In this study, an individual farmer's desire for control, value of personal relationships, and priorities to maximize profitability were the strongest determinants of design, management style, and practices that result in specific outcomes. For example, farmers that were able to give up control over their herd were more likely to increase "cow freedom" as well as their personal free time. Those farmers who were uncomfortable giving up control instead maintained forced-flow and/or structured milking routines and therefore failed to realize many of the potential lifestyle and animal welfare benefits of AMS. They continued to experience the rigid schedule of conventional dairy farm management and a more coercive and stressful relationship with their cows. A farmer's attachment to his/her cows also influenced how much time they spent on the farm observing the herd. Similarly a farmer's personal attachment to hired workers shaped decisions whether to retrain or lay-off wage-laborers. Priorities to maximize profitability and extent of debt load resulted in decisions to increase heard size or convert from a pasture-based operation to year-round confinement. In contrast, farmers who expressed a strong commitment to traditional production methods or protecting cow welfare were more likely to continue grazing their herd despite criticisms from manufacturers and other farmers. These decisions all have important implications for farmer lifestyle, animal welfare, labor, and the environment (see Table 1).

Manufacturers have promoted AMS as a way to sustain family farms, however, our findings demonstrate that AMS may increase the debt load, undermining farm resiliency and increasing the environmental intensity of production. Given the context of limited control over production decisions and heavy pressures to "get big or get out" AMS may seem to provide an alternative path for dairy farmers. It promises to increase production while reducing human labor. However, adopters reported few financial benefits and a trend to increase production to ensure that each robot is "working at full capacity" (Heikkila et al. 2010). In support of treadmill of technology theories, we find that technology may increase farm vulnerability for some farmers and may result in farm consolidation as farmers are pushed out during times of economic crises (Levins and Cochrane 1996). Replacing human labor with technology and increased pressures for productivity and profitability may also undermine the very features of family farm production—the ability to self-exploit family labor and a reduced profit incentive (Barnes and Gilbert 1995; Friedmann 1978; Roberts 1996)—that have supported its resilience. However, these pressures are not experienced universally and vary depending on debt load and financing. It remains too early to tell if AMS users will be too vulnerable to withstand future agricultural market fluctuations and crises. The ability to replace non-family wage labor and the quality-of-life benefits continues to motivate AMS adoption, despite a growing awareness of the risks of capital investment.

Increasingly, we see more robotic technologies emerging in agricultural settings. For example, scientists continue to work on the development of an army of robotic "farmhands" to perform watering, weeding, and nutrient management in crop production (Pocock 2006; Grooms et al. 2009). As technology continues to reshape relationships and outcomes in agriculture and in society at large, we agree with others that more nuanced research approaches and understandings are needed (Pinch and Bijker 1984; Bingham 1996; Kline and Pinch 1996; Schurman 2003; Pinch and Oushoorn 2005; Glenna et al. 2011). This study on robotic milking responds to growing calls to go beyond diffusion and determinism in our understanding of agricultural technology adoption. Instead of focusing on who adopts a particular technology and why, we have focused on how a technology is used and the possible range of associated impacts. We find that technology can be used in many ways with many possible outcomes. Uses and impacts are far from universal. This approach revealed new insights about the use of robotic technology in agriculture and we hope others will continue this work to identify specific causal mechanisms by which variation in technology implementation leads to variation in outcomes.

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