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Back to Nature With Fenceless Farms—Technology Opportunities to Reconnect People and Food

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The development and application of the fence was one of the earliest forms of agricultural technology in action. Managing the supply of animal protein required hunter gatherer communities to be able to domesticate and contain wild animals. Over the ages the fence has become ingrained in the very fabric of society and created a culture of control and ownership. Garett Hardin's article titled "The Tragedy of the Commons" suggested that shared land, typified by access to a fenceless common resource, was doomed to failure due to a human instinct for mistrust and exploitation. Perhaps the fence has created an ingrained societal cultural response. While natural ecosystems do have physical boundaries, these are based on natural environmental zones. Landscapes are more porous and resilience is built up through animal's being able to respond to dynamic changes. This paper explores the opportunity for remote monitoring technologies to create open fenceless landscapes and how this might be integrated into the growing need for humans to access animal protein.

Keywords: fence, virtual fence, technology, social licence, tragedy of the commons

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INTRODUCTION

The rise of *Homo sapiens* has seen unprecedented impacts on planet earth. The transition from small groups of nomadic hunter gathering communities to settled early agriculture marked the start of modern civilisation (Zeder, 2008). Managing landscapes to ensure a reliable food supply resulted in early domestication and tribal control of spatially important resources (Mysterud, 2010). Rather than hunting for food early agricultural practises started to control the supply of food (Zeder, 2008). This control ensured a regular supply of nutrients that were protected and could be stored. Delineating tribal boundaries that ensured domesticated livestock were accessible would have required a form of containment or fence (Mysterud, 2010). The change from group ownership and management to individual ownership and management of animals and nutrient supply, particularly in Western societies, especially Britain and her colonies, saw the rise in the use of containment or fences (hedges, drystone walls, and fences) to both keep in animals and keep out animals and delineate ownership lines. Pastoral agriculture systems differ from other forms of agriculture in that livestock are autonomous and mobile, therefore requiring containment, through training, breeding or physical barriers.

There are a wide range of contemporary grazing production systems that includes open-range domesticated livestock keeping, semi-domesticated pastoralism, and intensive fenced livestock farming systems. Estimating the current global distribution of these different pastoral livestock methods is challenging and uses coarse census data coupled with statistical models that estimate the geographical distribution. While fences are not used in all grazing systems they have played an important role in more intensive, low labour farming systems that are typical of pasture based systems in Australia, New Zealand, Europe, parts of southern Africa, North America and parts of South America.

The results of agricultural technological innovation have been far reaching (Klerkx and Begemann, 2020). For example boundaries and fences have become synonymous with identity and ownership, whether this applies to a farm or an individual house and garden or regional and national jurisdictions. The extent to which technological innovation has been driven by unique human cultural responses and the extent to which it sits within a broader natural environmental context poses many questions (Rosenberg, 1990; Gremmen et al., 2019; Fogarty and Kandler, 2020). However, current developed agricultural practises have diverged to a point where their very existence is only possible due to refined cultural practises that exploit innovation and in doing so creates ethical challenges for farmers and the broader community (Gremmen et al., 2019).

By exploring the transition of technological innovation, it is clear that unlike most natural systems that tend to evolve to optimise nutrient and energy efficiency, agricultural production has optimised labour efficiency often at the expense of energy efficiency (Pimentel and Pimentel, 2007). Humanities' ability to form cooperative social groups that desire meaning, that build stories and seek to spend time solving abstract problems has resulted in modern food supplies being delivered by small groups of farmers (Fogarty and Kandler, 2020). Efficient modern agriculture has exclusively optimised labour efficiency. In developed nations it is estimated that over 95% of the population have no direct involvement in growing food. The resultant disconnects between producing food and consuming food has created economic drivers that make it easy to mask the broader consequences associated with modern farming systems.

The "Tragedy of The Commons" explicitly speaks to selfish motivations driving individual behaviour within the context of shared resources (Hardin, 1968; Lloyd, 1980). Implicit in these articles is the broader dilemma underlying food security. While there has been debate over the validity of selfish motives driving use of shared resources (Ostrom, 1999) the analogy of livestock grazing common land talks to the desire to secure economic gain at the expense of long-term sustainability. While not essential fences do allow livestock farmers to not only contain animals but also to assign them responsibility for managing the land.

Emerging innovation in sensor networks built on the "internet of things" (IoT) is creating the opportunity for new agricultural farming practises. Rifkin talks about a move towards a third industrial revolution creating a green economy (Rifkin, 2016). Large jumps in industrialised activity have been built on synchronous advances in three key domains: energy, communication and transportation. The emerging revolution will utilise these drivers to facilitate increased democratisation and locally diverse productivity (Rifkin, 2016). We can already see the impact of these changes in areas such as education through video sharing platforms and new economic models for music sharing. The convergence of the IoT coupled with greater connectivity that empowers like minded individuals to find their tribe and collaborate from around the world could have a significant impact on how we farm.

This paper considers the role of the fence in modern industrialised farming systems and the benefits of containing livestock. There are important livestock production systems around the world that allow herbivores to graze in unfenced areas, however, this paper is focussed on fenced farms that are typical of livestock farming in Australia, New Zealand, North America, and Europe. At face value the fence is just a means to control livestock movement. However, the fence is also a metaphor for society's relationship with food production. The fence not only contains livestock but also restricts access to food production. This paper considers how the fence has led to a disconnect between growing food and consuming food. Emerging technologies are potentially shaping a new age of fenceless farming; this paper considers how fenceless farming could create new opportunities. This paper considers how remote automated livestock management technologies such as virtual fencing might enable fenceless farming. There are other forms of livestock farming systems that don't use fences. Currently fences fulfil the role to contain livestock, however we consider the opportunities for on-animal devices that can monitor and control livestock movement. These opportunities are extended to consider not just livestock management but also the opportunity to better connect the food supply chain. On-animal fenceless monitoring systems could re-imagine the relationship between food supplier and food consumer and create a new metaphor of open free access. Currently there are a number of research and development activities focussed on delivering automated animal control that have the potential to create fenceless farms. The first section of the paper reviews the role and scope of fences and the realistic potential to remove or replace them. It then explores the fence as a metaphor of disconnect between food producers and food consumers. This metaphor does not reflect the physical divide of farms but relates to the information divide and how fenceless farming technology can be used to monitor and share information. The paper considers why we might need to think about change, how that change might occur and what it might mean for the livestock, the farmers and the broader community throughout the supply chain. In looking to the future, the paper aims to present possible future scenarios, in so doing the authors acknowledge that this paper presents a limited set of options. The conclusion considers how the example of fenceless farming might have lessons for the future direction of farming and food supplies.

THE ROLE OF THE FENCE FOR LIVESTOCK PRODUCTION

The fence for livestock farming represents the ability to contain and manage domesticated livestock. There are a number of features of animal control systems that extend the notion of boundaries, and the descriptions represent varying functional features. We typically might envision controlling livestock with posts in the ground, wire hanging between them and a gate in one corner, while this is the most common form of control it is certainly not the only form. Livestock control can be represented by the variation in density or numbers of animals being contained, the form of the boundary and how permanent the boundary system is.

Containment in the broadest sense enables more efficient animal management. Extreme extensive livestock production systems that are typical of arid rangelands, such as those found in northern Australia, have highly variable seasonal forage growth. Studies in northern Australia provide an example of the importance of flexible stock management to avoid over or under grazing (Ash and Smith, 1996; Bortolussi et al., 2005; Hunt, 2008; Cullen et al., 2016; Pahl et al., 2016). Fencing these large and extensive areas is expensive and time consuming. The role of the fence in these extensive areas is to manage the feed-base, in particular to ensure there are grazing resources to carry cattle through extended dry seasons (Cullen et al., 2016). Fenced areas also provide easier access to cattle at key times in the production cycle. For example, drafting or separating cattle for sale or weaning calves from cows. There is an implicit connexion between the role of the fence and labour efficiency (Lomax et al., 2019). The extensive nature of the production environment in extensive rangelands makes it very difficult to locate and gather cattle and the fence provides an important role in trying to make this job more labour efficient.

The most intensive livestock production systems result in boundaries and fences that contain large numbers of individual animals in very small areas (Barry et al., 2015; Lomax et al., 2019). The most intensive production systems occur in fully contained housing where the livestock production results from fully controlled environmental conditions. Intensive housed production system optimises conditions to maximise food conversion efficiency as well as high levels of automation to optimise labour inputs (Astill et al., 2020; Martinelli et al., 2020).

The fence or boundary is considered a management tool to contain farm livestock. However, modern livestock agricultural systems sit within a broader supply chain and require external nutrient and energy inputs to sustain production. The lifecycle of livestock production includes movement between fenced areas both within a farm and between farms. Eventually the livestock enters the complexity of the human food chain.

In addition to enabling more efficient livestock production management a fence or boundary can be used to stop or reduce domesticated livestock damaging protected areas (Mysterud, 2010; Woodroffe et al., 2014; Jakes et al., 2018). These areas could have environmental value or have other uses that require livestock exclusion for example roads.

The fence is an example of a technology that has been used throughout modern agriculture to improve livestock management. The primary application of fences has been to restrict livestock movement. The ability to more easily manage larger groups of livestock has resulted in reductions in the number of people needed to manage livestock as a source of food for the broader population. A side effect of the fence has been for modern farming to be able to successfully keep the majority of people away from livestock production. In the context of Hardin's "Tragedy of the Commons" the fence removes the need for shared responsibility, the fence results in responsibility and consequences being assigned to "the owner."

THE FOUNDATIONS OF A SOCIAL CONTRACT TO DELIVER FOOD SECURITY—THE METAPHORICAL FENCE

The history of human food security from early hunter gatherers through to current farming systems is one of the trade-offs between time and energy or nutrients (Pimentel and Pimentel, 2007). Successful food security can be considered as a function of energy or nutrient supply per unit time. Technological innovation whether through improved hunting methods or improved farming systems is typically judged against the ability to deliver safe and healthy food security (Chávez-Dulanto et al., 2021). Measures of success for any given innovation might be efficiency of energy or nutrient supply. Key attributes of human food supply are founded on food sharing, labour exchange, and labour specialisation (Kramer and Ellison, 2010). The cooperative food model relies on individuals pooling food resources and this allows nutrients to be allocated to maintenance, production and a third pool of general activity (Kramer and Ellison, 2010). Cooperation in food supply leads to division of labour across a range of complex tasks, it supports specialisation especially when there are inequalities in the rates of return for specific activities. It also provides a foundation where time and effort allocation to acquire energy can vary between individuals within a cooperative group. This variation has particular value for humans that require long-term care of immature offspring (Charnov, 1991; Larke and Crews, 2006).

The cooperative food model results in innovation focussed on outcomes that maximises time allocation to general activity. In the context of nutrient or energy budgets the general activity is any activity that isn't directly related to an individuals own maintenance or reproductive effort i.e., activity that delivers to shared community value. Within the general activity allocation individuals can specialise in their contribution. The efficiency of food security creates opportunities for individuals to further specialise in activities that support the broader community goals. The progression and industrialisation of agricultural societies allows individuals to contribute to the community through the specialisation in the provision of livestock related nutrients. The adoption of fencing technology provides an example of an innovation that increases the labour efficiency of livestock rearing as well as the total productivity per person (Pimentel and Pimentel, 2007).

The pooling of resources, community cooperation and increased innovation through specialisation provides a foundation to deliver an increasing pool of nutrients and energy (Kramer and Ellison, 2010), in practical terms surplus energy and nutrients can be traded for time. The success of the pooled resource model relies on maintaining community co-operation, this becomes more challenging as the size of the community that is sharing the resource grows (Epstein et al., 2021). Specialisation results in a co-dependency that helps cement the cooperation. Community symbols that demonstrate the value of cooperative efforts can also help maintain the effort to pool resources as demonstrated in modern agricultural shared resource models (Cornée et al., 2020). There are examples of major human endeavours founded on a combination of innovations that deliver surplus nutrients freeing time to deliver symbols that demonstrate the power of pooled resources. It is estimated that the development of irrigation technologies coupled with fertile soils along the Nile in Egypt coincided with the building of the pyramids. Calculations have estimated that the surplus energy through efficiency and improved crop yields from the innovative irrigation practises was approximately equivalent to the energy required to build the pyramids (Cottrell, 1955). This energy was in the form of human labour that specialised in construction and was fed by the increased crops yields associated with irrigation innovation.

Livestock containment using fences, hedges and walls can be considered in the context of community driven energy and nutrient pooling and has been utilised to varying degrees throughout the development of modern agriculture. Increased division of activities through specialisation results in the fence as a symbol of the growing impact of the success of innovation. This success combined with other innovations has resulted in modern food supplies requiring a very small percentage of the population to deliver nutrients and energy to the broader community. Most community members have been completely excluded from delivering food security. Modern agriculture has liberated energy and nutrients that can be allocated to the broader community activities pool, but this success has resulted in a disconnect. Specialisation and innovation practises that support modern agricultural practise rely heavily on energy dense inputs such as fossil fuels in the form of agrochemicals, fertilisers and fuels for machinery. Disruptions to these energy dense farming practises creates a response that seeks to ensure the fundamental community need for food security is met. An example of a community response can be seen in the disruption to the Cuban food supply with the advent of the 1990's oil embargo. There was a shift from mechanised power to human power with more people directly involved growing food. Local community food supplies were prioritised over global food supplies with a shift away from commodity crops such as sugar and a shift towards crops that could be grown and consumed locally such as vegetables (USDA, 2008; Leitgeb et al., 2016).

As increasing numbers of people become more disconnected from growing food, they lose knowledge and understanding of the practical constraints to maintaining food supplies (Donald and Blay-Palmer, 2004; Sandover, 2020). This disconnect is further compounded with increased food processing that masks the origins of a particular food. Our biology demands that as individuals we need to secure a regular supply of food to ensure we have sufficient energy and nutrients. Within Maslow's hierarchy of needs food is considered as a base physiological need (Maslow, 1943). These base physiological motivations are important drivers of human behaviour. More recently researchers have been exploring a hierarchy of food needs (Satter, 2007). This hierarchy starts with meeting a basic need of having enough food. As food supplies become more abundant, we satisfy a goal for reliable ongoing access to food and our motivation moves towards greater food. Choices are initially driven by taste reflected in a desire to access novel foods. The highest motivation is a need for instrumental food that achieves a physical, cognitive or spiritual outcome and may or may not be supported by scientific evidence. This hierarchy of needs is where foods derive value beyond the nutrients they supply.

In designing future farming landscapes, the historical, physical, social, cultural, and psychological drivers of our individual responses to food security can be easily ignored. As we consider emerging agricultural innovations and how they might shape future farming landscapes we might consider the broader motivations that shape a community contract to access food and that have a strong foundation in the cooperative food model (Kramer and Ellison, 2010). Expanding the technological opportunities for fenceless livestock production to deliver value beyond the farm gate might be important for reconnecting farmers with the broader community. While the fence is not responsible for keeping people away from farms, however, in industrialised farming labour efficiency has resulted in consumers having less contact with food production. The technology driving fenceless farming provides an opportunity to provide consumers with virtual information and insight into livestock production methods. Finding ways to strengthen connexions might help shape understanding of the opportunities and constraints that modern agriculture faces.

TECHNOLOGY DEVELOPMENTS REQUIRED TO DELIVER FENCELESS LIVESTOCK FARMING

Removing the need for fences will require alternative methods that can be used to monitor and manage livestock. Current fencing provides a range of management benefits including controlling access to feed resources, delineation of livestock ownership, and to provide easier access to animals for routine management such as daily milking of cows. In addition to management requirements there are also a range of different production environments reflected in factors such as total farm or paddock size, numbers of animals contained in a paddock or across a farm (stocking rate) and the natural topographic and environmental features that form the basis for the livestock containment. Finally adjacent properties will be governed by different managers that have different goals. In some cases, these goals might require certain areas to not have access to livestock. These broad drivers define the role of the fence and need to be translated into technological solutions for fenceless farming systems (Barry et al., 2015; Jakes et al., 2018). Broadly speaking the fence characteristics can be defined by a combination of a permanency and permeability factor. Permanency defines the temporal requirement to contain livestock. Permeability defines the spatial requirements to contain livestock and determines how leaky the fence can be.

Fenceless technology that can be used to manage the movement of free ranging livestock will need to monitor, stop, and move animals without the need for a physical barrier. There are a range of technologies that are under various stages of research and development. Underpinning the spatial framework is access to digital maps and global positioning systems (GPS). It is now possible to use a GPS device combined with a digital map to identify the exact location and reference this location in regard to underlying resources e.g., the property you are located in and the exact location within the property. The development and application of these technologies for livestock systems warrants a paper in its own right. For the purposes of this paper, we accept there are challenges but the principles of remote and automated location and relative location are considered to be broadly solved but require some specific refinements mainly in power management related to location frequency and form factor related to the device being fitted and remaining in place and working on free ranging livestock (Swain et al., 2011). In general terms the technology framework for remote automated management of livestock falls under four broad categories. Off animal monitoring (Menzies et al., 2017a), off animal control, on animal monitoring (Swain et al., 2011), and on animal control or virtual fencing (Anderson, 2007; Bishop-Hurley et al., 2007; Umstatter, 2011; Umstatter et al., 2013; Anderson et al., 2014; Muminov et al., 2016; Lomax et al., 2019). Broadly speaking these technologies rely on manipulating behaviour through a combination of managing critical resources that livestock require on a regular basis e.g., watering points and directly controlling livestock behaviour through cues and controls. Livestock need to access certain resources on a regular basis (e.g., water), it is possible to control access to these resources and restrict when and how animals can gain access. An example of technologies that control resources to manage livestock is walk-over-weighing where livestock have a simple electronic identification tag that is read as the animals walk over a set of weigh scales. Their weight, ID, data and time and frequency of visits can be recorded. These data can be used to infer a range of production metrics such as growth rate, date of birth, oestrus detection and maternal parentage (Menzies et al., 2017a; Corbet et al., 2018; Imaz et al., 2020). The system can also have a drafting or control gate fitted, this allows the animals to be remotely and automatically drafted from the main group. On-animal monitoring requires livestock to be fitted with smart technology that can monitor the animals changing state. These changes include body movement, changing location and physiological parameters such as temperature or heart rate (Kour et al., 2018; Edwards et al., 2020; Högberg et al., 2020; Islam et al., 2020). The sensor devices log the data locally and then transfer it via a range of different communication technologies. Unlike the off-animal monitoring system that only requires electronic identification which has relatively small amounts of data (a few bytes) and can use radio frequency to power the tag, the on-animal monitoring technologies require a power source, local data storage, higher bandwidth communication, and potentially on board processing. The final stage of on-animal control uses animal sensors to provide real time monitoring that use location and behavioural sensing to track movement and then use this information to administer an aversive stimulus when the animal is required to stop or change direction (Anderson, 2007). The move from the simplest technologies that use off animal monitoring to the most complex on animal control sees increasing technical challenges and complexity of solutions. This complexity is reflected in the commercial readiness of the various stages of technical solutions, with off animal technologies already starting to be used by industry but on animal technologies are still in the development phase.

Individual animal management optimises fenceless farming systems. In most cases this optimisation utilises some form of electronic identification. In Australia the National Livestock Identification System (NLIS) was introduced to provide cattle producers with an electronic identification tag that utilised radio frequency identification (RFID) (Trevarthen, 2007; Iglesias and East, 2015). The NLIS has compliance requirements that all animals leaving a property have to have an electronic tag and that movement between properties was tracked via a central NLIS database. The imposition of RFID technology has created opportunities for software and hardware developers to deliver technologies that help with on-farm management (Trevarthen and Michael, 2008). For example, automatically reading cattle tags during routine cheques in the yards. The RFID technology is also a key component of walk-over-weighing technology. Electronic identification is not mandatory in all countries and there are additional costs for tags and readers. In remote locations there are challenges in identifying newborn animals that don't have ear tags. There has been initial development work on building vision recognition software that can identify individual animals for example sheep (Noor et al., 2020). Remote and automated vision recognition software could address the challenges of tracking individual animals. Some systems can also be used to track group performance and manage overall changes in the state of the herd.

The broader framework for delivering fenceless farming systems will be increasingly enabled by technical developments in what has been termed the "internet of things" or IoT (Astill et al., 2020; Ilyas and Ahmad, 2020; Prabowo et al., 2020). This framework is built on distributed sensors that connect through a hierarchy of communication layers with feedback, data processing and data integration. The hierarchy has three core layers: the node (the animal), an intermediary in field integration system (edge computing) and a centralised computing system (the cloud). The taxonomy and functional features required by the IoT to support fenceless farming systems has been overlooked. In line with a broader agenda driving a third industrial revolution the IoT framework creates opportunities for greater democratisation, broader participation, greater trust and a higher degree of automation. Integral to the success of the IoT is the extent to which it leverages applications based on algorithms, enhanced automation and greater trust through authenticated and encrypted data. The distributed nature of the problem and the opportunity to engage multiple stakeholders can add value across farming systems and built around small scale connected and shared services, IT developers typically refer to these as micro-services (Maia et al., 2020). The foundation for these services requires an interconnected IoT framework that is divided not by stakeholder ownership but by what each service delivers (Devi et al., 2019; Santana et al., 2021). The success of these systems requires an outward looking model, where developers and stakeholders aim to deliver value to clients through cooperative services (Iqbal and Butt, 2020). The use of application program interfaces (APIs) embedded across sensors, edge and cloud computing will enable a shared set of services

(Santana et al., 2021). In many cases remote locations that have poor connectivity will require innovative methods that ensure event-based services are delivered when data flows are interrupted and asynchronous (Devi et al., 2019). This is an area of development that needs much greater work in the context of remote systems that are typical of the backbone of livestock farming systems.

The rapid development of sensor-based technologies for livestock applications promises to deliver the potential for fenceless farming systems sometime in the next 10 years. In particular it is likely that practical applications of the technologies will result from using a range of technologies that complement each other and deliver increased efficacy and accuracy that is practical, sustainable, and meets consumer welfare expectations. This combination of technologies will manage livestock movement using a carrot and stick approach, where access to water and supplementary feed can be used as an attractant and virtual fencing can be used to restrict access across the landscape. It is yet to be seen whether it will be possible to remove all fences, however, even if internal property paddock fences are no longer required it is likely that livestock producers will still require cattle yards with fences which can be used for routine management such as administering animal health or preparing livestock to be sold. Event based microservices that are supported by the IoT are emerging as a potential framework to deliver enhanced value for fenceless farming systems. This technology will deliver broader benefits of fenceless farming technology and provide a framework to connect new value through the supply chain. Integral to the microservices framework is an intrinsic focus on enabling value through shared services and this feature has the potential to extend and potentially outweigh the value of fenceless technology beyond just controlling livestock. The next sections explore the direct and indirect opportunities and benefits of fenceless livestock farming technology.

THE APPLICATION OF FENCELESS FARMING—DEFINING A NEW PARADIGM

As previously stated, the fence is one of the oldest agricultural innovations and synonymous with livestock farming. The fence divides the landscape into discrete self-contained geographical units (farms, properties, paddocks, or fields) that are allocated to discrete groups of livestock at certain times of the year. Ownership or control of land and animals are tightly coupled, and this coupling addresses the potential for a "Tragedy of the Commons" by maintaining a productive landscape through managers that consider both the landscape and the animal and maintain a balance between them both (Hardin, 1968). Movement of livestock between properties usually coincided with the transfer of ownership. The fixed nature of a fence creates permanency and instils trust but also doesn't allow opportunities for more flexible and refined management options that might reflect a common approach (Cornée et al., 2020). Flexible and refined management options can be defined by the ability of the system to monitor, reconfigure and deliver customised individual animal grazing management.

Shared grazing commons form part of existing livestock production systems. How will on-animal technologies deliver new opportunities for shared grazing resources? Sensor based technologies provide continuous monitoring and feedback to allow more refined control of how grazing animals can access shared resources. The system also allows greater shared insight to all users of the shared grazing resource on how each individual animal is accessing the grazing resources. Automated monitoring and control can increase labour efficiency. It is not clear whether these are desirable characteristics, but they are points of difference for technology driven fenceless farming.

Integrated sensor-based systems have the potential to underpin the livestock management decision framework with regular updates on the state of each animal (Ilyas and Ahmad, 2020). The combination of on animal sensors coupled with edge computing modules that can add further data will provide the foundation for the customised individual animal management decision. Practical constraints for animal sensors such as power management and communication will require the edge computing capability to provide a layer of support in coordinating the individual animal monitoring (Alonso et al., 2019; Yang et al., 2020; Bergier et al., 2021). The monitoring systems will have embedded algorithms that can track a range of factors and use movement linked to behaviour as proxies for physiological state (Williams et al., 2017, 2020; Fogarty et al., 2020a,b). Examples of animal state information that will drive decision making would include health status, productivity including growth rates and reproductive status and welfare status (O'Neill et al., 2014; Swain et al., 2015; Menzies et al., 2017a,b; Corbet et al., 2018; Kour et al., 2018, 2021; Fogarty et al., 2020a,b). Animal location information can be used to determine livestock movement and livestock landscape preferences (Swain et al., 2011). Integrated micro-services will use baseline generic algorithms but these will be refined within the system to take account of individual animal parameters (Devi et al., 2019; Taneja et al., 2019; Maia et al., 2020; Santana et al., 2021). In addition to livestock monitoring external data will be added to the system to provide a further context for management decisions. These data could include remote sensing data for local grazing information, information on the broader feed resource options e.g., understanding the potential impact of a drought, individual market options, genetic improvement opportunities and general information that could impact any final decision e.g., the potential effect of a political decision, such as a trade deal, on supply chains (Swain et al., 2011). Critical to the foundation of the application of the fenceless management system is the integration of sensor data drawn from the animals through the edge computing and including cloud computing (Alonso et al., 2019; Yang et al., 2020; Santana et al., 2021).

The removal of fences across privately owned land creates a system that more closely resembles "the commons" as it provides the opportunity for cattle to move between private land parcels and access what can become a shared grazing resource. There are now no longer any boundaries between paddocks or properties. Using the example of cattle then producers still own their livestock and land but it is possible for a cattle owner to easily exploit their neighbours grazing resource. Given Hardin (1968) has already alerted us to the problem of selfish motives undermining sustainable resource use then fenceless farming technology could be doomed to failure. Unlike the traditional commons which rely on grazing managers being trusted the fenceless farming system has oversight underpinned by sensor technology that can be used to validate grazing managers claims.

Fenceless farming could be built on current farming operations and livestock management practises albeit with more refined control; the managers only access the land and grazing resources they control. While there are certainly potential cost saving and production benefits from this approach it misses the opportunity to adopt a more holistic management framework. Before fences were introduced grazing herbivores would form herds that moved across the landscape according to feed availability, these herds involved complex behavioural interactions (García et al., 2020). In natural unfenced grazing systems supply and demand ensured a natural balance was formed between forage availability and herbivore numbers, managed grazing systems integrate management technologies such as fences (Bailey et al., 2019). Virtual fencing technologies create an opportunity for fenceless farming systems to decouple livestock from land units. Farmers will own land or feed resources and cattle, but they may not always exist in the same location. The ability for livestock to move more freely and access available feed wherever it occurs capitalises on the removal of fences. The sensor systems could monitor the natural cattle preferences and subtly orchestrate broad scale movement. Restricted access to water could be used by owners to implement individual animal intervention strategies. The spatial movement of livestock could be linked to payments for landowners to receive payments from cattle owners for access to feed. The independent integrated and validated sensor-based systems would form the basis of pre-arranged contracts that ensured transparency and equity.

Commercialisation of virtual fencing technology is underway; however, widespread adoption has still not occurred. The technical challenge of powering and maintaining on-animal monitoring and control devices is significant. It is likely that early commercial applications will occur in more intensive livestock production systems such as dairy. These systems are more capital intensive to offset the costs of the equipment and they also allow more routine access to the cattle to upgrade or maintain the technologies. The long-term value proposition for these technologies will require the systems to derive multiple benefits for example providing feedback on animal health and welfare as well as containing the cattle.

RENEWING A SOCIAL CONTRACT—FENCELESS FARMING PUTTING COMMUNITY AT THE HEART OF FOOD SECURITY

In earlier sections, we explored how studies have shown the foundations of human food security is based on a model that supports an implicit social contract resulting in energy and nutrients being made available for activities that enable individual specialisation (Kramer and Ellison, 2010). The foundations for human specialisation have resulted in modern agriculture based on a cooperative model and relies on maintaining a social contract. The success of the agricultural model has been in labour use efficiency, that is the energy output per unit of time directly involved in supplying food (Pimentel and Pimentel, 2007). While total global food production has increased this has been largely as a result of energy intensive farming practises on the back of the introduction of fossil fuels. Overall energy efficiency [energy harvested per unit of energy input (not including solar energy)] has not significantly changed (Pimentel and Pimentel, 2007). The labour use efficiency for modern food production means that large proportions of the population no longer need to be directly involved in food production. Food is an essential foundation for our very existence. However, we also demonstrated that our relationship with food changes as food becomes more abundant. As basic food needs are met there is an increasing desire for foods to represent core values (Satter, 2007). These values can be related to how the food is grown, nutrient properties or taste. The food supply chain increasingly provides information that helps to connect the food grower with the food supplier.

As stated earlier the application of fenceless farming systems will require sensor technologies that can continuously monitor the state of the animal. These sensors will also be able to deliver a range of micro-services via communication infrastructure that can be used to manage the complexity of the system (Taneja et al., 2019; Maia et al., 2020). These services will be built on insight related to animal health and welfare, genetics and environmental (including but not limited to the feed-base) drivers. Micro-services will deliver technological insight through algorithms, efficiency through automation and trust through authenticated encrypted data streams. The underlying connectivity and availability of information will drive opportunities to create greater democratised responses to consumer needs and wants (Davies and Garrett, 2018; Suhail et al., 2020).

The driver for previous agricultural innovations has been labour efficiency increased output per unit labour input (Pimentel and Pimentel, 2007). Reducing labour reduces costs and the technologies driving this innovation have facilitated an industrialised approach to agricultural production. Homogenisation of technologies such as genetics refines the production methods. However, complex supply chains can make it difficult for farmers to connect with consumers and create value by delivering specialised products that consumers are willing to pay more for (Clark et al., 2020). Critical to raising the value of a product is the ability to differentiate it in the marketplace (Schulze-Ehlers and Anders, 2018). Product differentiation needs to connect the supply chain and create unique selling points that consumers understand and are willing to pay for (Polkinghorne et al., 2008). The technology that will sit behind fenceless farming systems provides an opportunity to have detailed monitoring of the production systems. When there is an abundant supply of food that is not price sensitive then consumers become more interested in food that reflects their environmental values, so they are willing to be more selective in purchasing food (Canavari and Coderoni, 2020). The sensor system embedded in virtual fencing can be combined with independent authenticated and encrypted information and used to demonstrate the efficacy of the food production systems (Mondal et al., 2019). Traceability is not dependent on virtual fencing, but it provides added value to this emerging technology. It is theoretically possible to be able to trace individual animals through the supply chain so that a final product can tell a storey not of a region or a farm or even a group of animals but can provide detailed information on an individual animal.

The ability to build a more meaningful and trusted social contract delivering not just food but information about that food can build value in the supply chain (Gale et al., 2017; Sharma et al., 2020; Zhang et al., 2020). Reconnecting community members that are no longer directly connected to growing food will help to build a greater awareness of the realities of managing farms that supply food (DesRivières et al., 2017; Raatikainen et al., 2020). The ultimate democratisation of food production might occur when we start to see a shift back to a greater percentage of the population having direct involvement in food production (Ikerd, 2019; Ochoa et al., 2020). The ability to track livestock assets has the potential to extend the idea of remote livestock ownership. Livestock producers could become landowners and get paid to manage livestock when they are within the geography of their property. As livestock owners the broader community will face the costs and benefits of raising animals. Consumers will be able to directly pay to take land out of livestock production and create conservation areas.

Technological innovation will provide the foundation to allow livestock management without fences (Anderson, 2007). That same technological innovation can also re-frame the relationship between farmers and consumers. Removing the metaphorical fence is to throw into question the social contract, the business and ownership of both livestock and land. When food is in short supply or technological innovation is disrupted, such as happened with Cuba during the oil embargo, then communities look to directly connect with growing food (Cederlöf, 2016). When food is in abundant supply then there is little need to directly connect with growing food. However, if fenceless farming provides a framework for communities to directly connect and shape food production to meet their values then it has the potential to build greater understanding between farmers and consumers. Not only will this help ensure profitable and sustainable food production, but it will also build a community that is more directly connected to growing food. The knowledge and understanding might be important if growing food needs to revert back to a more human centric activity.

CONCLUSIONS

Containing livestock using fences is an integral part of modern agriculture. The origin of fences provided an early foundation in the move from hunter gatherer communities to settled agrarian societies. While the practical animal management benefits are obvious, the impact of the fence in assigning property rights and the cultural impacts are more complex and potentially far reaching. The fence not only contains livestock but can also exclude access. Using a fence as a tool that divides the landscape and in so doing creates ownership has the potential to assign responsibility for societies expectations in regard to meeting welfare and environmental standards. In theory this approach should address the "Tragedy of the Commons" albeit through shared values rather than shared land (Hardin, 1968). The emerging opportunity for fenceless farming systems is founded on the premise of delivering more cost effective, flexible and refined management options for free ranging livestock. This goal addresses the containment issue. It is possible that the underpinning technology could address a far more important issue that reflects a greater connection between food producers and food consumers, enabling a value based social contract built on producers being able to realise greater market value.

There is growing evidence in the literature that the technical goal to contain and manage livestock using fenceless systems, referred to as virtual fencing, is making good progress. The implementation of virtual fencing as a management tool will need to match technology with practical and economic considerations before wide scale removal of traditional fencing can occur. There is currently little evidence to indicate what the economic or practical costs and benefits will be for virtual fencing. New innovative technology solutions like virtual fencing have the potential to create new and unimagined value. This value sometimes requires the technology to be extended and reframed. The opportunity for fenceless farms to reconnect consumers with producers could create opportunities for producers to drive new unrealised market value. This value will be based on trusted information that addresses broader societal values. To achieve this new value will require virtual fencing technology to become embedded within a broader information framework. Currently this broader outward focussed micro-service technology solution is missing from the more inward monolithic technology solution that is driving fenceless farming solutions such as virtual fencing.

Fenceless farming systems for livestock production provides the opportunity to explore how emerging technology might reshape and reconnect people's relationship with food. In general, the rise in digital technologies has impacted agricultural production systems. The IoT coupled with automation and algorithms is allowing tools such as machine learning to deliver refined and optimised solutions. Evolutionary trajectories show us that nature has been very good at tweaking phenotypes to find the best fit and this approach leads to diversity with local optimisation. The digital framework and IoT is yielding greater volumes of data that are delivering more refined local insight. Like evolution this insight creates opportunities for diversity and local optimisation. This opportunity should result in food production that moves away from homogenised gene pools, production systems will be based on local opportunities reflected in greater connexions between consumers and producers. Fenceless farming systems might put a new spin on the problem of the "Tragedy of the Commons," using data to confirm shared values and technology to deliver shared responsibilities.

AUTHOR CONTRIBUTIONS

The ideas for this paper and the writing of the manuscript came predominantly from DS. SC helped shape the ideas and reviewed the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.