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Review

Virtual herding for flexible livestock management – a review

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Abstract. Free-ranging livestock play a pivotal role globally in the conversion of plant tissue into products and services that support man's many and changing lifestyles. With domestication came the task of providing livestock with an adequate plane of nutrition while simultaneously managing vegetation for sustainable production. Attempting to meld these two seemingly opposing management goals continues to be a major focus of rangeland research. Demand for multiple goods and services from rangelands today requires that livestock production make the smallest possible 'negative hoof-print'. Advancements in global navigation satellite system, geographic information systems, and electronic/computing technologies, coupled with improved understanding of animal behaviour, positions virtual fencing (VF) as an increasingly attractive option for managing free-ranging livestock. VF offers an alternative to conventional fencing by replacing physical barriers with sensory cues to control an animal's forward movement. Currently, audio and electrical stimulation are the cues employed. When VF becomes a commercial reality, manual labour will be replaced in large part with cognitive labour for real-time prescription-based livestock distribution management that is robust, accurate, precise and flexible. The goal is to manage rangeland ecosystems optimally for soils, plants, herbivores in addition to the plant and animal's microflora. However, maximising the benefits of VF will require a paradigm shift in management by using VF as a 'virtual herder' rather than simply as a tool to manage livestock within static physical barriers.

Additional keywords: grazing systems, hoof-action, livestock management, paddocks, pastures, plant–animal interface, rumen dynamics, stocking rate.

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Introduction

Management of rangelands in a sustainable manner remains one of the most complex challenges that face extensive livestock production (Holechek *et al*. 2011; Ripple *et al*. 2014). The spatial and temporal variability of soils, vegetation and climate, and foraging behaviour by livestock, are key influences on the ability to manage rangeland sustainability. Until recently, most of our understanding of the plant–animal interface has come from small research plot data (Ash and Stafford Smith 1996; Barnes and Hild 2013; Teague *et al*. 2013). However, a proper understanding of free-ranging animal behaviour requires both small plot- and landscape-based data in which the interactions among plants (Soder *et al*. 2007) and livestock (Estevez *et al*. 2007) influence foraging behaviour at both these scales. Foraging behaviour is affected by both the physiology of animals (Provenza *et al*. 2007; Finger *et al*. 2014) in addition to many factors external to the animal (Anderson 2010) and both are significant when large numbers of physiologically diverse animals forage on large heterogeneous landscapes (Barnes and Hild 2013; Norton *et al*. 2013). Therefore, scale is a key to our understanding of the plant–animal interface as it influences the behaviour of livestock. A developing trend to combine information from scientific studies with producer-based experience/observations promises to increase understanding that embraces interdependent and dynamic sustainable outcomes (Briske *et al*. 2008, 2011; Brunson and Burritt 2009; Provenza *et al*. 2013) through adaptive management (Williams and Brown 2014).

The objective of this review is to focus on a developing methodology for managing free-ranging livestock termed virtual fencing (VF). It promises to change how foraging is managed through cognitive rather than manual labour. Since VF uses sensory cues rather than physical barriers to alter an animal's forward movement, it must be used in situations where health or safety of humans or animals is not jeopardised. The value of VF is its ability to facilitate management of the distribution of livestock in stocking strategies ranging from continuous through mob stocking (Allen *et al*. 2011) within landscapes where perimeters are secured using conventional fencing when the virtual boundaries[1] (VB™) become 'leaky'. Its eventual commercialisation will offer real-time flexible management of the distribution of livestock to positively influence the management of soils, vegetation and livestock (Anderson 2001, 2006, 2007; Umstätter 2011; Howery *et al.* 2013).

Stocking rate

The amount of forage a particular landscape produces impacts on many aspects of its stewardship including fuel for prescribed burns (Hunt *et al.* 2014), soil stabilisation (Wolfe and Nickling 1993) as well as fulfilling the nutritional and behavioural requirements for wildlife (Robbins 1983) and livestock (Smith 1998; Holechek *et al.* 2011) and ultimately economics (MacLeod *et al.* 2004). The focus of stocking rate in this manuscript is to optimise the relationship between forage production and livestock nutrition within the context of sustainable management.

The appropriate number of livestock assigned to a given area of land should be determined by the amount of forage the land can produce within a specific period of time (Allen *et al.* 2011). How much forage is available and how many livestock it will support can be mathematically calculated (Holechek 1988, Holechek *et al.* 2011). However, managing this relationship remains challenging because of the non-static nature of the biotic and abiotic factors that affect both forage and livestock. Regardless of its limitations, stocking rate remains the cornerstone for all free-ranging livestock management on rangelands (Ash and Stafford Smith 1996; Briske *et al.* 2008; Holechek *et al.* 2011). Landscapes that support foraging livestock must be managed using a sustainable long-term carrying capacity, i.e. an appropriate stocking rate to ensure safe paddock utilisation rates that enhance sustainability of palatable, perennial and productive (3P) grasses (Hunt *et al.* 2014). Attempts to manage free-ranging livestock without an appropriate stocking rate only forestall inevitable failure (Frasier and Steffens 2013). In Wyoming, Derner *et al.* (2008) documented that, over 25 years, stocking rate was the primary factor responsible for influencing liveweight gains of cattle. Van Poollen and Lacey (1979) argued that an appropriate stocking rate is far more important than the stocking strategy used. Furthermore, stocking rates are not static over time but should be periodically adjusted, preferably from an initial conservative value, in order to maintain optimum production from both forage and livestock (Grissom and Steffens 2013; Ortega-S *et al.* 2013; Owensby and Auen 2013). Although high stocking rates may periodically generate high financial returns, this management approach increases ecological and economic risks and requires crisis management (Hunt *et al.* 2014) when transitioning from periods of growth characterised by abundant precipitation to drought in which precipitation is below the long-term mean. O'Reagain and Scanlan (2013) suggested using a 'constrained flexible stocking rate strategy' in which the long-term carrying capacity is increased modestly during good years followed by a substantial reduction in stocking rate in poor years. The underlying key principle when setting a stocking rate is being able to embrace differences in the amount and timing of precipitation both within and among years. Using a stocking rate near the paddock's long-term carrying capacity will provide the least risky long-term economic outcome since stocking rate and financial returns are intricately linked (O'Reagain and Scanlan 2013). Under extremely favourable conditions i.e. precipitation above the long-term mean, high stocking rates for short periods will probably have little detrimental effect on either vegetation or animal production (Hunt *et al.* 2014).

Overall, conservative stocking has been scientifically and practically shown to be the best approach to maximise plant productivity and improve rangeland regardless of timing and amount of precipitation received (Holechek *et al.* 2000). Frequently the economically optimum stocking rate is lower than the stocking rate producing maximum liveweight gain per unit area (Riewe 1981; Frasier and Steffens 2013).

Moisture appears to be the major driver shaping arid and semiarid ecosystems (Fynn and O'Connor 2000; Fuhlendorf *et al.* 2001; Belnap *et al.* 2005); therefore, the temporal variation in forage growth is largely dictated by variability in precipitation (Ash and McIvor 2005). This reality complicates the task of using set stocking rates since predicting effective precipitation remains as much art as science.

The co-evolution of plants and animals has resulted in an interface that ranges from detrimental to beneficial (McNaughton 1979; Belsky 1986). Appropriate forage utilisation can maintain shading at a level that enhances seedling emergence and survival to facilitate plant colonisation and fill gaps within the vegetation matrix (Bullock *et al.* 1995). Furthermore, changes in phenotypic traits, such as height, prostrateness, leaf width and length, treading tolerance, and number of low mass tillers, are just some of the factors foraging impacts (Falkner and Casler 2000). From a biodiversity perspective, foraging can increase the number of grass species (Reid *et al.* 2010) while browsing may benefit shrubs (Van Der Heyden and Stock 1996).

Stocking strategies

Foraging requires the expenditure of energy (Osuji 1974). This influences where animals choose to walk, i.e. where trails develop (Ganskopp *et al.* 2000), and ultimately where foraging takes place. Livestock do not forage randomly or uniformly over a landscape because of the irregular distribution of resources they require and prefer (Coughenour 1991). Stocking strategies other than continuous stocking remove livestock from some or all of the landscape for varying time intervals either within or among years or both. Removing livestock from a landscape promotes uninterrupted vegetative growth (Mott *et al.* 1992), as well as growth of reproductive structures (Tainton 1981), to ensure the future forage supply will be consistent and sustainable. Although resting a paddock can have a positive influence on the landscape, providing rest is not universally accepted as a management principle due to equivocal results (Hunt *et al.* 2014).

Smith (1896) is credited with suggesting the first rotational grazing plan. Since then, some research has suggested plants, as

[1]In this manuscript a trademark highlights terms used in conjunction with a new specialised methodology of animal control designed and implemented to improve or maintain optimum ecological and economic output from soils, plants and animals and should not be confused with terms associated with conventional fencing strategies.

well as livestock, benefit when paddocks are rested from herbivory (Sampson 1951; Voisin 1959; Davies 1976; Undersander *et al*. 2002; Oates *et al*. 2011; O'Reagain *et al*. 2011; Teague *et al*. 2013). However, other research does not support this (Herbel 1974; Gammon 1978; Van Poollen and Lacey 1979; Fales *et al*. 1995; Hodgson and Illius 1996; Pulido and Leaver 2003; Briske *et al*. 2008; Orr and O'Reagain 2011). The reasons for this disparity are many, some clear cut while others are more controversial (Briske *et al.* 2014; Teague 2014). When considering changing a stocking strategy, the most important question is: will the new stocking strategy consistently and unequivocally improve the distribution of foraging over a landscape? If the answer is yes, economic benefits can follow.

Hunt *et al*. (2014) indicated that stocking rate, and especially rainfall, were more important than resting, but that season, duration and number of rest periods were critical when evaluating the impact of a rest on a landscape. In general, longer rest periods appear to be more effective than shorter periods especially on degraded landscapes in poor condition. These landscapes may require more frequent rest to recuperate than landscapes in fair condition (Tainton 1981). During spelling (resting), feral or native herbivores should also be excluded from a paddock; however, this can be quite challenging and is often impossible.

In general, a rest of proper duration in the growing season is usually more beneficial than resting paddocks during dormancy especially when precipitation occurs during growth (Hunt *et al.* 2014). Fifty-five years earlier, Voisin (1959) wrote that it is 'outrageous' to apply the same length of rest periods in all seasons since plant growth rate is not uniform throughout the year. However, O'Reagain *et al*. (2008) found some benefit to resting vegetation during the non-growing dry season, while Hacker and Tunbridge (1991) found that rest periods in the wet and dry season resulted in similar responses. No meaningful differences in vegetation response were observed with different combinations of grazing and rest periods on tallgrass prairie (Gillen *et al*. 1998, 1990). These authors emphasised the complexity and need for flexible management options when managing the plant–animal interface. It is safe to assume that landscapes in better condition will have higher growth rates (assuming adequate precipitation) and therefore may benefit from shorter periods of rest even though rest for an entire growing season may provide the most reliable benefit under Australian conditions (Hunt *et al*. 2014).

Savory (1983) suggests the length of a grazing period should be tied to the rate of plant growth by season; this he termed 'timed-controlled' grazing. Providing livestock with the highest possible diet quality usually means minimising stem intake (Minson 1981) and allowing animals to exhibit maximum selectivity (Cassini 2013) and this normally coincides with the period of maximum growth (Davies 1976).

Even in a stocked paddock certain areas of vegetation may receive rest because of the location of drinking water and topography (Pinchak *et al*. 1991). Other factors that can influence the spatial location of foraging are breed of livestock (Dwyer and Lawrence 2000; Bailey *et al*. 2001; Dolev *et al*. 2014), influence of peers (Howery *et al*. 1998), and the managerial ability of humans (Savory 1988; Smith 1998).

How livestock are grouped changes their distribution and the impact on stocking density. Peterson *et al*. (2013) suggested that training may be required to adapt cattle gradually when management is changed from low to high density stocking. Young animals are influenced by their dams and similarly aged peers, while older animals are also influenced by peers because internal and external stimuli both impact behaviour (Launchbaugh and Howery 2005). Possibly, younger cattle may adapt to high density stocking faster than mature cows (M. Kothmann, pers. comm.) and age has been shown to influence foraging location (Walburger *et al*. 2009).

Between 1926 and 2009, 68 landscape and or animal attributes were reported to affect free-ranging livestock distribution singly or in combination (Anderson 2010). More recently, Barnes and Howell (2013) referred to the use of multiple paddocks as adaptive management. Multi-paddock stocking strategies offer time-controlled defoliation (Willms *et al*. 1990) but normally fall short of expectations, especially if movement is based on calendar dates rather than changes in the forage mass (Anderson 1988; Jacobo *et al*. 2006).

No current stocking strategies provide optimum flexibility for embracing variability in rapid growing conditions across years (Steffens *et al*. 2013) or within years (Myoung *et al*. 2013). Although heterogeneity among plant species, available to free-ranging livestock, is nutritionally beneficial (Provenza *et al*. 2007), as well as to landscape ecology (Fuhlendorf and Engle 2001), it should be more desirable to create or direct vegetation heterogeneity rather than allow it to develop haphazardly as when herbivores are left unmanaged.

Frequently the detrimental effects of defoliation increase as the intensity or frequency of defoliation increases (Briske 1991). Stocking strategies, in which livestock are moved among paddocks based on fixed movement schedules, are the most inflexible (Barnes and Hild 2013) and should be avoided.

Forage quality may be as important as quantity in driving diet selection (Bailey and Brown 2011). Diet heterogeneity has been shown to stimulate an animal's appetite (Provenza *et al*. 2013), improve mineral balance through exposure to many different plant species (Yoshihara *et al*. 2013), and assist in coping with secondary plant compounds (Provenza *et al*. 2007). Prior to fencing, free-ranging animals were not confined to specific locations on the landscape giving them a much broader range of plants to select from. By confining animals to a paddock, diet quality begins to decline following the first bite and continues as long as animals remain in the paddock. Currently to provide spatio-temporal control of foraging, livestock are rotated among paddocks (Teague *et al*. 2013); however, even with this approach, time-controlled defoliation of individual plants or groups of plants within the paddock is still not possible.

Rotational stocking

Rotating livestock through a number of paddocks is not itself a flawed management concept. The flaw is in man's inability to properly and consistently control the spatio-temporal aspects of foraging on a cost-effective basis while livestock are in a paddock (Weber and Horst 2011). Peterson *et al*. (2013) suggested 'the more moves there are each day the more opportunities there are for each cow to balance her diet'. However, on a fixed rotation schedule, some plants will be overutilised while others will be underutilised (Anderson 1988). Foraging strategies should be designed to fit the situation, not vice versa (Holechek 2013).

Foraging has two components, direction and speed (Stafford Smith 1988), and it is the frequency and severity of defoliation of individual plants (Heitschmidt and Walker 1983) that must be controlled. The most recent approaches to manage defoliation have been through the use of wire fencing and drinking water developments. Fencing has been man's attempt to replace herders (Williams 1954) or range riders (Skovlin 1957; Rhodes and Marlow 1997). However, fenced paddocks simply cannot provide the level of temporal and spatial management astute herders can provide. This is one reason static fences are often a hindrance to dynamic foraging (Samson *et al*. 2004). Livestock left on their own seldom use the landscape uniformly, thus some plants are under defoliated while others are over defoliated. Even in small paddocks grazed at high stock density, uneven utilisation results (Anderson 1988; Norton *et al*. 2013).

Although moving livestock based on a flexible schedule may produce a more uniform pattern of use than a fixed schedule (Anderson 1988), even in relatively small paddocks that are lightly stocked some vegetation will not be used (Anderson 1967; Senft *et al.* 1985) suggesting that the numbers of livestock, size of paddock and the time livestock are in a paddock are all factors that require management.

Herders manage livestock on complex landscapes by moving them in real time (Reid *et al*. 2008) to provide an organised sequence of vegetation encounters that stimulates their appetite (Meuret *et al*. 1994). With the advent of barbed wire (McCallum and McCallum 1965) and the eventual evolution of electric fencing, the need for direct human involvement in husbandry (i.e. herders) was deemed to be less necessary. Unfortunately this lack of human discernment in making real-time decisions set the stage for mismanagement to become more prevalent under the guise of improved efficiency.

Management that continually moves livestock while they are foraging allows them the opportunity to optimise their nutrition, and respond appropriately to weather, predators, and biotic and abiotic cues (Fuhlendorf and Engle 2004). Current strategies have no control over the rate of movements by livestock. Although herding remains important in certain parts of the world (Turner *et al*. 2005) and has even been advocated to be a cost-effective way to solve uneven grazing distribution between upland and riparian areas in the United States (Bailey 2005), in general herding is impractical in developed countries because of the economic cost and availability of skilled labour (Tanaka *et al.* 2007). Furthermore, herding is impractical if not impossible in large cattle herds (Hunt *et al*. 2007). Even though herding can facilitate appropriate use, man's fallibility in consistently making correct choices has not always shown herding to improve livestock distribution (Pitts and Bryant 1987) or positively benefit the amount of forage and its nutritive value; therefore, VF will only be as good as those who operate this virtual herding system.

Virtual fencing – a flexible methodology adaptable to any stocking strategy

VF refers to a developing methodology for controlling free-ranging animals that originated in the 1970s as a fencing alternative for pets (Invisible Fence® Brand History 2013) but has yet to be commercialised for livestock. Prototypes have demonstrated that audio sound and/or electrical stimulation cues from electronics on a platform worn by the animal can alter forward movement and, in the case of directional VF (DVF™) (Anderson 2007), the forward trajectory angle of cattle across a landscape. Recently, Umstätter *et al*. (2013) demonstrated that programmed audio cues from speakers located on the landscape may be sufficient to alter cattle movement. Proof-of-concept studies to date have demonstrated that VF, using sound and electrical stimulation, provides a low-stress (Smith 1998; Anderson *et al*. 2011) methodology for holding (Tiedemann *et al*. 1999; Anderson *et al*. 2003; Ruiz-Mirazo *et al*. 2011; Jouven *et al*. 2012), moving (Anderson *et al*. 2004*a*; Butler *et al*. 2006) or autonomously gathering free-ranging cattle (Donniec *et al*. 2010). The ability to provide flexible seamless spatio-temporal movement of livestock across a landscape in real time is what VF can offer plant–livestock management. The number of actual virtual paddock (VP™) configurations the electronically generated polygon (paddock) can assume is limitless (described in greater detail later). A single VP in which animals are contained can be held stationary on the landscape or programmed to move in a seamless fashion in any trajectory at variable rates in real time while the perimeter of the VP can be morphed into any shape based on a manager's desire to provide or prevent access to specific areas on the landscape. A moving VP can be thought of as an 'amoeba-like' configuration in which animals can be moved in space and time across a landscape with the only need for human involvement to verify that proper results are being realised. All of this can occur without the need for building, maintaining, or moving physical structures on the landscape. Literally, VF can be considered a 21st-century 'virtual shepherd' (quoting Ian Gordon, pers. comm. 2003). VF will decrease manual labour costs associated with fencing in intensive stocking strategies (e.g. rotational stocking) that reduce paddock size with the goal of improving forage utilisation (Dunn 2013). Although multiple, conventionally fenced paddocks may improve distribution, the cost of implementing such systems may not be economically and ecologically justifiable (Pieper and Heitschmidt 1988); this is no longer a challenge with VF.

Unfortunately today's livestock management systems often lead to resource degradation because they are not agile enough to respond to changes caused by heterogeneity of precipitation across a landscape (Asner and Archer 2010). Rook and Tallowin (2003) indicate a need for manipulating the temporal foraging pattern of free-ranging animals because foraging creates sward heterogeneity due to selective defoliation among and within species as certain plants and plant parts are selected or avoided. In fact, the ineffectiveness of most stocking strategies is rooted in the inability of managers to control the extent of defoliation of individual plants (Anderson 1981). Being unable to manage the 'where, when and how long' of defoliation has been and remains the major nemesis of free-ranging livestock management (Jardine and Anderson 1919; Bailey 2005; Aldezabal *et al*. 2013).

With VF, cognitive labour will increase and many of the paradigms associated with conventional management using wire fencing will require modification or may need to be eliminated. Not only will routine decisions be needed (e.g. should livestock be placed on the landscape and if so, what kind, how many, and for how long?) but adopters of VF must also have a working knowledge in several areas, including but not limited to: range animal ecology, plant and animal nutrition, soils, animal behaviour, computer programming, electronic hardware maintenance, global navigation satellite system (GNSS) and geographic information system (GIS) data. Non-traditional disciplines associated with VF will be required to address spatio-temporal control through the use of programmable electronic cues.

Because of the range of expertise on which VF relies, it is unreasonable to assume VF can be properly implemented, at least initially, without a multi-disciplinary team. Changes to the landscape and among livestock through VF use will require frequent visual monitoring to determine its effectiveness in achieving management goals. If the electronics do not elicit proper animal behaviours, destruction of rangeland vegetation and animal performance may occur at a rate substantially faster than what might occur with conventional fencing, especially for VF applications in which animal density is high. Therefore, frequent monitoring of the system's operation must be an integral part with this form of management.

Heitschmidt *et al.* (1982) proposed that carrying capacity of livestock-dominated landscapes can be increased by increasing forage quality, quantity or by improving harvest efficiency. Dahl (1986) suggested harvest efficiency can be improved by improving the distribution of livestock. Teague *et al*. (2013) proposed that harvest efficiency can be enhanced by controlling both the location and timing of defoliation with multi-paddock stocking strategies. Unfortunately, fencing landscapes to make smaller paddocks does not necessarily foster even use of plants or species (Hunt *et al*. 2007). Because rangeland paddocks can be spatially quite diverse with respect to plant species and topography, free-ranging livestock consistently must choose where and what to eat due to differences in quality, quantity and proximity to drinking water (Hodder and Low 1978). Simply reducing paddock size does not eliminate uneven distribution because livestock tend to seek preferred areas regardless of paddock size. Therefore, adjusting livestock numbers is extremely important when the response of forage is sensitive to stocking strategy (Van Poollen and Lacey 1979). Livestock left to their own devices seldom make decisions that produce optimal spatial-use patterns.

With VF, only one VP need be electronically programmed for managing a group of livestock that all receive the same management. Such a VP, if held constant, would emulate continuous stocking; however, unlike a conventionally stocked continuously managed paddock constructed with static fencing materials, the VP's shape and size can be programmed to change over time to include or exclude certain plants, soils or other items. If, at some point, it becomes desirable for livestock to move across the landscape, this same paddock could be programmed to move at a rate and in a direction that would emulate rotational stocking. The shape and size of the paddock can concurrently change, hence the analogy to a moving amoeba. Furthermore, by accomplishing light defoliation with a single moving paddock, the negative factors related to frequent paddock moves that can stress livestock (Savory and Parsons 1980) would be eliminated.

There are practical guidelines that must be followed when implementing VF, including but not limited to paddock shape and number of VP's on any one landscape. Although the number of paddock (polygon) shapes is theoretically infinite, the perimeter of a VP should not contain narrow acute angles that could cause animal confusion in interpreting the sensory cues. The straight line segments of a polygon's perimeter should always be connected using angles $\geq 90^{o}$ when turns or corners are required to prevent 'trapping animals'. Such congested areas may cause an animal to respond improperly to sensory stimuli designed to make them aware of an impending boundary. This is especially true when cues are designed to produce directional animal movement (Anderson 2007). Furthermore, because most livestock are gregarious and seek to group with peers, the perimeters of two or more VP's should be separated by as much distance as possible to create a buffer zone. Even though different groupings of livestock may not readily mix on a landscape (Hart 2004), if two or more groups of livestock are to remain separated on the same landscape, it would not be prudent for VP boundaries to overlap. Early research to control cattle using VF found that instrumented animals may be willing to follow non-instrumented peers even though the instrumented animals received sensory stimulation (Tiedemann *et al*. (1999). Therefore, maintaining a buffer zone between VP's in close proximity would be appropriate; however, buffer width has not been examined.

Virtual fencing and rangeland ecology

The following areas could be positively impacted by VF methodology.

Paddock design

Fences affect foraging location and other behaviours of cattle and sheep (Dean and Rice 1974). With conventional fencing, corners and water tanks may receive disproportionate use from travelling, standing, resting and bedding of livestock (Senft 1983). These uses can influence N redistribution within a paddock (Augustine *et al*. 2013). Furthermore, construction and maintenance costs associated with conventional fencing influence the number (Kothmann 1980), shape (Sevi *et al*. 2001; Scott 2006) and size of paddocks (Barnes *et al*. 2008). Cattle tend to prefer riparian plant communities until the forage in these areas has been depleted (Hodder and Low 1978). Although riparian areas are vulnerable to overuse by cattle (Fleischner 1994), exclusion of livestock from these areas using conventional fencing is often cost-prohibitive (Platts and Wagstaff 1984).

The capital outlay to build conventional paddocks often outweighs the return on investment (Holechek 1992), especially if the growing season is limited (Allison *et al*. 1982). The cost to establish and operate a short-duration stocking strategy with several paddocks may not economically justify the expense (Bryant *et al*. 1989). The costs of building and maintaining fencing, together with upkeep and limited forage mass, are frequently cited as reasons that rotational stocking strategies may be inappropriate under arid or semiarid conditions. Another negative aspect of conventional fencing is the fragmentation of existing landscapes which can alter wildlife migration routes (Boone and Hobbs 2004). Neither materials nor upkeep costs associated with conventional fencing nor fragmentation are issues with VF.

Walker and Heitschmidt (1986) demonstrated that paddock shape influences trail density. Triangular paddocks with a cell centre (or hub) with water and working facilities contain about 6% of the paddock's area and essentially become a sacrifice area because of the high density of primary and secondary trails with little or no vegetation. Though grazing cells are not essential and do not in themselves benefit the range, they do positively influence the administration of labour and handling (Savory and Parsons 1980).

Smaller rather than larger paddocks have been advocated to provide better control of animals and improve distribution (Hart *et al*. 1993). However, Kellner and Bosch (1992) have pointed out a frequently overlooked fact that stocking rates are based on the assumption that the entire area will be used without considering that, especially in semiarid rangelands, a mosaic of patches usually exists, some of which are used and others unused (Teague *et al*. 2004); this mix makes it difficult to accurately determine an optimum stocking rate. Hunt *et al*. (2007) found cattle spent ≈50% of their time in as little as 13% of a 9-km^2 paddock. Global positioning system (GPS) technology to track cattle (Anderson *et al*. 2012, 2013) and examine animal distribution across a landscape may make it possible to adjust stocking rate calculations (Holechek 1988) using GNSS technology (Anderson *et al*. 2003). Anderson *et al*. (2003) monitored a single cow/calf pair using GPS for 5 days and observed that the cow frequented less than 24% of a 466-ha paddock. When paddock size was reduced to 48 ha, again only about 21% of the 48 ha was frequented. It was concluded that areas within both paddocks, regardless of size, incurred a stocking density much higher than that calculated based on stocking rate alone (Anderson *et al*. 2003). More than 50 years earlier, Moorefield and Hopkins (1951) indicated better distribution was needed on mixed-prairie rangeland pastures stocked with cattle since ~50% of the use was confined to <10% of the forage base. This pattern is not exclusive to cattle. Cheviot sheep used only 25% of a 102-ha hillside paddock 51% of the time (Hunter 1962). Historically it has been recognised that rangelands that are used non-uniformly have a lower carrying capacity than those with more uniform use (Fleming 1922; Williams 1954). Frontal grazing has been shown to result in nearly 100% of grass tillers being defoliated, this enhanced production of 'Plains' Old World bluestem [*Bothriochloa ischaemum* (L.) Keng], which subsequently permitted higher stocking rates (Volesky 1994). With VF, it will be possible to guide foraging over the entire landscape, which could increase the carrying capacity of a landscape.

Paddock geometry influences construction and maintenance costs of conventional fencing systems. Circles are the most efficient geometry to enclose the greatest area with the least amount of material. To enclose a 0.405-ha (one acre) circle requires 227 m (744 feet) of material (Henning *et al*. 2000). However, a square of the same area requires only 12.4% more material to construct and is frequently the paddock geometry of choice. Edwards (2012) reported labour costs to construct conventional fences ranged between 11% (≈240 US$) and 33% (1614 US$) of the total cost to build 402 m (1320 feet) of conventional fence in 2005, with annual maintenance costs ranging between 5 and 8% of the total original cost. In mountainous country or for fence lines that are not straight, these authors projected that labour can far exceed the cost of materials. In the Victoria River District of Australia, the economics become cost-prohibitive if 144-km^2-size paddocks are subdivided into smaller paddocks that are less than 30 km^2 in size (Hunt *et al*. 2013). In 2012, a bid to fence an extremely rugged area near Globe, Arizona, USA requiring approximately 4.6 km (2.5 miles) of four-strand barbed wire fence and metal 'T' posts every 6 m (20 feet) was reported to cost approximately US$63 000 (Ernie Gipson, US Forest Service, pers. comm.). Each time the direction of a conventional wire fence line is changed, a corner post and brace posts must be set. Thus even conventional geometries (i.e. squares and rectangles) makes conventional fencing a very costly endeavour and fencing highly convoluted perimeters would be financially unrealistic. With VF, perimeters are no longer a design constraint. The perimeter of a virtual paddock (VP) is electronically generated and results in polygons that can change shape over time and be held in a static configuration or be moved spatially and temporally over a landscape based on management goals. Except for the recent study by Umstätter *et al*. (2013), in which speakers were located on the landscape, all VF methodologies using GNSS technologies require nothing on the landscape except the instrumented animal (Howery *et al*. 2013). VF accomplishes control through sensory cues rather than physical barriers; therefore, adopters of the VF methodology must be willing to accept 'leaky boundaries'. Therefore, the perimeter of landscapes managed with VF must be fenced with conventional fence materials that provide a physical boundary that livestock cannot breach.

Costs of implementing virtual fencing

To date, VF devices that have been built have been experimental and do not accurately reflect the cost of high volume commercial production prices. The DVF research units built by the Massachusetts Institute of Technology cost approximately $600 apiece in 2008 but, if produced in large quantities, they were projected to cost ~$100 per unit (Waxer 2008–09). However, Osborne (2012) suggested the ideal price for a VF device per animal must be <A$50. Although it may not be necessary to instrument every animal inside a VP, data are currently not available to confirm this supposition. However, preliminary research suggests it may be possible to instrument only part of the herd (Anderson *et al*. 2004*b*; Anderson 2005, 2006; Fig. 2). Individual animal behaviours and topographic landscape features will most likely dictate the optimum ratio of instrumented to non-instrumented animals to achieve an acceptable level of control. Dumont *et al*. (2005) suggest that the more stable a cattle herd, the higher the probability that leadership is the exclusive right of a single older female. Šárová *et al*. (2010) suggested that the greater a cow's dominance, the stronger her influence over the movements of the herd. This information could be used to select which animals to instrument if economics or other constraints prevent the entire herd from being instrumented. However, the most appropriate number of animals to be instrumented will require more research.

An example using virtual fencing

Drinking water locations for livestock, soils, vegetation and topography are components of every livestock-dominated landscape and should be considered when designing paddocks in which animals are to forage.

The US Department of Agriculture-Agricultural Research Service's Jornada Experimental Range (78 266 ha in area) located in South Central New Mexico is used to illustrate how VF could be applied to a landscape in which livestock management is one of several research objectives. Figure 1 shows (*a*) the location of water wells and earthen water tanks that provide water for livestock, (*b*) 19 conventional barbed wire enclosed paddocks surrounding the headquarters (HQ; –106.7414, 32.6169), (*c*) 38 proposed VP's if all internal fencing was eliminated and the VP's were designed using water to assist in directing animal movement, and (*d*) 11 possible shapes a VP could assume as it moves within an area (GG). These 11 shapes were constructed based on unique soils and vegetation and could be stocked to optimise vegetation growth using a flexible spatial and temporal management strategy of livestock that takes advantage of ephemeral vegetation characteristic of desert rangelands in this region of the United States (Peters and Gibbens 2006). The specific grouping of soils and plants to be stocked at any point in time using a VP would depend on the manager's goals. A single livestock group placed in the area GG (Fig. 1*d*) results in at least 11 possible paddock shapes. This example emulates time-controlled stocking (Tainton 1985), but in a dynamic and flexible manner. Within any of the 11 areas, the paddock's actual size could be reduced, held static or programmed to move animals across the area in a much more efficient manner than using conventionally fenced paddocks through which animals would be rotated. The leading edge of the VP could continually advance into 'fresh' forage and would provide a high-quality 'moving feed bunk' or 'smorgasbord line' much like the frontal grazing proposed by Volesky (1990, 1994; Volesky *et al*. 1994). However, unlike frontal grazing, which is limited to shrub-free landscapes with minor topographical variations, most VF relies only on programmed radio frequency signals emanating from satellites (Anderson *et al*. 2013) to activate cues that influence direction and rate of travel based on how fast the VP perimeter is programmed to move.

Since livestock can also be excluded from a polygon, time-sensitive management strategies can be imposed, i.e. avoiding consumption of poisonous plants due to abrupt weather changes (Ralphs *et al*. 1994), excluding foraging in the habitat of an endangered plant species (Warshauer and Jacobi 1982), protecting nesting bird habitat (Schultz 2010), designing fuel accumulation protocols for later burning (Diamond *et al*. 2009), or controlling mating within a multi-sire herd (Lee *et al*. 2008). These and other management issues could be addressed using VF to positively benefit vegetation (Stahlheber and D'Antonio 2013) as well as livestock.

The soil, hoof action and virtual fencing

Steinfeld *et al*. (2006) attributes 20% of the world's degraded paddocks and rangelands to compaction resulting from overstocking. Cattle tracks tend to form along conventional fences and can cause serious erosion problems especially on slopes (Hosokawa 1990). Hart *et al*. (1993) determined that for each kilometre a cow travels, ~90 m^2 of soil is trampled, which can cause changes in soil physical properties (Warren *et al*. 1986*b*). Soils will be compacted to some extent by livestock and, along with defoliation, can affect water infiltration, increase soil erosion and decrease plant growth, all of which influence soil physical properties (Greenwood and McKenzie 2001). If paddock layout involves a hub or cell design characteristic of many high density grazing strategies (Savory and Parsons 1980), the cell centre should be constructed on soils with little tendency to aggregate or that are poorly structured since these soils are probably least affected by animal treading (Tanner and Mamaril 1959).

Soil compaction is strongly related to soil characteristics and water content (Warren *et al*. 1986*a*); thus, hoof activity increases bulk density and decreases macroporosity, both key characteristics influencing water infiltration (Drewry *et al*. 2008). By restricting stocking on seasonally wet soils, anaerobicity is reduced (Eckard *et al*. 2010). Although stocking at high densities, using rapid rotation, has been touted as beneficial to the soil compared with other stocking strategies (Savory 1978, 1983), it has yet to be substantiated by research. Hoof-action not only influences the soil's physical properties, but in semiarid rangelands may directly damage plants and pulverises the soil surface (Greene *et al*. 1994).

Hoof action can be an important tool for eliciting vegetation change, especially in the formation and colonisation of gaps (Bullock *et al*.1995). On rangeland near Burns, Oregon, USA, paddocks between 825 and 859 ha had trail densities (a unique type of gap) ranging between 1.5 and 2.4 km^{-2} (Ganskopp *et al*. 2000). Since trails are not distributed uniformly or randomly on a landscape but tend to radiate from water, management of the area around this site (pieosphere) has a major impact on vegetation and soils (Voisin 1959). In Australia, activity of cattle away from water declined markedly beyond 3–4 km (Hunt *et al*. 2013).

With VF, it will be possible using a few key strokes on a laptop to move livestock from wet soils in real time, change paddock geometry to alter travel routes and trail formation, concentrate livestock on areas that may benefit from hoof action or completely remove livestock from certain areas (e.g. riparian areas). The key is that VF will provide flexibility to accomplish site-specific management goals.

The rumen and virtual fencing

Foraging has a positive impact on a ruminant's welfare (Kondo 2011) and ruminal function (Jung and Allen 1995). The rumen microbial population is dynamic within a day (de Veth and Kolver 2001) and across days and can be influenced by the ruminant's physiological state. Mohammed *et al*. (2012) found the bacterial community within the rumen of 14 Holstein heifers between pre- and post-partum periods not to be influenced by dietary treatment or period yet some of the cows showed a greater shift in their bacterial community than others. With increasing time in a paddock, mean diet quality declines not only due to seasonal senescence but also to preferential removal of leafy plant material initially in lieu of stems. Furthermore, seasonal changes in forage quality can impact rumen microbes.

Digestible energy (DE) and crude protein (CP) contents were measured in extrusa of oesophageally fistulated heifers foraging on the Rolling Plains near Throckmorton, Texas (Anderson

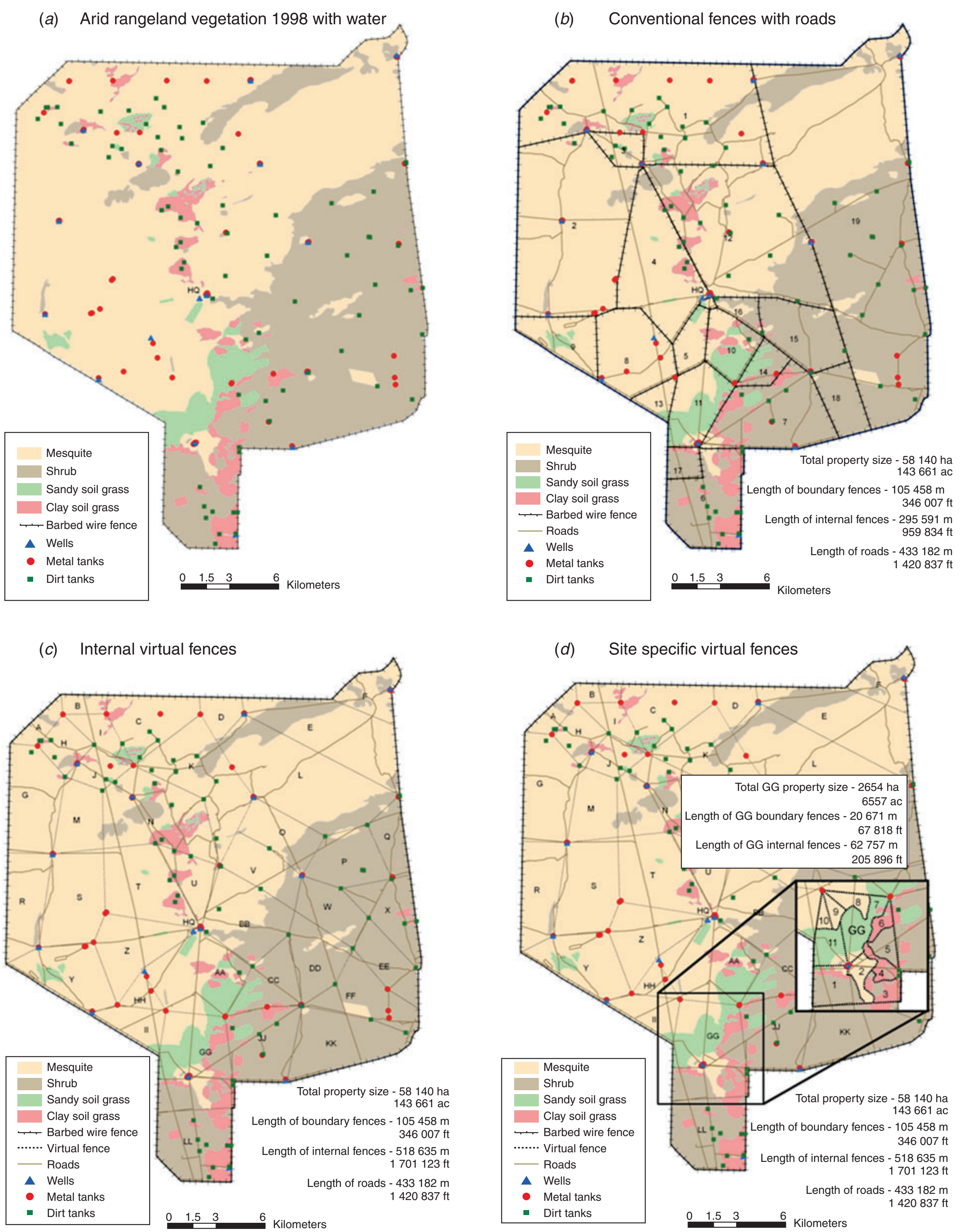

Fig. 1. Jornada Experimental Range (JER) map with 1998 soil/vegetation sites and livestock drinking water locations (*a*), overlay of internal fences and roads showing 19 paddocks (*b*), area without internal wire fences showing possible virtual fence locations resulting in 38 paddocks based on livestock drinking water locations (*c*), insert showing how virtual fences could be constructed to focus on soils, vegetation differences to utilise available livestock drinking water locations (*d*).

1977). A five-paddock short duration grazing (SDG) system in which rotations occurred on a fixed 28-day schedule was compared with a continuously stocked paddock between March and December (12 Hereford heifers per treatment). This area was a predominantly Texas wintergrass (*Stipa leucotricha* Trin. and Rupr.) and mesquite (*Prosopis glandulosa* Torr. var. *glandulosa*)-infested rangeland. Data were collected weekly from the 20-ha continuously stocked paddock (Fig. 2*a*, *b*) and the stocked paddock of the SDG system (Fig. 2*c*, *d*). The two stocking strategies exhibited different diet quality patterns, especially between the last day (Day 28) in a SDG paddock and the first day (Day 1) after heifers were rotated to the adjoining 'fresh' SDG paddock. Overall, DE (Fig. 2*a*, *c*) and CP (Fig. 2*b*, *d*) contents did not differ between stocking treatments but declined in a linear fashion over the 1-year study. However, at a finer scale, the last day in a SDG paddock (Day 28) and the first day in a 'fresh' SDG stocked paddock exhibited noticeable differences in diet quality for both DE ($P = 0.0019$) and CP ($P = 0.0012$) contents compared with the continuously stocked treatment. In all but one instance, mean DE and mean CP contents increased between Day 28 and Day 1 in the SDG paddocks between March and December (Fig. 2). The only exception was a minor decline in DE content when heifers were rotated into a 'fresh' paddock during the April to May period (Fig. 2*c*). There may be a number of reasons for this single deviation from the pattern but the most likely explanation is day-to-day variation in diets is due to the heterogeneous nature of rangeland vegetation coupled with selectivity by the cattle, both of which were dynamic in time and space. McCaughey *et al*. (1997) observed a similar seasonal and within paddock trend during 140 days under stocking durations lasting 3–5 days in a 10-paddock rotational stocking strategy.

The 'saw tooth' pattern from a lower to a higher nutritional quality that occurred on the fixed schedule rotation compared with the rather haphazard change in diet quality observed over

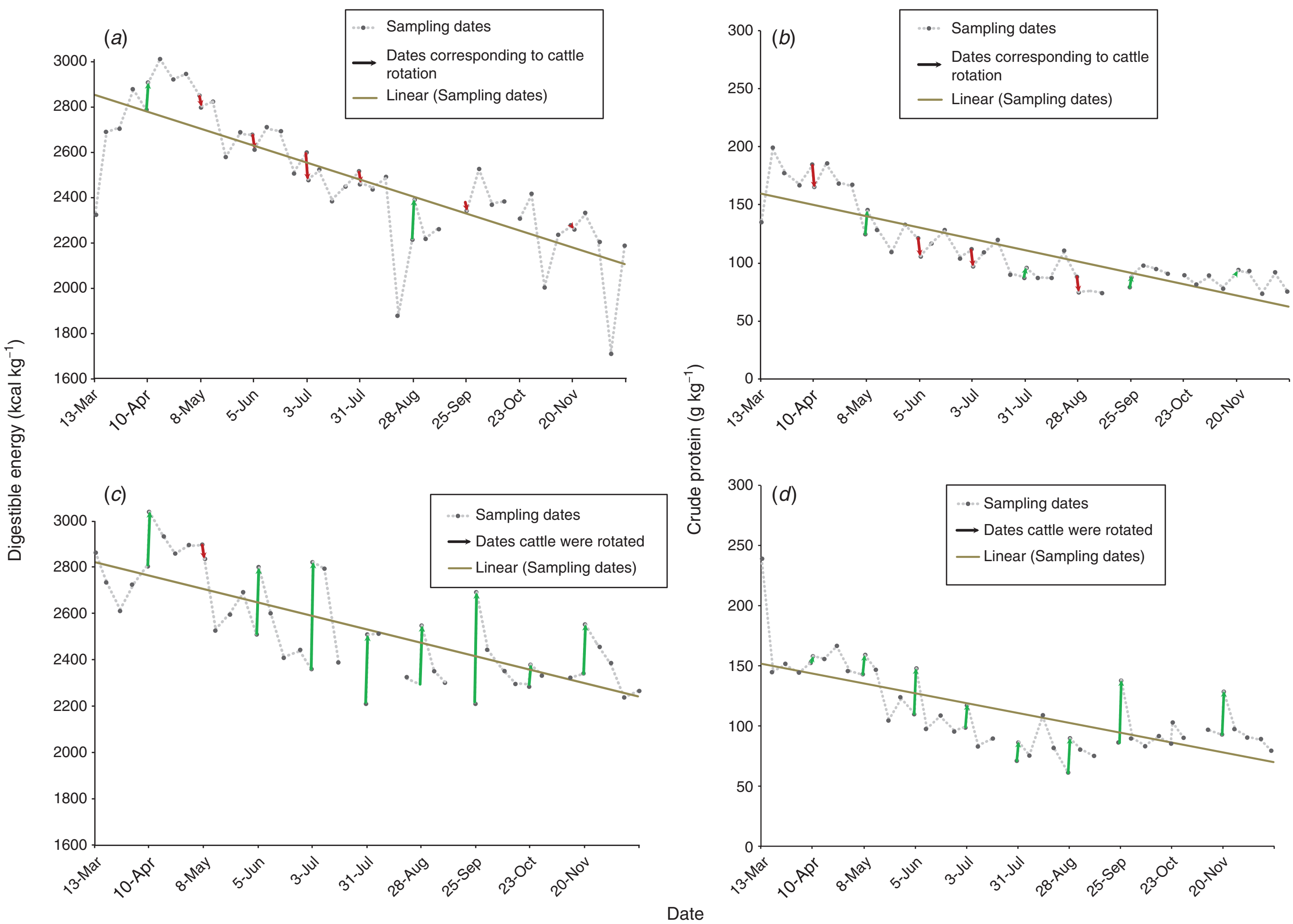

Fig. 2. Mean dietary digestible energy (kcal kg^{-1} OM; *a* and *c*) and crude protein content (g kg^{-1} OM; *b* and *d*) obtained from four esophageally fistulated heifers, two in each of two stocking treatments between 13 March and 17 December 1975. Stocking treatments consisted of one 20-ha paddock stocked continuously (*a* and *b*) and five paddocks each 4 ha in size rotationally (*c* and *d*) managed and stocked sequentially for 28 days. Note the exaggerated saw-tooth pattern of dietary digestible energy and crude protein contents occurring between the rotationally stocked paddocks over the season (*c* and *d*). Diet samples were collected on identical dates in both stocking treatments based on 0, 7, 14, 21, and 28 days during which time cattle were in each rotationally stocked paddock. Coloured vertical lines with arrows indicated an increase (green) or a decrease (red) in digestible energy and crude protein contents between the last day (28) in a paddock and the first day (1) in a 'fresh' paddock. Data from Anderson (1977).

these same dates in the continuously stocked paddock raises the question; could this be important to rumen function and overall livestock production? Ruminal bacterial population shifts in response to altered grass forage diets are not completely understood (Pitta *et al*. 2010). In particular, a dearth of information exists regarding how changing from a low to a rapidly declining high-quality forage diet, characteristic of some rotational stocking strategies, would impact dynamics in the rumen. Tajima *et al*. (2001) detected changes in bacterial DNA concentrations in as little as 3 days in ruminants switched from a hay to a grain diet. However, this type of information is not available for changes in forage quality. The literature is replete with studies describing how the addition of grain to a ruminant's diet alters rumen dynamics and how using grain to produce ruminant meat is problematic in a protein-deficient world because of the poor conversion efficiency (Provenza *et al*. 2007). Although efficiency of converting forage to high-quality protein may only be 10–35% of the energy intake (because 20–70% of the cellulolytic material may not be digested) (Varga and Kolver 1997), research must seek to understand and optimise the conversion of plants into animal products in the most efficient manner possible.

The recurring 'saw tooth' pattern in the data of Anderson (1977) illustrates that the higher DE and CP content (green arrows) between the last day in a SDG paddock and the first day in a 'fresh' SDG paddock (Fig. 2) and the 'roller coaster' pattern (some green and some red arrows) for the continuously stocked paddock (Fig. 2) are distinctly different and deserve consideration. Moseley *et al*. (1976) noted that abrupt changes in diet (forage to concentrate and vice versa) among 68 lactating dairy cows caused a slight disruption to fermentation that required 15 days over which to stabilise. Performance of ruminants on high-quality forage can be reduced if followed by lower-quality forage (Riewe 1981). However, the importance of this cyclicity in fixed interval rotational strategies is presently unknown. If a more 'seasonally dynamic' decline is optimum for free-ranging ruminant production rather than a 'roller coaster' pattern, a VP that can move temporally and spatially over a landscape could enhance the efficiency of livestock production.

Ruminal chemical and microbial dynamics differ between forage and grain-based diets. Clauss *et al*. (2003) suggested that ruminants morphologically adapted to a grass diet have relatively little problem processing browse but the reverse is not true. Ruminal fiber digestion decreases with ruminal pH and in turn decreases the efficiency of microbial protein synthesis (Firkins 1996). Fernando *et al*. (2010) reported that hay-fed animals contain more bacteria of the phylum *Fibrobacteres* while grain-fed animals have more bacteria belonging to the phylum *Bacteroidetes*. Gordon *et al*. (2002) demonstrated that sheep and red deer, adapted to high-quality diets, digested them differently than when adapted to low-quality diets. Although the evidence is not conclusive, ruminal bacterial numbers appear to be higher on higher-quality forage than on lower-quality forage (Dehority and Orpin 1997). Fermentation appears to be stabilised when ruminants are provided a mixed diet adequate to provide an optimal balance of nutrients to the microorganisms (Varga and Kolver 1997). Studying rumen microflora is challenging for many reasons, one being that microbial population differences and their metabolic potential may vary even among ruminants fed the same diet (Brulc *et al*. 2009; Jami and Mizrahi 2012).

Parsons *et al*. (1994) documented that free-ranging sheep consume a small amounts of spatially and temporally rare foods, resulting in maintenance of a diverse gut flora that can quickly react to changes in the foraging environment. Because ruminant livestock have access to a lower range in quality over time when they remain static on the landscape, it could adversely affect this relationship. Furthermore, McSweeney *et al*. (2001) proposed that rumen microbial populations adapt to diet components; e.g. populations adapted to tannin-containing forages may differ from those adapted to forage devoid of tannins, and this can influence protein and carbohydrate digestion.

Voisin (1959) suggested that the mean length of time a group of livestock should remain in a paddock is 2 days, yet longer periods have been reported (Hart *et al*. 1988). Ralphs *et al*. (1986) reported that diet quality declined even within a 3-day stocking period. Rook and Tallowin (2003) suggested that it may be possible to exploit temporal dietary choices of free-ranging livestock by moving animals within a day. Walker *et al*. (1989) reported rotation schedules between 0.75 and 2 days among 42 paddocks. McCaughey *et al*. (1997) observed with short stocking durations (3–5 days) in a 10-paddock rotational stocking strategy, diet quality declined dramatically over a 140-day period in both continuously stocked and rotationally stocked paddocks, especially from paddock entry to exit. Because of the uniqueness of each situation, making broad generalisations is risky; nevertheless, Savory and Parsons (1980) suggested foraging time should range from 1 to 5 days with subsequent rest periods of 30–60 days, and that both periods may be longer during dormancy. The most accurate generalisation that can be made is that when animals are rotated into a 'fresh' paddock, diet quality is normally improved if adequate time has passed for regrowth, regardless of season.

How important is diet quality on rumen function?

Although conventional rotation schedules may be short if the number of days a particular paddock is stocked is inflexible, frequently there is not a major increase in liveweight gains (Gammon 1978; Jung *et al*. 1985). With VF, in which a VP can be programmed to move at a variable rate across the landscape to keep pace with seasonal senescence, diet quality would be more stable and maintained at the highest possible level at any point in time based on the forage mass and its maturity. The rate a VP can be moved across a landscape need not be constant but can vary based on the quantity and quality of the forage mass. Furthermore, using VF, livestock can remain in a polygon while its geometry changes based on the mosaic pattern of the forage mass. This moving feed bunk concept of VF (Anderson *et al*. 2004*a*) could be designed to provide the highest diet quality possible by shaping polygons to fit heterogeneous vegetation associations. Stocking by vegetation type, soil type or other appropriate criteria could provide the least and most gradual changes in diet quality, which might benefit rumen function and translate to increased livestock performance.

Management of individual animals and virtual fencing

Managing cattle with VF could facilitate management of individual animals. Cattle represent an important source of methane (CH_4) production (Crutzen *et al*. 1986; Johnson and Johnson 1995; Wang *et al.* 2014). Currently no robust viable methods for reducing CH_4 emissions from foraging ruminants exist (Buddle *et al*. 2011). However, research suggests if free-ranging cattle are provided a high-quality diet, CH_4 emissions can be reduced (Ricci *et al*. 2014) and pasture-fed ruminants may be able to achieve comparable performance and greater muscle percentage compared with pen-fed ruminants with similar diets (Agastin *et al*. 2014). Therefore, the potential to optimise diet quality of free-ranging cattle by keeping them moving to the highest quality forage on a landscape using VF may offer management that can lower CH_4 emissions from ruminant-dominated landscapes worldwide. McAllister and Newbold (2008) demonstrated that it is possible to reduce CH_4 production by decreasing protozoa numbers with defaunation agents to reduce methanogens that are often attached to the surface of or are endosymmbionts with rumen ciliate protozoa. Unfortunately the use of defaunation agents appears to be transitory (Eckard *et al*. 2010), making the addition of such chemicals impractical under conventional management strategies. Possibly, with VF, the administering of defaunation agents could be made easier since cattle could be autonomously gathered (see Donniec *et al*. 2010) to locations where such procedures could be carried out on a routine basis.

Conclusions

Throughout the world, free-ranging livestock management remains one of the essential features of many rangeland landscapes. The heterogeneous nature of these landscapes requires management capable of providing flexibility. Even with smaller conventional paddocks and the optimum location and number of watering points, uneven foraging occurs due to non-uniform distribution of livestock. Patchiness is the norm in natural environments and has specific causes and measurable attributes (Hutchings *et al*. 2000); thus, management must be 'prescription-based' for spatial-temporal control of livestock.

Certainly VF is still a maturing methodology for managing free-ranging livestock and, therefore, many scientific questions regarding its possibilities and limitations are yet to be answered. However, if the reality of periodically dealing with 'leaky boundaries' is acceptable, VF will offer managers real-time control over stocking density, something not currently possible with existing methodologies.

It is recognised that more research is needed but a commercial VF device could be ready for 'first adopters' within ≤2 years if a concerted team effort was made to reach this goal. By melding what is already known with feedback from 'first adopters', progress in using this methodology of animal management would be possible because:

- VF has been shown effective to control livestock (Tiedemann *et al*. 1999; Anderson 2001, 2006; Monod *et al*. 2009; Jouven *et al*. 2012; Umstätter *et al*. 2013),
- VF offers more flexible control of livestock than what multiple-paddock conventional fencing strategies provide in an ecologically and economically sound framework, and
- VF will enhance selectivity by livestock from heterogeneous rangeland forage using a moving 'feed bunk' approach that focuses on optimum individual plant use by season and location.

Furthermore, the following should underpin the evolution of VF research and eventual producer applications:

- VF can assist in achieving the appropriate stocking rate that matches the landscape being stocked,
- VF should only be implemented using low-stress animal handling principles (Smith 1998),
- VF will require a multi-disciplinary team to ensure optimum results, at least initially,
- VF data must be analysed using proper spatio-temporal statistics (Anderson 2010), and
- VF research protocols should be standardised (Anderson *et al*. 2013) and use non-traditional approaches, when appropriate, for reporting results (Twilley and Manaugh 2013).

Dahl (1986) proposed a number of factors that must precede implementation of a particular stocking strategy, including but not limited to: appropriate stocking and distribution of appropriate livestock on the landscape, and appropriate use during specific seasons of the year. Although VF is not a panacea for correcting every problem facing livestock-dominated landscapes, it can largely replace physical labour with cognitive labour for management of free-ranging livestock by providing real-time control over stocking density, thus allowing the management of distribution, a characteristic second only of importance to stocking rate in livestock-dominated landscapes. With a multitude of potential paddock polygon shapes for including or excluding livestock, it can provide managers flexibility to manipulate the spatio-temporal aspects of foraging in real-time with flexible, reproducible precision down to the scale of individual plant communities and even species.

Disclaimer

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