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Virtual fencing – past, present and future[1]

D. M. Anderson

U.S. Department of Agriculture, Agriculture Research Service, Jornada Experimental Range, Box 30003,
MSC 3JER, NMSU, Las Cruces, New Mexico 88003-8003, USA. Email: deanders@nmsu.edu

Abstract. Virtual fencing is a method of controlling animals without ground-based fencing. Control occurs by altering an animal's behaviour through one or more sensory cues administered to the animal after it has attempted to penetrate an electronically-generated boundary. This boundary can be of any geometrical shape, and though unseen by the eye, is detected by a computer system worn by the animal. The most recent autonomous programmable systems use radio frequency (RF) signals, emanating from global positioning system (GPS) satellites to generate boundaries. Algorithms within a geographic information system (GIS) within the device's computer use the GPS and other data to determine where on the animal a cue, or cues, should be applied and for how long. The first commercial virtual fencing system was patented in 1973 for controlling domestic dogs. Virtual fencing was used for the first time to control livestock in 1987. Since then proof-of-concept research using commercial, as well as custom designed systems have demonstrated that virtual fencing can successfully hold as well as move livestock over the landscape. Commercial virtual livestock control systems do not yet exist but research continues towards this goal. Pending research needs relating to this method of animal control are discussed in light of currently available technologies.

Additional keywords: animal tracking, biotelemetry systems, directional virtual fencing (DVF^{TM}), dog training collars, electronic fences, global positioning system (GPS).

Introduction

Rangelands occupy between 18 and 80% of the earth's land surface with estimates of degradation within these ecosystems ranging between 20 and 73% (Lund 2007). Therefore, the management of free-ranging animals is essential in 21st century agriculture systems. After determining a proper stocking rate, the second biggest challenge in free-ranging animal management involves obtaining proper forage utilisation by managing animal distribution (Roath and Krueger 1982; Coughenour 1991; Pinchak *et al.* 1991; Bailey *et al.* 1996, 2001; Bailey 2004, 2005; DelCurto *et al.* 2005). Anderson (2001) listed 22 factors in six categories that influence animal distribution. Before fencing replaced herding as the predominant method to manage animal distribution proper forage utilisation was less of a challenge. Conventional fences are static tools that are very effective in controlling animal ingress or egress but fail to offer managers the flexibility they need to optimise the physiological requirements of the vegetation with the nutritional needs of foraging animals.

Fencing was the single greatest expense in 19th century production agriculture (Simmons 1935), and it remains a substantial expense today (Mayer and Olsen 2005). Fencing costs extend far beyond economics and include social and environmental concerns as we enter the 21st century (Beh-Shahar 1993; Boone and Hobbs 2004). Dairy farmers in The Netherlands, Australia, and New Zealand are interested in virtual fencing not only to optimize ecological and financial goals, but because virtual fencing promises a potential improvement in life style, such as shorter working hours (K. Lokhorst, T. Davison, pers. comm.).

Virtual fencing offers the possibility of controlling herbivory by placing a visually unseen boundary around individual animals or on landscapes, much like conventional fencing. The separation of individual animals has recently been demonstrated to prevent fighting between bulls that were maintained together in the same paddock with a cow in oestrous (K. Prayaga, personal communication). However, the predominant virtual fencing research has involved keeping animals in or out of a particular area (polygon) on the landscape. The radio frequency (RF) signals used in early livestock containment studies came from ground based transmitters (Fay *et al.* 1989; Browning and Moreton 1992), but systems in which the RF signals emanate from satellites appear to have the most potential for free-ranging animal control (Anderson *et al.* 2003).

Virtual fences incorporate many of the advantages of herding by using electronic technology to replace manual labour without being encumbered with the biggest challenge of conventional fencing, its being static and difficult to move. Without being able to control free-ranging animals in a flexible manner, their nutritional landscape cannot be utilised in an efficient and optimum spatial and temporal way. Once an animal is located on the landscape algorithms in the virtual fencing device's computer system activate the electromechanical cues that make

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the animal aware of the non visible boundary, and, subsequently elicit behaviours to alter its direction of movement. In this paper, cue and stimulus are used interchangeably and refer to any event perceived by the animal that subsequently produces a noticeable change in the animal's behaviour to facilitate its control. Since animal behaviour is never 100% predictable, virtual fencing should not be used if absolute animal control is required for the health or safety of either humans or animals. However, to control gregarious herbivory where ecosystem health is the paramount focus of management, and 'leaky boundaries' are acceptable, virtual fencing offers many exciting possibilities. The objective of this paper is to bring the past and present virtual fencing research together and present some unresolved challenges that must be addressed before virtual fencing can become a viable commercial reality for controlling free-ranging herbivory.

Global navigation satellite system (GNSS) and animal location

Our most recent source of RF signals come from satellites. Hurn (1993) describes the United States Navigation Satellite Timing and Ranging (NAVSTAR) GPS as our most recent utility for determining an object's location (Hurn 1995; Herring 1996; Enge 2004; Kaplan and Hegarty 2005). Besides GPS there are three other satellite location systems, the Russian (GLONASS) system, the evolving European Union Galileo positioning system and the regional Chinese Compass (Beidou) system (Anonymous 2006; Hein *et al.* 2007). However, GPS has been the preferred technology for ethological studies to date.

The first study to use GPS in locating animals began in March 1994 using collars designed and manufactured by Lotek Engineering Inc. (Newmarket Ontario, CA; Rodgers and Lawson 1997). GPS has been used successfully to track domestic sheep (Roberts *et al.* 1995; Rutter *et al.* 1997; Hulbert *et al.* 1998) and cattle (Udal *et al.* 1998, 1999; Turner *et al.* 2000; Schlecht *et al.* 2004; Ungar *et al.* 2005; Ganskopp and Bohnert 2006) as well as numerous wildlife species (Austin and Pietz 1997; Mech and Barber 2002) with spatial accuracies never before possible (Tomkiewicz 1997; Hulbert and French 2001).

The most useful practical modification of GPS technology for locating objects was the elimination of selective availability (SA) at midnight on May 1, 2000. This allowed civilian users to pinpoint locations up to 10 times more accurately ±20 m than the ±100 m accuracy previously advertised (Divis 2000). Recent research by the author in Las Cruces, New Mexico, has shown measurement error (standard deviations) of 1–3 m using low cost Trimble® receivers without special processing during periods of cattle inactivity. However, this accuracy will probably vary by geographic location. If higher position accuracy is required differential global positioning system (DGPS) data can be used (Hurn 1995; Moen *et al.* 1997). Autonomous GPS receiver data remains the least accurate location data available preceded by data coming from the wide-area augmentation system (WAAS), then satellite-based L-band corrected data, followed by DGPS beacon corrected data and finally post-processed data being the most accurate (Karsky 2004). Furthermore, software exists to improve position accuracy (Oh *et al.* 2005) and convert among accuracy measures (van Diggelen 2007).

After the development of GPS tracking, it was a short step to automate the control of animal movement. The first recorded control of a free-ranging cow using GPS technology combined with autonomously-applied sensory audio and electric stimulation cues occurred on 2 April 2001, on the Jornada Experimental Range (JER). Shock collars for training dogs (Files 1999) and devices to control large animals (Manning 1998; Marsh 1999; Anderson and Hale 2001; Butler *et al.* 2006; Bishop-Hurley *et al.* 2007) have incorporated GPS technology.

History of virtual fencing through February 2007

Richard Peck turned the concept of virtual fencing into reality with his December 1971 USA patent describing a method and apparatus for controlling an animal (Peck 1973). Since then pet containment systems have become big business in the United States with sales of electronic fences growing from $8 million in 1990 to $150 million in 2000 (Salmon 2000). Radio Systems Corporation research indicated USA pet owners purchased more than 2 million remote training devices, pet containment systems, and bark collars in 2001 with unit sales of electronic training devices projected to reach 4 million annually by 2007 (Brudecki 2004).

In 1987 equipment manufactured by Peck's Invisible Fence® Co. provided the first virtual control devices used on domestic livestock in the United States (Fay *et al.* 1989). In this research Peck's devices were successfully used to contain meat-type goats on leafy spurge (*Euphorbia esula* L.). Using modified and non-modified Invisible Fence® Co. equipment Browning and Moreton (1992) reported various levels of livestock control were achieved in England among sheep, goats, cattle and ponies between April 1990 and October 1992. However, cattle have been the animal of choice in all subsequent research using various devices to establish proof-of-concept that virtual fencing is a viable method of animal control (Quigley *et al.* 1990; Markus *et al.* 1998*a*, 1998*b*; Tiedemann *et al.* 1999; Anderson 2001; Butler *et al.* 2004; Crowther 2006; Bishop-Hurley *et al.* 2007). Other virtual fencing devices have been proposed, but to date have not been built or field tested (Rose 1991; Rouda 1999, 2003; Rouda *et al.* 2000; Steve Ravston 2005, pers. comm.). Though virtual fencing systems for free-ranging animals are not yet commercially available, advertisements from companies in South Africa (Kearney and Buys 2007) and North America (Marsh 2006) suggest such systems are not far off.

Commercial pet collars and ear tags

In two separate 12-day trials, 12 randomly-selected Spanish meat-type goats of mixed age and sex (six per trial) were collared and subsequently controlled using commercial dog shock collars manufactured by the Invisible Fence® Co. (Fay *et al.* 1989). To ensure skin contact with the electrodes, hair around the goat's neck was shaved before applying and tightening the collar. Within 30 min of training, goats were controlled with the cue package consisting of a beeping tone (37 Hz) followed 2 s later with a mild shock (65 V at 45 mA). Most of the goats adapted quickly and though they received five or six shocks during the first 5 min of a 30 min training interval, no shocks were necessary thereafter.

Tiedemann *et al*. (1999) noted that heifers learned where the exclusion zone was after receiving as few as one or two cuing packages. D. M. Anderson (unpubl. data) also observed that beef cattle learn quickly to avoid irritating cues. Cattle in a paddock remained just out of range of an observer carrying a hand activated device capable of delivering audio and electrical stimulation cues after previously experiencing only a few cue packages. In a replicated study, Bishop-Hurley *et al*. (2007) determined mean rate of travel of five steers per treatment through a 40 m long × 6 m wide alley decreased following the application of irritating sensory cues. In this research, a single cue package consisting of either a vibration (3 s) followed by electric stimulation (1 kV for 1 s) or sound (3 s) followed by electric stimulation (1 kV for 1 s) was found to cause steers to hesitate during movement through the alley towards feed and peers located at the opposite end. On the third trial through the alley steers hesitated (4–8 times longer) after receiving just the audio or vibration cues and did not require electrical stimulation to prevent them from moving through the alley.

Though animals learn quickly how to avoid sensory cues, not all animals react to cues in an identical fashion. In the Fay *et al*. (1989) study one goat was termed ‘un-trainable’ because it remained motionless during shocking and had to be removed from the study and another goat, would not endure the pain of the electric shock to join peers outside the enclosure. However, none of the six collared goats in the Fay *et al*. (1989) study left the containment area during the initial trial. As a result, the non-collared control goats never wandered more than 50 m from the confined animals and demonstrated anxiousness if their nearest neighbour distances exceeded 20 m. Tiedemann *et al*. (1999) reported this same behaviour during several occasions; when animals wearing ear tags designed to administer sensory cues moved back into the grazing zone followed by the control animals.

Quigley *et al*. (1990) used Tri-tronics® A1–90 remote dog training collars set at a level four electrical stimulation to cause four Hereford steers to turn 90 degrees and jump. Over a 4-day trial designed to keep steers out of a polygon within a corral and pasture, correct responses to audio-electrical stimulation were 83, 93, 97 and 100%, respectively. Furthermore, when two steers were grazing relatively close to each other and one received a cue, the other steer moved in tandem with the cued steer. By day four Quigley *et al*. (1990) found the steers were responding to an audio cue (buzz) only in a manner similar to that of audio-electrical stimulation in which electrical stimulation lasted ≤ 5 s.

The largest virtual fencing study to date was reported by Tiedemann *et al*. (1999). They used a 113 g prototype electronic ear tag manufactured by Schell Electronics (Chanute, KS) that measured ~7.6 × 15.2 cm and was powered by two 1.5 V AAA batteries with an audio emitter near its top. These electronic tags were about twice the length of commercial ear tags. Data were collected on 90 steers in Texas for 8 weeks and 90 crossbred heifers in Nevada for 5 weeks. Details on both these studies have been summarised previously (Anderson 2006).

The Texas trials revealed: (1) training may be necessary before attempting to control animals using virtual fencing. Training was accomplished by establishing an electric fence across the paddock near three ground based RF transmitters for 1.5 days. As instrumented animals approached the visual cue (electric cross-fence), technicians stood up and waved their arms in an effort to turn animals away and stop the cues. It was assumed the training was successful because once the electric fence was removed most animals turned away from the virtual fencing cues emitted from the RF transmitters when the virtual exclusion boundary was encountered even though not all ear tags were found to receive a signal at the same distance from the transmitters. (2) Animals should not be agitated and caused to run when released into an area delineated using virtual fencing, because they are likely to run through the virtual fence when they encounter it for the first time. (3) Identifying lead animals and controlling them appears essential because if the ear tag ceased to function and the animal wearing the non-functional ear tag left the zone of inclusion, other animals would endure the audio-electrical stimulus and follow. (4) The 8500 Hz audio cue was similar to insect sounds and if animals encountered live insects they would move as if in response to the audio cue. (5) The 1-s audio cue was considered too long. (6) The cuing sequence was a single audio warning signal (length of delivery not given) followed by 4 s of silence and then an electrical stimulation (intensity and time not given). If the steer did not move appropriately following another 4 s of silence a second electrical stimulus was given. If a third electrical stimulation was required, the system locked up after it was delivered. (7) The ear tag attachment stud was too short, causing physical damage to the ear. Overall the Texas trials revealed that animals without virtual fence ear tags were in the grazing zone and the transition plus exclusion zone 52 and 48% of the time, respectively. In contrast, steers wearing virtual fence ear tags spent 93 and 7% of the time in the grazing zone and transition plus exclusion zone, respectively.

In Nevada the 90 yearling Hereford-Angus cross heifers were evaluated over a 5 week foraging trial that took place along a riparian area ~1.6–2.4 km long and 0.4–0.8 km wide (Tiedemann *et al*. 1999). The Nevada test differed from the Texas test in four ways: (1) the audio cuing frequency was lowered by a factor of 10 to 850 Hz, (2) the period of electrical stimulation lasted ~12% as long as in the Texas test, (3) the ear tag attachment stud was increased from 2.54 to 3.81 cm and holes were drilled through the nylon washer placed between the ear pinna and the hardware, (4) the RF transmitters, designed to ‘unlock’ ear tags, were set up at the water troughs in the treatment paddocks.

After only one or two stimuli, the animals seemed to know where the exclusion zone was. The cue package was as follows: 850 Hz audio stimulation (0.125 s), 4 s of silence, electrical stimulation (time and intensity not provided), and 4 s of silence. This package was repeated four consecutive times before the unit locked up. As in the Texas trial ‘follower type’ animals would endure the irritation of the audio-electric stimulus and enter the exclusion zone. To attempt a more rigorous test of the transmitter signal boundary, animals wearing virtual fence ear tags ($n = 17$) were separated from control animals by an electric fence. Animals were trained to virtual fence control by placing RF transmitters along the electric fence and confining the animals to an area behind the transmitters/electric fence. Following one day of training, 23 correct responses and two incorrect responses were observed. The boundary was never challenged by heifers the first day of the trial (transmitters were shut off at night due to negative weather/electronics interactions). Over the next three days, 32 of 36 observed encounters resulted in heifers being turned back into the grazing zone.

Following the Nevada tests it was concluded that (1) shortening the cuing interval to 0.125 s was preferable to the previous 1 s interval; (2) the ear tag must be made smaller and weigh $\leq$28 g to be robust; (3) audio stimulation alone may be adequate to elicit animal movement without electrical stimulation; (4) training may be an essential part to implementing this technology. In a second part of the trial, 44% of the control animals spent time in the exclusion zone while 0% of the animals wearing functional virtual fencing ear tags entered the exclusion zone during the day. The overall conclusion was that virtual fencing has a strong potential for excluding livestock from specific areas.

Neck saddles and directional virtual fencing (DVF^{TM})

Directional virtual fencing (DVF$^{\mathrm{TM}}$; Comis 2000; Anderson 2001; Anderson and Hale 2001) is a patented, trademarked methodology for autonomously controlling an animal's location, and, subsequently its direction of movement on a landscape through the use of a series of ramped bilaterally applied cues that increase in severity if an animal attempts to penetrate through the perimeter of an electronically generated RF boundary. An animal's innate behavioural response will be to move away from an irritating cue or stimulus if given the opportunity. With DVF$^{\mathrm{TM}}$, movement is initiated and maintained by administering a repertoire of ramped cues to the animal to produce directed movement. Cues applied to the right side of the animal normally produce movement to the left and *vice versa* (Fig. 1). DVF$^{\mathrm{TM}}$ requires a virtual boundary (VB$^{\mathrm{TM}}$) and a virtual center line (VCL$^{\mathrm{TM}}$). The VCL$^{\mathrm{TM}}$ can be thought of as the physical location on a landscape where a conventional fence would have been constructed. A VB$^{\mathrm{TM}}$ is the area in which the irritating cues are administered in a ramped fashion if penetrated by an animal wearing a DVF$^{\mathrm{TM}}$ device. Because DVF$^{\mathrm{TM}}$ provides a ramped repertoire of cues a VB$^{\mathrm{TM}}$ will always be wider than a conventional fence. The VCL$^{\mathrm{TM}}$ represents the line that defines one or more sides of a polygon (virtual paddock, VP$^{\mathrm{TM}}$) in which animals wearing the DVF$^{\mathrm{TM}}$ device are to be included or excluded. Both the VB$^{\mathrm{TM}}$ and the VCL$^{\mathrm{TM}}$ are programmable as to location on the landscape

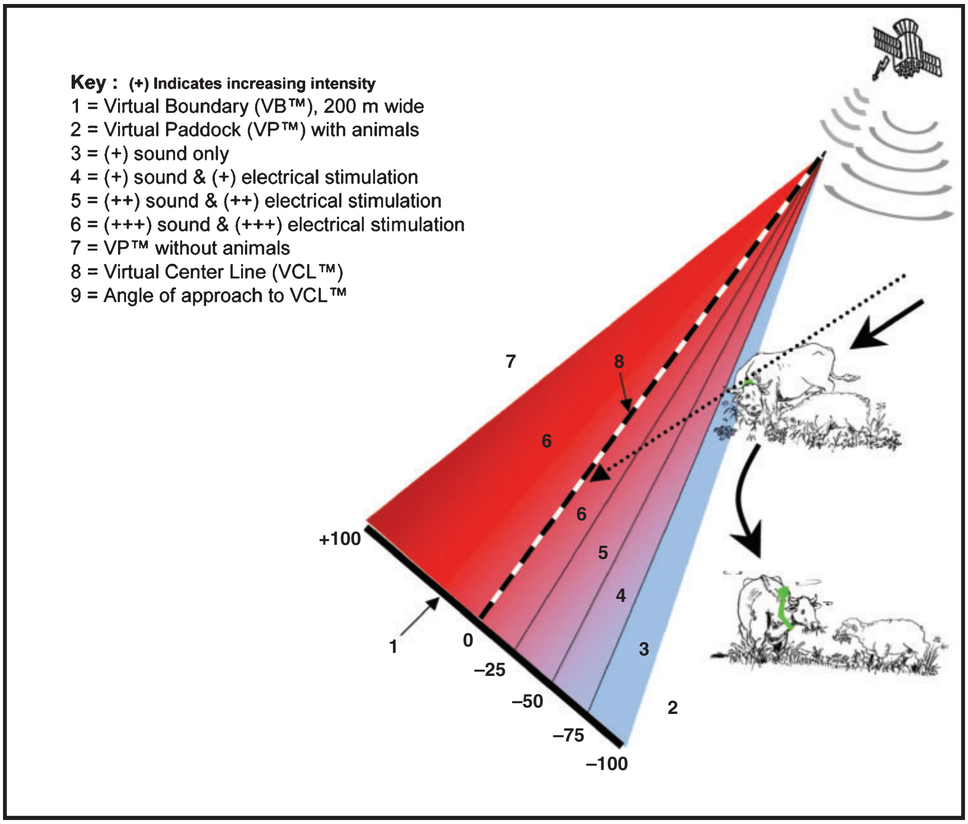

Fig. 1. Schematic representation of how directional virtual fencing (DVF$^{\mathrm{TM}}$) operates. A magnetometer located in the DVF$^{\mathrm{TM}}$ device worn on the cow's head or neck determines the animal's angle of approach to a virtual center line (VCL$^{\mathrm{TM}}$). Once the animal penetrates the virtual boundary (VB$^{\mathrm{TM}}$), determined with the systems global positioning system (GPS), algorithms in the unit's geographical information system (GIS) use these raw data to determine to which side of the animal and how intense the electromechanical stimulation (cues) should be to cause the animal to turn away from the VCL$^{\mathrm{TM}}$ and return to the virtual paddock (VP$^{\mathrm{TM}}$) in the shortest distance and time. The VCL$^{\mathrm{TM}}$ represents where a conventional fence would be constructed on the landscape. (Adapted from Anderson *et al*. 2003.)

and width and are contained in the DVF^{TM} device's GIS (USDI-USGS 2006).

Rather than attempting *a priori* to determine the level of irritation required to produce a directional change in an animal's movement, the system provides a suite of ramped cues from least to most irritating based on the animal's distance from the closest VCL^{TM}. With DVF^{TM}, the animal chooses the level of irritation it will no longer tolerate before changing its direction of movement. It may be possible to elicit cuing using any of the senses, but audible sound and electrical stimulation were the two used to establish the proof-of-concept that DVF^{TM} works.

If an animal leaves the VP^{TM} and enters the VB^{TM}, cuing begins on the side of the animal that forms an acute angle with the VCL^{TM} (Fig. 1). Cuing continues until the animal's direction of movement is at an angle of $\geq 3°$ away from the VCL^{TM}, cuing then immediately stops. However, if the animal does not turn back towards the VP^{TM} but passes through the VCL^{TM}, cuing continues on the same side of the animal that now forms an obtuse angle with the VCL^{TM}. Algorithms in the device's computer use this angle information to ensure the animal receives cues on the side that will move the animal back into the VP^{TM} over the shortest distance and in the least amount of time with the least amount of cuing stress. In contrast, Tiedemann *et al.* (1999) initially used a cue package that lasted 1 s. In some cases, this was too long and the animal turned 360° and ended up moving towards the exclusion zone after being cued.

The angle of approach of the DVF^{TM} device to the VCL^{TM} is determined by an electronic magnetometer (GPS data also contains magnetometer information but an animal's normal rate of travel is too slow for it to be useful in determining to which side of the animal the bilateral cues should be applied). However, if the animal passes through the VCL^{TM} and continues walking away from the VCL^{TM}, cuing ceased as soon as the animal's distance from the VCL^{TM} exceeds the programmed width of the VB^{TM}. Should the animal not move out of the VB^{TM} and continue to face the VCL^{TM} it was possible to stop cuing after a programmed period of time had elapsed to prevent unnecessary stress to an animal that got confused or simply did not learn the required movement routine in order to cause the cues to stop. However, if an animal at any time moved completely through the VB^{TM}, but at some later time decided to return to the VP^{TM}, it could walk back through the VB^{TM} and into the VP^{TM} without receiving cues. The DVF^{TM} system using raw GPS location data has successfully held animals behind a static boundary (Anderson *et al.* 2003) as well as within a VP^{TM} programmed to move in time and space across a landscape (Anderson *et al.* 2004).

Though no formal training was used with the animals controlled with DVF^{TM}, they quickly learned to respond correctly to cues programmed into the device's computer. Over numerous studies it was found that some animals learned rapidly with minimal cuing to turn and leave a VB^{TM} but other animals required more time to learn the routine or required a more severe cue package to leave a VB^{TM}. This can be seen in Fig. 2 from the 'worm-like' trails penetrating into the east VB^{TM}. Though both cows were experienced to receiving DVF^{TM} control at the onset of this experiment cow 4130 never moved past zone 2 (audio sound only) before returning to the VP^{TM} but cow 4132 appeared to consistently require more irritation in the form of audio and electrical stimulation before returning to the VP^{TM}.

The DVF^{TM} proof-of-concept was established using a VB^{TM} of 100 m on either side of the VCL^{TM}. However, the initial VB^{TM} width used was only 65 m and this was too narrow. Data were recorded approximately every minute while an instrumented animal was inside a VP^{TM}, but once the animal penetrated the VB^{TM}, data were recorded every second. When an animal in a VP^{TM} was at the interface between the VP^{TM} and a VB^{TM} and a GPS fix was recorded, if the animal's movement penetrated the VB^{TM} at the next GPS fix ($\sim$1 min later) the animal would have travelled to within a few meters of the VCL^{TM}. Walking travel of a cow through a VB^{TM} was recorded to be $\sim$54 m per minute during a 27 June 2002 trial. At this rate of travel this put the cow only 11 m from the VCL^{TM} when data recording changes from approximately once per minute with no cues to once every second with cues. With the distance from the VCL^{TM} being only a few meters away the cuing package was immediately quite severe. Therefore, regardless of the side on which the sound and electrical stimulation was delivered, the animal would most often lunge forward through the VB^{TM} rather than turning away from the bilaterally applied cue and back into the VP^{TM}. This bolting response was also reported by Tiedemann *et al.* (1999) who reported a variable response to cuing severity among steers, some animals moved in circles while others shook their heads as they ran through the virtual fence.

Radio Systems Corporation suggest electrical stimulation should be more startling than painful and should impart the sensation of an electric current rather than produce muscle contraction, which is many magnitudes more severe than the electric stimulation produced by most dog training collars (Brudecki 2004). Most current commercial electronic training devices have eliminated the 'one size fits all' approach and allows from 5–18 modes of operation (Thoms 2004). However, most commercial dog collars rely on manually selecting the 'appropriate' cuing level and not on an autonomous and programmable distance from a RF generated boundary.

The DVF^{TM} data described in this paper used only a 100 m wide VB^{TM} on either side of the VCL^{TM} because it was impractical to increase memory storage and power requirements making 1 s rather than 1 min data acquisition practical in these prototype devices. By using a 100 m wide VB^{TM} this eliminated the animal's close proximity to the VCL^{TM}, and the most severe cue package (Fig. 1), when the VB^{TM} was initially encountered by the animal. Current equipment has surpassed these earlier memory storage and power limitations. Hence, a VB^{TM} no longer needs to be 100 m wide on the VB^{TM} facing into a VP^{TM}. Furthermore, with the prototype equipment VBs^{TM} were symmetrical around the VCL^{TM}, this is no longer necessary because zones comprising the VB^{TM} as well as the VB^{TM} itself are fully programmable.

The ability of animals without DVF^{TM} devices to be controlled by animals wearing DVF^{TM} devices has been demonstrated. Three cows with DVF^{TM} devices controlled three steers wearing only GPS collars (Fig. 3). Furthermore, in a 2004 study, a small mixed species group of cattle and sheep termed a flerd (flock + herd; Anderson *et al.* 1988) was controlled by equipping only the cattle with DVF^{TM} devices (Table 1). The sheep stayed with the cattle because they had previously been bonded (Anderson 1998) to cattle,

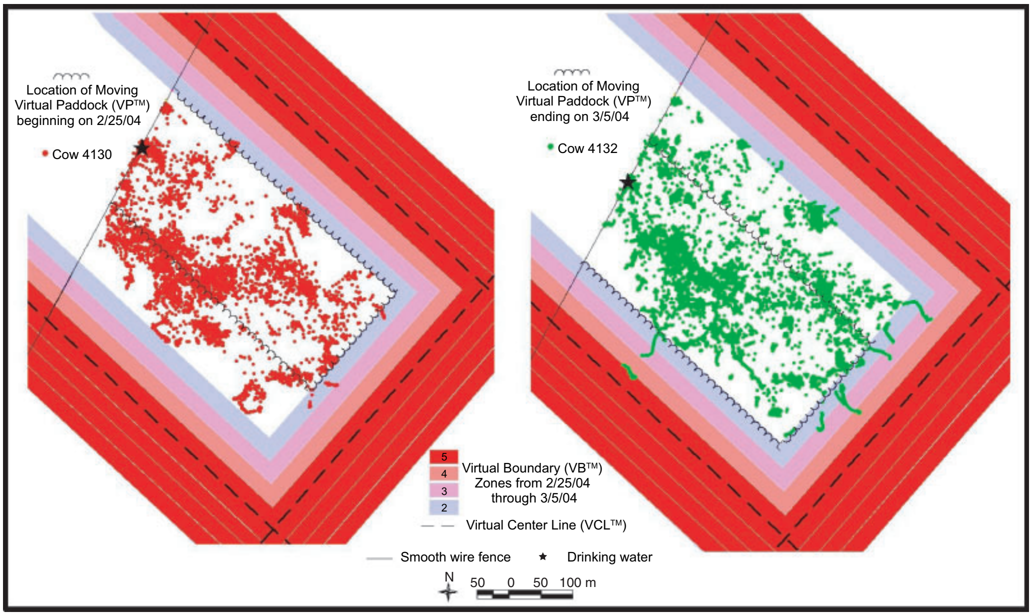

Fig. 2. Raw global positioning system (GPS) data showing the spatial occupation of a 200 × 486 m virtual paddock (VP$^{\text{TM}}$) stocked with two free-ranging mature, cross-bred beef cows instrumented with directional virtual fencing (DVF$^{\text{TM}}$) devices between 25 February and 5 March 2004. The north and south virtual boundary (VB$^{\text{TM}}$) were each programmed to move in a south-westerly direction at a rate of 1.1 m per hour between 0700 and 1700 h, thus, moving the rectangular VP$^{\text{TM}}$ $\approx$100 m south during the 9 consecutive day trial. Though neither cow escaped from the rectangular VP$^{\text{TM}}$ both cows, shown separately, 'challenged' the VB$^{\text{TM}}$ several times as clearly shown by the 'worm-like lines' penetrating into the east VB$^{\text{TM}}$. Each VB$^{\text{TM}}$ consisted of four 25 m wide zones on either side of a virtual center line (VCL$^{\text{TM}}$). Data from the east VB$^{\text{TM}}$ indicates cow 4130 was always returned to the VP$^{\text{TM}}$ after receiving only bilateral audio cues (Zone 2) but cow 4132, though never reaching the most severe cue package (Zone 5), did require both audio plus electrical stimulation in the form of bilateral cues before returning to the VP$^{\text{TM}}$. The east VB$^{\text{TM}}$ remained static throughout the trial and the west boundary was a smooth wire fence to allow for orientation while observing the animals from outside the VP$^{\text{TM}}$. Drinking water and salt were maintained approximately centred between the north and south VBs$^{\text{TM}}$ on the west side of the VP$^{\text{TM}}$ beginning at an initial location on 25 February 2004 (cow 4130) and subsequently moved to a second location on 1 March 2004 (cow 4132). (Adapted from Anderson *et al*. 2004.)

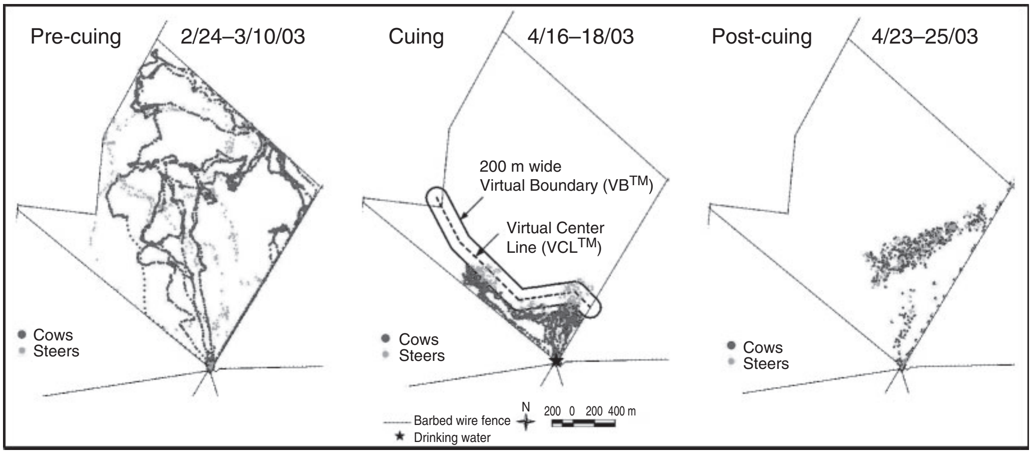

Fig. 3. The spatial location of six cattle within a 466 ha Jornada Experimental Range (JER) paddock between 24 February and 25 April 2003 before, during and following three of the cattle (cows = large dots) having their location controlled by directional virtual fencing (DVF$^{\text{TM}}$) devices on 16–18 April. Throughout the trial the three steers (smaller dots) wore Lotek collars that provided no cues but only location. The location data (raw) from the DVF$^{\text{TM}}$ devices and Lotek collars were recorded every 1 and 5 min, respectively. Precipitation received during the trial caused growth of desirable herbaceous vegetation on a red sand sheet landform giving the false appearance there was an activated VB$^{\text{TM}}$ surrounding this landform during the post-cuing period.

Table 1. Area (ha) occupied by cattle and sheep that had previously been bonded to cattle (Anderson 1998) in a 466 ha paddock on the Jornada Experimental Range (JER) between 26 April and 17 May 2004

The mixed species cattle and sheep group termed a flerd (Anderson *et al.* 1988) remained together when controlled by three mature cross-bred cows wearing directional virtual fencing (DVF^{TM}) devices programmed to provide bilateral electromechanical cues to the cattle only if they attempted to cross a virtual boundary (VB^{TM}) during the cuing phase of the trial. The mature white-faced sheep and single calf wore commercial global positioning system (GPS) equipment without receiving electromechanical cues

Dates in 2004[A]	Treatments[B]	Number Cattle[C]	Number Sheep	Available area (ha)	Polygon area[D] (ha) Cattle[E]	Polygon area[D] (ha) Sheep[E]	Path area[F] (ha) Cattle[E]	Path area[F] (ha) Sheep[E]
April 26–28	Pre-cuing	3	3	466	37	27	1.3	0.6
May 2–5	Cuing	4	2	58	40	37	2.4	0.9
May 5–7	Cuing	4	7	58	50	47	1.5	0.6
May 10–12	Cuing	4	7	108	75	62	1.3	0.6
May 12–14	Cuing	4	14	108	70	68	1.7	0.6
May 17–19	Post-cuing	4	14	466	82	73	1.1	0.6

[A] Consecutive days of data missing between 28 April and 17 May are the result of malfunctioning in one or more of the three DVF^{TM} devices used to control animals behind the VB^{TM}.

[B] During pre- and post-cuing only location data were obtained from all animals using global positioning system (GPS) data while during cuing the DVF^{TM} devices were activated to give location data in addition to animal control within the confines of a virtual paddock (VP^{TM}) composed of three conventional fences and one VB^{TM}.

[C] Three cows and one calf were used. On 26–28 April the calf was not instrumented with a GPS unit.

[D] Area enclosing the smallest polygon that would include all animals of the same species without excluding areas from within these polygons in which animals were not found.

[E] Garmin e-Trex Legends^{TM} and a Geiko 201^{TM} units were used to collect GPS data at a rate of one location per minute for the calf, all the sheep, and cow 4127 during post-cuing. All other GPS data were obtained using DVF^{TM} devices.

[F] Area based on a band 1m wide × the total distance travelled (m) for each animal species excluding the calf.

thus, allowing the flerd to be controlled using DVF^{TM}. The implications of this type of stocking appear exciting if one considers the possibility of managing noxious weeds using animal groups that have different dietary preferences when combined with a control system that capitalizes on behavioural modification and electronic technology.

Topics awaiting completion

Terminology

The word 'virtual' when used with fencing has been described in different ways, and as yet, there is no agreed definition (Anderson 2001; Palmer *et al.* 2004). It is essential that terms used with virtual fencing be defined especially for written communication. This will immediately be a challenge because some items remain inadequately documented or incompletely understood, partly as a result of the evolving nature of virtual fencing research.

Expressing, producing and storing power

A commonly-accepted way to express the intensity of the various types of cues does not currently exist but is needed to allow meaningful comparisons among future virtual fencing studies. How should electrical stimulation be expressed? Currently, cuing intensity is either determined by a manufacturer (pet containment equipment) or 'tested' and deemed appropriate by the designers of the equipment. Designer tested equipment has literally been a 'hands on (off)' experience by a technician touching 'energised' electrodes and verbally indicating when the recipient believed they were experiencing a stimulus adequate to cause the animal's behaviour to change appropriately when given the same level of stimulation. This setting then became what was used in the experiment. Though not totally inappropriate, this approach lacks an objective evaluation and may not accurately represent what a free-ranging animal experiences. This same lack of uniformity in terms of expressing intensity for any of the other sensory cues that have been or will be used also needs to be addressed.

The various ways previously used to describe the 'amount' of electrical stimulation have not been uniform, making conversion to a common standard impossible. Fay *et al.* (1989) indicated the Invisible Fence® Co. system used a shock pulse of 65 V at 45 mA. Browning and Moreton (1992) report the English version of the Invisible Fence® Co. system provided a 1.1 MJ/pulse from the device's single setting. Bishop-Hurley *et al.* (2007) used an electrical stimulus level of 1 kV for 1 s and Crowther (2006) used a Petsafe® Stubborn dog RF 275 unit calculated to have a maximum electrical stimulation of 30 MJ. The initial electrical stimulation produced by the DVF^{TM} system was 50 pulses ($\simeq$80 MJ/pulse) with a maximum of 400 pulses in the zone surrounding the VCL^{TM} (Anderson *et al.* 2003). Most recently, Lee *et al.* (2007) used an electrical stimulus of 600 V at 250 mW on heifers for $\leq$5 s. It is difficult to accurately express what the animal actually experiences in the way of an electric stimulus. Electrode composition, size, placement and contact with the skin, physiological state of the animal and ambient weather conditions are just some of the factors that may affect what an animal actually 'feels' upon receiving the stimulus. Possibly, developing an appropriate 'pain' scale for an animal's response to an electrical stimulation cue might be one approach to solving this challenge.

Solar panels have successfully been used to generate power for DVF^{TM} devices (Fig. 4) with the most recent configuration being a flexible solar panel attached to a neck belt (Rango *et al.* 2003). However, solar panels may not work in environments with inconsistent or inadequate periods of sunlight. Therefore, it may be necessary to generate energy from animal motion.

Fig. 4. A grazing cross-bred beef cow wearing a directional virtual fencing (DVF^{TM}) battery (1) powered neck saddle device equipped with spring loaded electrodes (only left side pair shown 2) for providing electrical stimulation and left (3) and right (4) piezo speakers housed inside poly vinyl chloride (PVC) pipe for audio stimulation. A global positioning system (GPS) antenna (5) is located in the centre of a panel of solar cells (6). This prototype platform may appear clumsy but was remarkably robust during numerous field trials conducted between 2001 and 2005.

If the concept of a 'cow boot' described by Horn (1981) were combined with the electronics described in a patent by Le *et al*. (2001), it might be possible to convert animal movement into power adequate to keep an on-board battery charged, allowing the virtual fencing device to operate for extended periods unattended. Regardless of the approach, power needs to be generated on board the animal to avoid frequent human intervention. Recent innovations in hardware applications (Schmitt and Schell 2005) as well as software (Schwager *et al*. 2007) may be useful in managing power requirements.

Once power has been generated, the most likely storage device is a battery. Where battery contact is required to complete a circuit, a dielectric compound has been found useful (Tiedemann *et al*. 1999). However, battery life expectancy tends to be the most limiting factor affecting how long electronically instrumented animals can be successfully deployed (Clark *et al*. 2006). New technology, such as the all-polymer batteries, may someday prove to be the storage source of choice because they are efficient in hot and cold environments, contain no liquids and can be formed to take on any configuration the user desires (Strümpler and Glatz-Reichenbach 1999). Though polymer batteries currently cost more and are not as common as other battery technologies, they are available through companies such as Ultralife® (Pope 2007).

Equipment platforms

As confirmed by the research by Tiedemann *et al*. (1999), the actual device to be worn by the animal must have a small footprint, low mass, and be able to withstand reasonable impact, moisture and dust. Collars remain the platform of choice for pet containment systems and have been used on free-ranging cattle (Browning and Moreton 1992; Butler *et al*. 2004; Crowther 2006). However, collars offer their own challenges as a virtual fencing hardware platform. If electrical stimulation is used as one of the cues, collars will not work unless they are maintained tightly around the animal's neck to keep electrodes in constant contact with the animal's skin which can cause abrasion to the skin. In contrast, a loose collar can rotate, resulting in intervals when electrodes lose skin contact, besides potentially causing harm to the animal if its foot is caught in the collar during body grooming (Fraser 1985) or if the collar is caught on obstacles in the environment or horned sheep become entangled in each others' collars (Browning and Moreton 1992). If collars rotate, antennas can move to non-optimum locations for capturing the GPS signal and receiving or sending signals for wireless communication (Wang *et al*. 2006). Recently, rotated antennas were shown to cause signal interruption due to attenuation from bodies of nearest neighbours (D'eon and Departe 2005; Butler *et al*. 2006; Bishop-Hurley *et al*. 2007).

Browning and Moreton (1992) devised a ram harness with electrodes fitted under the sheep's body where no wool grows. Neck saddles (Anderson 2001; Rango *et al*. 2003) of varying designs have been satisfactorily used for experiments with cattle but are too bulky (Fig. 4) for commercial application. The most recent study that has been published combined a modified horse halter and a neck belt for use on cattle (Bishop-Hurley *et al*. 2007). However, none of these platforms are suitable for long-term field studies or commercial application because of exposed wires and the potential for abrasion to the animal's skin from an improper fit.

The mass of the electronics and power required to implement virtual fencing made ear tags unsatisfactory in early trials (Tiedemann *et al*. 1999). However, current technology has reduced the mass and electronic footprint required to implement virtual fencing. Testing began in February 2007 on the JER using virtual fencing software and hardware designed and built by the Massachusetts Institute of Technology (MIT) that incorporates GPS and wireless communication capability. The complete circuit board (potential maximum size 5 × 5 × 1 cm) with electrical stimulation hardware and two audio speakers has a mass without batteries or solar panels of <400 g (D. Rus, I. Vasilescu, pers. comm.). However, if an accurate magnetometer reading is essential to make the hardware operate correctly as in DVF^{TM}, even light-weight ear tags are probably not the answer owing to the near constant movement of an animal's ears in response to environmental sounds.

The most recent equipment platform that appears promising has been termed an 'ear-a-round' (EAR^{TM}; Anderson 2005). This platform looks much like a donut which fits over the animal's ear. Depending on the requirements of the virtual fencing device chosen, either single or pairs of EAR^{TM} devices could be deployed on an animal. The outer ring can be manufactured to contain all of the hardware necessary for virtual fencing. Because it is positioned next to the animal's head at the base of the ear pinna, mass of electronics is no longer a significant issue. Furthermore, because the EAR™ moves with the animal's head, the magnetometer reading correlates with the direction the animal is moving. Also the platform's position over the ear places it in an optimum location for receiving RF signals. The only consistently higher position on a free-ranging animal would be on top of its backbone. Petrusevics and Davisson (1975) used this location to hold an equipment saddle on the animal using a girth strap. However, a girth strap has the same challenges as harnesses, neck belts and collars due to changing gut fill that must be accounted for in a girth belt design. Field tests are currently underway to determine the EAR™'s suitability and limitations for housing virtual fencing electronics.

Safety and security

Virtual fencing relies on altering animal behaviour and, therefore, equipment must be designed with fail-safe features to prevent excess cuing (especially cues that could elicit physiological long-term stress). What causes little or no stress to one animal may cause excess stress to another because stress is not a constant from animal-to-animal (Stricklin and Mench 1990). Therefore, it may be most appropriate to allow the animal to choose the 'irritation' level it will not tolerate by providing ramped cues from least to most severe in a manner similar to those designed into DVF™. Furthermore, virtual fencing electronics must be designed to ensure that if an animal escapes from the polygon, it can return on its own without receiving unwanted cues. Tiedemann *et al.* (1999) accomplished this by providing electronics to unlock ear tags at a site animals had to frequent with some periodicity such as drinking water, and Anderson and Hale (2001) used the animal's distance from, and angle of approach to a VCL™ to activate or deactivate cuing.

Most producers and research animal scientists know low-stress animal husbandry practices make practical as well as economic sense (Smith 1998). However, if electrical stimulation is necessary in virtual fencing, should it take place on the animal's skin or in its brain? To date only external stimulation has been used. However, internal cuing using brain micro-stimulation has been demonstrated in rats from a brief train of stimulus pulses of 80 μA; typically 10 biphasic pulses, each 0.5 ms, 100 Hz, per train directed at the somatosensory cortical and medial forebrain bundle to produce autonomously directed animal navigation (Talwar *et al.* 2002; Xu *et al.* 2004). However, moral and ethical issues must be adequately addressed before brain micro-stimulation as a cuing approach can be considered for virtual fencing. Most likely, these kind of issues will have to be resolved in courts of law and interpreted through venues such as Institutional Animal Care and Use Committees (IACUC) (For further information see AALAS 2007).

The livestock industry has been catapulted into the computer age with individual electronic animal identification (Anderson and Weeks 1989), and with it has come security and theft issues. When virtual fencing and individual electronic animal identification including retinal vascular pattern (RVP) analysis (Ishmael 2006) are combined the potential for theft may be reduced. However, no amount of electronic technology can ever replace good husbandry that requires quality human animal interactions to provide safe and secure animal production systems. Husbandry is not replaceable by science, but should use and correct it (Berry 2005).

Animal stress

Reducing stress when handling animals benefits both husbandry and economics (Smith 1998; Durham 2006). Stressors affect many systems in animals (Dantzer and Morméde 1983), and of these heart rate (HR) is one of the easier physiological parameters to monitor in free-ranging animals. Values of 48–84 beats per minute (bpm) have been reported for dairy cattle (Dukes 1970; Aiello 1998) with peaks of 186 bpm recorded by Rometsch and Becker (1993) for Simmental cattle during exercise. The cues delivered with a DVF™ device do not appear to cause undue stress to HR based on data recorded on 27 June 2002 (Fig. 5) in which HR peaked at 94 bpm following the first audio plus electrical stimulation cue package ranked at a moderate level of irritation. Overall, this cow had a mean HR of 56 ± 7 bpm over ~8 h, preceding and following the 94-bpm spike. The animal's HR returned to its mean value in ~13 min after the initial cue. The 94 bpm spike was recorded at 0653 h from a Polar Accurex Plus® Heart Rate Monitor attached using a girth strap similar to the one described by (Hopster and Blokhuis 1994). A second spike >90 bpm was recorded about an hour later when the cow was being observed standing near drinking water in the complete absence of any DVF™ cuing. Quigley *et al.* (1990) reported steers resumed foraging in as few as 10 s following audio-electrical stimulation, suggesting this type of animal control was not producing noticeable stress. During numerous observations the author has likewise observed cattle that have received a cue package involving sound and electrical stimulation to return to foraging in less than one minute with no noticeable agitation, but the behaviour of foraging and its relationship to cuing stress has yet to be rigorously evaluated under free-ranging conditions.

Monitoring and management

From the earliest research into virtual fencing it has been realised that virtual fencing requires a higher level of stockmanship than other types of fencing (Browning and Moreton 1992), yet the greatest potential management advantage with virtual fencing will be the ability to change an animal's location on the landscape in real or near-real time. The information on which these kinds of decisions will be based most likely will come from remote sensed data gathered over large areas at a relatively low cost. Satellite technology will probably form the basis from which virtual fencing will be administered in the future and also provide the data required for monitoring (Rango *et al.* 2003). Research to determine standing crop quantity (Thoma *et al.* 2002) and quality is progressing (Tueller 2001). With virtual fencing, it will be possible to reduce the time lag between observing a condition on the landscape and moving animals to or away from the situation. Management options such as maintaining single drinking waters will help ensure animal groups remain together. This will foster more time efficient management and facilitate the use of virtual fencing.

The effect of poisonous plants on livestock production is an example. Nielsen and James (1992) estimate poisonous plants account for death and abortion in livestock in excess of $340 million annually in the 17 western states of USA. With optical techniques such as fluorometry (Anderson *et al.* 2006),

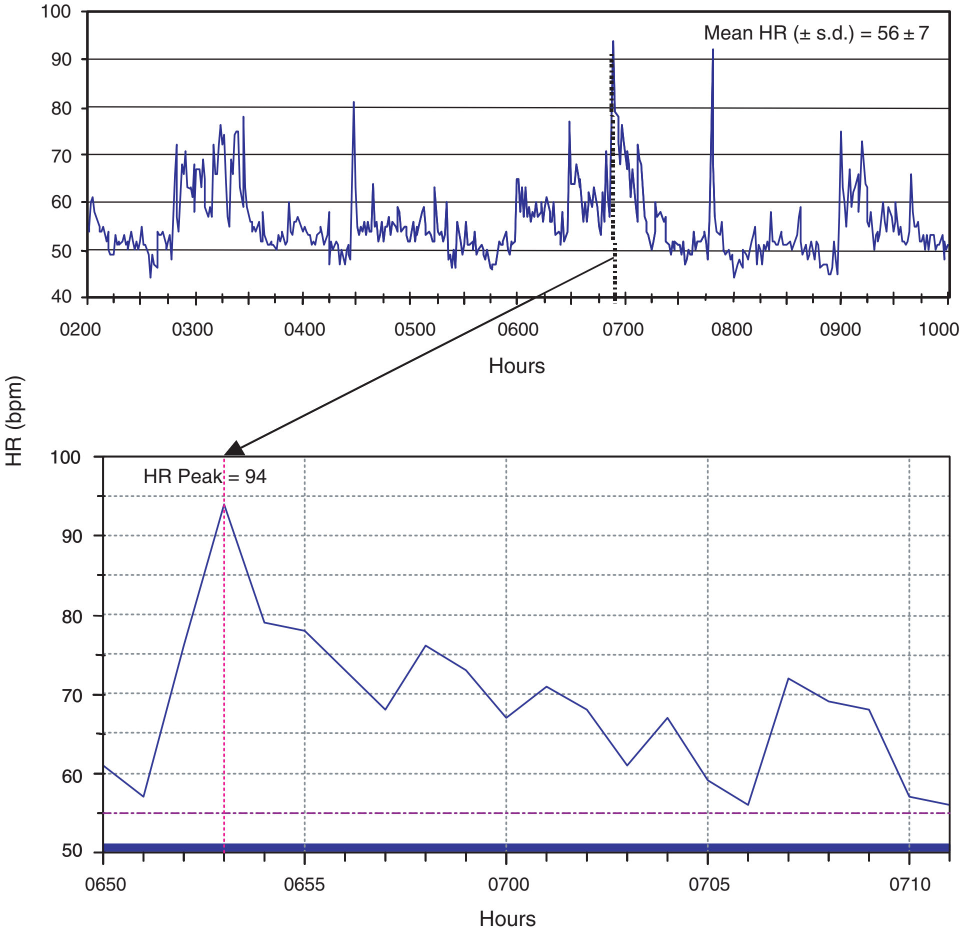

Fig. 5. Heart rate (HR) profile of an 8-year-old free-ranging cross-bred beef cow expressed in beats per minute (bpm) on 27 June 2002 between 0200 and 1000 h while being monitored with a Polar Accurex Plus® Heart Rate Monitor before, during and following an audio plus electric stimulation cue from a directional virtual fencing (DVF™) device delivered at 0653 h. The second spike in HR >90 bpm was not due to electromechanical cues as the animal was observed to be standing near drinking water during this time.

it is possible to identify different forages in a rapid manner. Therefore, within a few hours after determining what an animal has been eating it would be theoretically possible to move animals using virtual fencing. What remains to be investigated in considering this scenario is determining the optimum rate(s) at which animals can be moved across a landscape using virtual fencing.

DVF™ differs from conventional fencing in several aspects, the most important being formation of a corridor formed by the VB™ that delineates the foraging area from those areas excluded from foraging. The ecological value, if any, of the 'corridor' remains controversial (Anderson 2006). However, for DVF™ to have the greatest positive impact on free-ranging animal ecology it must be implemented in a proactive management system that considers all aspects of the ecosystem. By using trade marks with the terms associated with DVF™ (Anderson *et al*. 2004), it is hoped that who ever eventually licenses DVF™ will advocate ecosystem management with this method of animal control and that it will be done within a proactive management package designed to optimise husbandry as well as resource stewardship. Such a framework will embrace low-stress animal handling techniques (Smith 1998), together with monitoring of both animal (Jameson and Holechek 1987) as well as plant and soil components of the ecosystem (Herrick *et al*. 2005).

The next step(s)

As with all emerging methodologies, virtual fencing is fraught with challenges. Will control using virtual fencing require animal training? Browning and Moreton (1992) after observing several animal species controlled with virtual fencing suggests training is necessary. Yet current opinion and data principally from cattle are divided on this subject. However, if training is necessary what should it include? A dynamic training protocol currently has not been written. Furthermore, it is not known if 'refresher' training will periodically be required and if so what must it include and on what schedule will it be required for virtual fencing to remain a viable animal control tool? If virtual fencing is to surround individual animals in order to affect aggregation or dispersion of individuals than certainly every animal will have to be wearing electronic devices. However, if the goal is to control landscape utilisation with animal groups it may not be necessary to instrument all animals. In addition, deciding which animals and how many among a group should be instrumented for optimum control awaits investigation. Certainly the answer to these questions will differ among different topographies since line of sight affects animal behaviour. Preliminary research using virtual fencing in small groups of gregarious animals (Stricklin and Mench 1987) suggests, it may not be necessary for an entire group to be instrumented. However, virtual fencing studies involving large groups (probably 20–50 or more animals) will need to be evaluated in various ecosystems in order to accurately predict how many animals within a group will need to be instrumented with virtual fencing devices in order to realise acceptable levels of control.

Canadian research (Markus *et al*. 2000; Markus 2002) found that cows with functional fenceless control equipment (commercial dog training devices) did not enter an exclusion area, but herdmates without functional equipment readily entered the exclusion zone. However, it appears that in a group of animals wearing virtual fencing devices even if only a ‘few’ instruments fail to function control of the remaining herd may not be compromised (Browning and Moreton 1992; Tiedemann *et al*. 1999; Markus 2002).

The most efficient way to attain consistent control of groups may be to instrument leader animals. Herein lies another significant challenge – to determine how to identify leaders among foraging groups and determine if those leadership characteristics can be taught (learned) or are innate. Most probably, it is a combination of nurture and nature making several factors including prior experience, age, gender and breed important components of study. Because leadership changes with group size and structure (Albright and Arave 1997; Phillips 2002) such a test, though potentially challenging to develop, will be worthwhile and should be attempted.

No definitive studies currently exist on how virtual fencing may influence animal production. Though Tiedemann *et al.* (1999) found steers controlled using virtual fencing lost weight compared to the controls, yet they did not attribute this to the method of control, but rather to the training protocol they employed to prepare the steers for virtual fencing control.

Conclusion

Virtual fencing, when commercially available on a worldwide basis, will allow better stewardship of rangeland and tame pasture through proactive management that real-time decision makes possible. Even though it holds great positive potential for management, if incorrectly used virtual fencing can compress the effects of temporal and spatial mis-management resulting in the destruction of landscapes at a rate faster than using conventional fencing.

Because virtual fencing has the potential to elicit changes on the landscape in a rapid manner, virtual fencing should only be used in conjunction with proper soil and plant management practices. Monitoring (with feedback) linked to decision making involving soils, plants, and animals must be practiced rather than attempting to apply virtual fencing as just a management tool in a thoughtless and cavalier manner that may require less physical labour than conventional methods of animal control. Virtual fencing should free-up labour from the menial tasks of conventional animal control while increasing the intellectual demands of those charged with the responsibility of administering virtual fencing management.

Proof-of-concept that virtual fencing works to control herbivory has been established through the melding of many different disciplines. The following remain to be accomplished: (1) reducing the size and mass of the equipment platform and electronic hardware worn by the animals, (2) using the best source of power generation and storage, and (3) developing an optimum suite of sensory cues to elicit consistent behaviours that are humane, efficiently produced (low power requirement) and provide only a low-stress impact on the animal’s physiology. Ethologically, virtual fencing will require further research into understanding individual as well as group behaviours. Animals learn with every experience, therefore, the rate at which animals learn and retain the consequences of receiving sensory cues and the range of behaviours animals express when exposed to sensory stimuli must be better understood. Replicated studies involving large numbers of animals conducted in several different ecosystems are needed.

Ultimately, the properly-trained eye of a resource manager who understands the ecological implications and solutions to over-stocking as well as under-stocking should never be replaced by algorithms or electronics regardless of how sophisticated computer hardware and software may become.

Disclaimer

Mention of a trade name, proprietary product or vendor does not constitute a warranty of the product by the USDA or imply its approval to the exclusion of other products or vendors that may also be suitable.

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References

AALAS (American Association for Laboratory Animal Science) (2007). Institutional Animal Care and Use Committee (IACUC). Available at: www.iacuc.org/aboutus.htm (accessed 20 February 2007).

Aiello, S. E. (1998). ‘The Merck veterinary manual.’ 8th edn. (Merck and Co, Inc.: Whitehouse Station, NJ.)

Albright, J. L., and Arave, C. W. (1997). ‘The behaviour of cattle.’ (CAB International: Wallingford, UK.)

Anderson, D. M. (1998). Pro-active livestock management – capitalizing on animal behavior. *Journal of Arid Land Studies* **7S**, 113–116.

Anderson, D. M. (2001). Virtual fencing – a prescription range animal management tool for the 21st century. *In*: ‘Proceedings of the conference tracking animals with GPS’. (Eds A. M. Sibbald and I. J. Gordon.) pp. 85–94. (Macaulay Land Use Research Institute: Aberdeen.)

Anderson, D. M. (2005). Ear-A-Round equipment platform for animals. Application No. 60/754, 409 (Patent application filed for in U.S. Patent and Trademark Office).

Anderson, D. M. (2006). Virtual fencing – a concept into reality. *In*: ‘Proceedings of the Spatial Grazing Behavior Workshop’. (Ed. G. J. Bishop-Hurley.) pp. 61–91. (J. M. Rendel Laboratory: Rockhampton, QLD.)

Anderson, D. M., and Weeks, D. L. (1989). Cattle liveweight sampled on a continuous vs. intermittent basis. *Livestock Production Science* **23**, 117–135. doi: 10.1016/0301-6226(89)90010-9

Anderson, D. M., and Hale, C. S. inventors; The United States of America as represented by the Secretary of Agriculture, assignee. (2001). Animal control system using global positioning and instrumental animal conditioning. U.S. patent 6 232 880. May 15. 18 p. Int. C1^7 G08B 23/00.

Anderson, D. M., Hale, C. S., Libeau, R., and Nolen, B. (2003). Managing stocking density in real time. *In*: ‘Proceedings of the VIIth International Rangeland Congress’. Durban, South Africa. (Eds H. Allsopp, A. R. Palmer, S. J. Milton, K. P. Kirkman, G. I. H. Kerley, C. R. Hurt and C. J. Brown.) pp. 840–843. (Grassland Society of Southern Africa: Grahamstown.)

Anderson, D. M., Hulet, C. V., Shupe, W. L., Smith, J. N., and Murray, L. W. (1988). Response of bonded and non-bonded sheep to the approach of a trained border collie. *Applied Animal Behaviour Science* **21**, 251–257. doi: 10.1016/0168-1591(88)90114-1

Anderson, D. M., Nolen, B., Fredrickson, E., Havstad, K., Hale, C., and Nayak, P. (2004). Representing spatially explicit directional virtual fencing (DVF$^{\mathrm{TM}}$) data. [CD-ROM]. *In*: ‘Proceedings of the 24th Annual ESRI International User Conference’. (ESRI: San Diego, CA.)

Anderson, D. M., Rayson, G. D., Obeidat, S. M., Ralphs, M., Estell, R., Fredrickson, E. L., Parker, E., and Gray, P. (2006). Use of fluorometry to differentiate among clipped species in the genera, *Astragalus*, *Oxytropis* and *Pleuraphis*. *Rangeland Ecology and Management* **59**, 557–563. doi: 10.2111/05-212R1.1

Anonymous (2006). China wants one of its very own. *GPS World* **17**, 14–18.

Austin, J. E., and Pietz, P. J. (1997). Forum on wildlife telemetry. *In*: ‘The Wildlife Society and Biological Resources Division’. (Chairpersons J. E. Austin and P. J. Pietz.) pp. 1–82. (US Geological Survey: Snowmass Village, CO.)

Bailey, D. W. (2004). Management strategies for optimal grazing distribution and use of arid rangelands. *Journal of Animal Science* **82**, E147–E153

Bailey, D. W. (2005). Identification and creation of optimum habitat conditions for livestock. *Rangeland Ecology and Management* **58**, 109–118. doi: 10.2111/03-147.1

Bailey, D. W., Gross, J. E., Laca, E. A., Rittenhouse, L. R., Coughenour, M. B., Swift, D. M., and Sims, P. L. (1996). Mechanisms that result in large herbivore grazing distribution patterns. *Journal of Range Management* **49**, 386–400.

Bailey, D. W., Kress, D. D., Anderson, D. C., Boss, D. L., and Miller, E. T. (2001). Relationship between terrain use and performance of beef cows grazing foothill rangeland. *Journal of Animal Science* **79**, 1883–1891.

Beh-Shahar, R. (1993). Does fencing reduce the carrying capacity for populations of large herbivores? *Journal of Tropical Ecology* **9**, 249–253.

Berry, W. (2005). Renewing husbandry after mechanization, can modern agriculture reclaim its soul? *Orion* September/October, 40–47.

Bishop-Hurley, G. J., Swain, D. L., Anderson, D. M., Sikka, P., Crossman, C., and Corke, P. (2007). Virtual fencing applications: implementing and testing an automated cattle control system. *Computers and Electronics in Agriculture* **56**, 14–22.

Boone, R. B., and Hobbs, N. T. (2004). Lines around fragments: effects of fencing on large herbivores. *African Journal of Range and Forage Science* **21**, 147–158.

Browning, P. and Moreton, H. (1992). ‘Stock control on conservation land final report to English Nature and The Countryside Commission.’ (Centre for Rural Studies, Royal Agricultural College: Cirencester.)

Brudecki, C. (2004). ‘The facts about modern electronic training devices.’ (Radio Systems Corporation: Knoxville.)

Butler, Z., Corke, P., Peterson, R., and Rus, D. (2004). Virtual fences for controlling cows. *In*: ‘Proceedings on the 2004 IEEE international conference on robotics and automation’. pp. 4429–4436. (IEEE: New Orleans.)

Butler, Z., Corke, P., Peterson, R., and Rus, D. (2006). From robots to animals: virtual fences for controlling cows. *International Journal of Robotics Research* **25**, 485–508. doi: 10.1177/0278364906065375

Clark, P. E., Johnson, D. E., Kniep, M. A., Jermann, P., Huttash, B., Wood, A., Johnson, M., McGillivan, C., and Titus, K. (2006). An advanced, low-cost, GPS-based animal tracking system. *Rangeland Ecology and Management* **59**, 334–340. doi: 10.2111/05-162R.1

Comis, D. (2000). The cyber cow whisperer and his virtual fence. *Agricultural Research* **48**, 4–7.

Coughenour, M. B. (1991). Spatial components of plant-herbivore interactions in pastoral, ranching, and native ungulate ecosystems. *Journal of Range Management* **44**, 530–542.

Crowther, M. E. (2006). ‘Report of trial of invisible fence collars and a small herd of one bull and four cows.’ (Cranham Common Committee invisible fencing trials: Cranham Common, Cranham, Gloucestershire, UK.)

Dantzer, R., and Morméde, P. (1983). Stress in farm animals: a need for reevaluation. *Journal of Animal Science* **57**, 6–18.

DelCurto, T., Porath, M., Parsons, C. T., and Morrison, J. A. (2005). Management strategies for sustainable beef cattle grazing on forested rangelands in the Pacific Northwest. *Rangeland Ecology and Management* **58**, 119–127. doi: 10.2111/1551-5028(2005)58<119:MSFSBC>2.0.CO;2

D’eon, R., and Departe, D. (2005). Effects of radio-collar position and orientation on GPS radio-collar performance, and the implications of PDOP in data screening. *Journal of Applied Ecology* **42**, 383–388. doi: 10.1111/j.1365-2664.2005.01010.x

van Diggelen, F. (2007). GNSS accuracy: lies, damn lies, and statistics. *GPS World* **18**, 26–32.

Divis, D. A. (2000). Capitol outlook SA no more GPS accuracy increases 10 fold. *Geospatial Solutions* **10**, 18–20.

Dukes, H. H. (1970). ‘The physiology of domestic animals.’ 8th edn. (Comstock Publishing Co.: Ithaca, NY.)

Durham, S. (2006). Relaxed management improves cattle disposition. *Agricultural Research* **54**, 22.

Enge, P. (2004). Retooling the global positioning system. *Scientific American* **290**, 90–97.

Fay, P. K., McElligott, V. T., and Havstad, K. M. (1989). Containment of free-ranging goats using pulsed-radio-wave activated shock collars. *Applied Animal Behaviour Science* **23**, 165–171. doi: 10.1016/0168-1591(89)90016-6

Files, J. C. inventor; Files, J. C., assignee. (1999). Animal training and tracking device having global positioning satellite unit. U.S. Patent 5 857 433. Jan 12. 10 p. Int Cl^6 A01K 15/02.

Fraser, A. F. (1985). Body care. *In*: ‘World animal science basic information’. (Ed. A. F. Fraser.) pp. 215–231. (Elsevier: Amsterdam, The Netherlands.)

Ganskopp, D., and Bohnert, D. (2006). Do pasture-scale nutritional patterns affect cattle distribution on rangelands? *Rangeland Ecology and Management* **59**, 189–196. doi: 10.2111/04-152R1.1

Hein, G. W., Ávila-Rodŕiguez, J. A., Wallner, S., Eissfeller, B., Pany, T., and Hartl, P. (2007). Envisioning a future GNSS system of systems, part 1. *Inside GNSS* **2**, 58–67.

Herrick, J. E., Van Zee, J. W., Havstad, K. M., Burkett, L. M., and Whitford, W. G. (2005). ‘Monitoring manual for grassland, shrubland and savanna ecosystems. Vol. II: Design, supplementary methods and interpretation.’ (University of Arizona Press: Tucson.)

Herring, T. A. (1996). The global positioning system. *Scientific American* **274**, 44–50.

Hopster, H., and Blokhuis, H. J. (1994). Validation of a heart-rate monitor for measuring a stress response in dairy cows. *Canadian Journal of Animal Science* **74**, 465–474.

Horn, F. P. (1981). Direct measurement of voluntary intake of grazing livestock by telemetry. *In*: 'Forage evaluation concepts and techniques'. (Eds J. L. Wheeler and R. D. Mochrie.) pp. 367–372. (Giffin Press Ltd.: Netley.)

Hulbert, I. A. R., and French, J. (2001). The accuracy of GPS for wildlife telemetry and habitat mapping. *Journal of Applied Ecology* **38**, 869–878. doi: 10.1046/j.1365-2664.2001.00624.x

Hulbert, I. A. R., Wyllie, J. T. B., Waterhouse, A., French, J., and McNulty, D. (1998). A note on the circadian rhythm and feeding behavior of sheep fitted with a lightweight GPS collar. *Applied Animal Behaviour Science* **60**, 359–364. doi: 10.1016/S0168-1591(98)00155-5

Hurn, J. (1993). GPS a guide to the next utility. Trimble Navigation. Pt. No. 16778.

Hurn, J. (1995). Differential GPS explained. Trimble Navigation. Pt. No. 23036.

Ishmael, W. (2006). Gotcha, biometric livestock ID leaves no place to hide. *Beef* **43**, 28–30.

Jameson, D. A., and Holechek, J. (1987). Monitoring animal performance and production. *In*: 'Symposium Proceedings, Society for Range Management'. Boise, ID. (Society for Range Management: Denver.)

Kaplan, E. D., and Hegarty, C. J. (2005). 'Understanding GPS: principles and applications.' 2nd edn. (Artech House Publishers: Boston.)

Karsky, D. (2004). 'Comparing four methods of correcting GPS data: DGPS, WAAS, L-band, and postprocessing. Tech Tip 0471-2307-MTDC.' Missoula, MT. (U.S. Department of Agriculture, Forest Service: Missoula Technology and Development Center.)

Kearney, W., and Buys, J. (2007). Virtual fencing. Available at: www.geoft.co.za/home.htm (accessed 20 February 2007).

Le, B. Q., Lew, A. L., Schwarts, P. D., Sadilek, A. C., Suter, J. J., Jenkins, J. E., and Ling, S. X. inventors; The John Hopkins University, assignee. (2001). Rechargeable shoe. U.S. patent 6 255 799. July 3. 8 p. Int. Cl^7 H02J 7/00; H02K 5/00; A43B 7/02.

Lee, C., Prayaga, K., Reed, M., and Henshall, J. (2007). Methods of training cattle to avoid a location using electrical cues. *Applied Animal Behaviour Science* **69**, (In press).

Lund, G. H. (2007). Accounting for the world's rangelands. *Rangelands* **29**, 3–10. doi: 10.2111/1551-501X(2007)29[3:AFTWR]2.0.CO;2

Manning, C. D. H. inventor; Trimble navigation, assignee. (1998). Position and physiological data monitoring and control system for animal herding. U.S. Patent 5 791 294. August 11. 18 p. Int Cl^6 A01K 3/00.

Markus, S. (2002). Development of a fenceless livestock control system: behavioral responses of cattle. PhD thesis, University of Alberta, Edmondton, Canada.

Markus, S., Bailey, D. W., Jensen, D., and Price, M. (1998*a*). Preliminary evaluation of a fenceless livestock control system. *Journal of Animal Science* **76**, 103. [Abstract]

Markus, S., Jensen, D., Bailey, W., and Price, M. (1998*b*). Effect of location and intensity of electrical shock on cattle movements. *Journal of Animal Science* **76**, 97. [Abstract]

Markus, S., Bailey, W., and Price, M. (2000). Evaluation of a simulated fenceless livestock control system. *Journal of Animal Science* **78**, 228. [Abstract].

Marsh B. (2006). 'Virtual fencing.' Available at: www.agritechelec.com (accessed 20 February 2007).

Marsh, R. E. inventor; AgriTech Electronics L. C., assignee. (1999). Fenceless animal control system using GPS location information. U.S. patent 5 868 100. Feb 9. 9 p. Int Cl^6 A01K 15/02; G08B 23/00.

Mayer, R., and Olsen, T. (2005). 'Estimated costs for livestock fencing.' (Iowa State University Extension Publication, Economics: Ames, IA.)

Mech, D. L., and Barber, S. M. (2002). A critique of wildlife radio-tracking and its use in national parks: a report to the U.S. National Park Service. Publication 1164. U.S. Geological Survey, Northern Prairie Wildlife Research Center, Jamestown.

Moen, R. A., Pastor, J., and Cohen, Y. (1997). Accuracy of GPS telemetry collar locations with differential correction. *Journal of Wildlife Management* **61**, 530–539. doi: 10.2307/3802612

Nielsen, D. B., and James, L. F. (1992). The economic impacts of livestock poisonings by plants. *In*: 'Poisonous plants. Proceedings of the 3rd International Symposium'. Logan, UT. (Eds L. F. James, R. F. Keeler, E. M. Bailey, Jr., P. R. Cheeke and M. P. Hegarty.) pp. 3–10. (Iowa State University Press: Ames.)

Oh, K. R., Kim, J. C., and Nam, G. W. (2005). Development of navigation algorithm to improve position accuracy by using multi-DGPS reference stations' PRD information. *Journal of Global Positioning Systems* **4**, 144–150.

Palmer, D., James, G., and Corke, P. (2004). ElectricCow: a simulator for mobile sensors and actuators mounted on herds of cattle. *In*: 'LCN 2004: 29th Annual IEEE International Conference on Local Computer Networks. Proceedings First IEEE Workshop on Eembedded Networked Sensors'. Tampa, Florida. pp. 556–557. (IEEE Computer Society: Los Alamitos, CA.)

Peck, R. M. (1973). Method and apparatus for controlling an animal. U.S. patent 3 753 421. Aug. 21. 6p. Int. Cl A01k 15/00.

Petrusevics, P. E., and Davisson, T. W. (1975). A biotelemetry system for cattle behaviour studies. *Proceedings of the IREE* **36**, 72–76.

Phillips, C. (2002). 'Cattle behaviour and welfare.' 2nd edn. (Blackwell Science Ltd.: Osney Mead, UK.)

Pinchak, W. E., Smith, M. A., Hart, R. H., and Waggoner, J. W. Jr (1991). Beef cattle distribution patterns on foothill range. *Journal of Range Management* **44**, 267–275.

Pope, J. (2007). 'Ultralife batteries.' Available at: www.ultralifebatteries.com/ (accessed 20 February 2007).

Quigley, T. M., Sanderson, H. R., Tiedemann, A. R., and McInnis, M. L. (1990). Livestock control with electrical and audio stimulation. *Rangelands* **12**, 152–155.

Rango, A., Anderson, D. M., Hale, C. S., and Havstad, K. M. (2003). A developing method for directional virtual fencing (DVF^{TM}) and real time range management using remote sensing, GIS and GPS. *In*: 'Proceedings of the 30th International Symposium on Remote Sensing of Environment'. Honolulu, Hawaii. pp. 419–422. (International Center for Remote Sensing of Environment: Tuscon.)

Roath, L. R., and Krueger, W. C. (1982). Cattle grazing and behavior on a forested range. *Journal of Range Management* **35**, 332–338.

Roberts, G., Williams, A., Last, J. D., Penning, P. D., and Rutter, S. M. (1995). A low-power post processed DGPS system for logging the locations of sheep on hill pastures. *Navigation* **42**, 327–336.

Rodgers, A. R., and Lawson, E. J. G. (1997). Field trials of the Lotek GPS collar on moose. *In*: 'The Wildlife Society and Biological Resources Division'. (Chairpersons J. E. Austin and P. J. Pietz.) pp. 58. (U.S. Geological Survey: Snowmass Village.)

Rometsch, M., and Becker, K. (1993). Determination of the reaction of heart rate of oxen to draught work with a portable data-acquisition system. *Journal of Agricultural Engineering Research* **54**, 29–36. doi: 10.1006/jaer.1993.1002

Rose, A. F. (1991). An alternative to fences. *Rangelands* **13**, 144–145.

Rouda R. R. (1999). Virtual fencing – grazing animal control for the 21st century; feasibility of developing alternative cattle control devices. Bulletin 4366, 34 pp. (Department of Agriculture Western Australia: Bunbury, WA.)

Rouda, R. R. (2003). Virtual fencing for maximum environmental protection and grazing animal production. *In*: 'Paper presented at the national environment conference'. (Environmental Engineering Society: Brisbane, QLD.)

Rouda, R. R., Lake, R. J. W., and Moore, J. C. inventors; Chief executive officer of the department of agriculture. The land and water resources research and development corporation, secretary, department of environment and heritage, assignee. (2000). Apparatus and method for controlling animal movement. International Application Number PCT/AU00/00247, March 25, 66 p. International Publication No. WO 00/57692.

Rutter, S. M., Beresford, N. A., and Roberts, G. (1997). Use of GPS to identify the grazing areas of hill sheep. *Computers and Electronics in Agriculture* **17**, 177–188. doi: 10.1016/S0168-1699(96)01303-8

Salmon, J. L. (2000). Some fences come without walls. Washington Post article reprinted in *Southwest Home Sun News*, December 31, p. 1, 9.

Schmitt, D., and Schell, J. inventors; Agric.-Tech Electronics LC, assignee. (2005). Animal control apparatus with ultrasonic link. U.S. patent 6 956 483. October 18. 16 p. Int. Cl^7 G0B 23/00.

Schlecht, E., Hulsenbusch, C., Mahler, F., and Becker, K. (2004). The use of differentially corrected global positioning system to monitor activities of cattle at pasture. *Applied Animal Behaviour Science* **85**, 185–202. doi: 10.1016/j.applanim.2003.11.003

Schwager, M., Anderson, D. M., Butler, Z., and Rus, D. (2007). Robust classification of animal tracking data. *Computers and Electronics in Agriculture* **56**, 46–59.

Simmons, C. W. (1935). Fences, gates and cattle guards. *The Cattleman* **22**, 32.

Smith, B. (1998). 'Moving 'em – a guide to low stress animal handling.' (The Graziers: Hui, Kamela.)

Stricklin, W. R., and Mench, J. A. (1987). Social organization. *Veterinary Clinics of North America. Food Animal Practice* **3**, 307–322.

Stricklin, W. R., and Mench, J. A. (1990). Stress and stressors in rangeland domestic ruminants with emphasis on behavioral stressors. *In*: 'Stress and the free-ranging animal'. Regional Research Report 646. (Eds D. M. Anderson, K. M. Havstad and F. C. Hinds.) pp. 1–14. (New Mexico Agricultural Experiment Station: Las Cruces.)

Strümpler, R., and Glatz-Reichenbach, J. (1999). Conducting polymer composites. *Journal of Electroceramics* **3**, 329–346. doi: 10.1023/A:1009909812823

Talwar, S. K., Xu, S., Hawley, E. S., Weiss, S. A., Moxon, K. A., and Chapin, J. K. (2002). Rat navigation guided by remote control. *Nature* **417**, 37–38. doi: 10.1038/417037a

Thoma, D. P., Bailey, D. W., Long, D. S., Nielsen, G. A., Henry, M. P., Breneman, M. C., and Montagne, C. (2002). Short-term monitoring of rangeland forage conditions with AVHRR imagery. *Journal of Range Management* **55**, 383–389.

Thoms, J. (2004). The modern remote-training collar – this is not your father's 'shock collar'. *Gun Dog Magazine* June/July, 56–61.

Tiedemann, A. R., Quigley, T. M., White, L. D., Lauritzen, W. S., Thomas, J. W., and McInnis, M. L. (1999). Electronic (fenceless) control of livestock. U.S. Department of Agriculture Forest Service Pacific Northwest Research Station PNW-RP-510.

Tomkiewicz, S. M. Jr. (1997). Advancements in the use of GPS technology in obtaining position information from free-ranging wildlife. *In*: 'The Wildlife Society and Biological Resources Division'. (Chairpersons J. E. Austin and P. J. Pietz.) p. 70. (U.S. Geological Survey: Snowmass Village.)

Tueller, P. T. (2001). Remote sensing of range production and utilization. *Journal of Range Management* **54**, A77–A89.

Turner, L. W., Udal, M. C., Larson, B. T., and Shearer, S. A. (2000). Monitoring cattle behavior and pasture use with GPS and GIS. *Canadian Journal of Animal Science* **80**, 405–413.

Udal, M. C., Turner, L. W., Larson, B. L., and Shearer, S. A. (1998). GPS tracking of cattle on pasture. *In*: 'Presented at the July 1998 American Society of Agricultural Engineers Meeting'. Paper No. 983134. (ASAE: St. Joseph, MI.)

Udal, M. C., Turner, L. W., Larson, B. T., Driedger, L. J., and Shearer, S. A. (1999). Grazing time and assessment for beef cows on pasture using GPS. *Journal of Animal Science* **77**, 203. [Abstract].

Ungar, E. D., Henkin, Z., Gutman, M., Dolev, A., Geniai, A., and Ganskopp, D. (2005). Inference of animal activity from GPS collar data on free-ranging cattle. *Rangeland Ecology and Management* **58**, 256–266. doi: 10.2111/1551-5028(2005)58[256:IOAAFG]2.0.CO;2

USDI-USGS (United States Department of Interior – United States Geological Survey) (2006). Geographic information systems. Available at: http://erg.usgs.gov/isb/pubs/gis_poster/ (accessed 20 February 2007).

Wang, N., Zhang, N., and Wang, M. (2006). Wireless sensors in agriculture and food industry – recent development and future perspectives. *Computers and Electronics in Agriculture* **50**, 1–14. doi: 10.1016/j.compag.2005.09.003

Xu, S., Talwar, S. K., Hawley, E. S., Li, L., and Chapin, J. K. (2004). A multi-channel telemetry system for brain micro stimulation in freely roaming animals. *Journal of Neuroscience Methods* **133**, 57–63. doi: 10.1016/j.jneumeth.2003.09.012

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