Cattle responses to a type of virtual fence

Umstatter, C; Morgan-Davies, J; Waterhouse, A

Published in:
Rangeland Ecology & Management

DOI:
10.1016/j.rama.2014.12.004

First published: 01/01/2015

Document Version
Peer reviewed version

Cattle Responses to a Type of Virtual Fence

Christina Umstatter, Justin Morgan-Davies and Tony Waterhouse

---

Scotland's Rural College (SRUC), West Mains Road, Edinburgh, EH9 3JG, Scotland, UK

Correspondence: Christina Umstatter, Agroscope ISS, Tänikon 1, CH-8356 Ettenhausen, Switzerland. Email: christina.umstaetter@agroscope.admin.ch

SRUC receives financial support from the Rural and Environment Science and Analytical Services Division of Scottish Government.

Mention of a proprietary product does not constitute a guarantee or warranty of the product by SRUC or the authors and does not imply its approval to the exclusion of the other products that also may be suitable.

ABSTRACT

Interest in developing more flexible fencing technology to improve pasture and rangeland management is increasing. The objective of this study was to test the efficacy of a new virtual fencing product and measure impact on behaviour thus potentially allowing positive development of virtual fence systems. The Boviguard® (Agrifence, Henderson Products Ltd., Gloucester, UK) invisible fence is now commercially available, consisting of cow collars, a battery-based transformer and an induction cable laid on the ground or buried in the ground. As the Boviguard® collar comes close to the induction cable, a warning sound is triggered and if the animal continues to move closer, an electrical stimulus is triggered. We tested this novel system on 10 cows wearing GPS collars to pinpoint location and activity sensors to gather behavioural data. Two separate exclusion zones were created consecutively in different areas of a test field, with alternate periods of control, with no fence activity, and virtual fence activation. The system successfully prevented the animals from crossing the virtual fence line. No changes in general activity or lying behaviour were found. There were significant changes in the pattern of use of the rest of the field area when the fencing system was activated. When only the un-activated cable was left on the ground in a final control period, the visual cue alone deterred animals from entering the exclusion area. The trial showed the effectiveness of a collar-based electrical stimuli system. This approach to virtual fencing could provide solutions for management systems were moving fences frequently is required, such as for strip grazing; for nature conservation management of specific areas and habitats and for graziers of land where physical fences are not preferred or feasible.

KEY WORDS

animal behaviour, Boviguard, GPS, Invisible Fence, cattle distribution, grazing

INTRODUCTION

Grazing lands cover 32 million km^2, approximately 25% of the earth's land surface (Reid et al. 2004) and play a vital role in many agricultural systems. Optimising pasture management and increasing the output from existing grasslands requires significant resources in terms of costs and labour. Over the past two centuries, the development of fencing systems has been a revolution in the management of livestock, as it has allowed the stockperson to control the location of the animals. It is crucial for successful livestock management to have the capacity and capability to retain animals within areas and exclude them from others. However, for extensive systems it is not always feasible or cost effective to build fences in some areas. In addition, a more flexible approach to grazing management could lead to improved utilisation of biomass, such as by better exploitation of seasonal growth, or aid nature conservation and re-establishment of biodiversity habitats through temporary or permanent exclusion of livestock to certain areas. The development of virtual fences has been ongoing over recent decades. A very early approach was the so called 'Invisible Fence', filed as a patent by Peck in 1971 (Peck 1973). The system was originally developed mainly for cats and dogs. Fay et al. (1989) tested the 'Invisible Fence' system on goats and a similar approach was later tested on cattle (Monod et al. 2009). Based on that patent, the Boviguard® system (marketed as registered brand in the UK as Boviguard® Invisible Cattle Fence, Agrifence, Henderson Products Ltd., Gloucester, UK) was developed as a new commercial system for cattle that consists of cow collars and a transformer connected to an induction cable that represents the fence line. The system works through an electromagnetic coupling between the collar and the induction cable. As the Boviguard® collar comes close to the induction cable, a warning sound is triggered and if the animal continues to approach the cable, an electric stimulus is triggered in the collar. Monod et al. (2009) provides a detailed description of the technological design.

The aim of this study was to investigate behavioural responses of animals to the novel Boviguard® system, specifically, if they respected the exclusion area and if any strong behavioural changes were detected which might compromise their welfare. Detailed animal behavioural investigation of this system, using GPS tracking and activity sensors to monitor cattle responses had not been carried out previously, thus the resulting information would be novel and critically important to further developments in virtual fencing.

METHODS

Animals and Location

Ten adult, female, non-lactating cows, in a mixed herd consisting of eight Aberdeen Angus x Limousin and two Charolais were used in this study. During the period of the trial (17 October 2011 – 08 November 2011) all cows were maintained in a field consisting of improved pasture and measuring 7.88 ha. All ten animals were fitted (Fig. 1) with the Boviguard® collars, separate GPS (Global Positioning System) collars (AgTrex, BlueSky Telemetry, Aberfeldy, Scotland, UK) and leg-mounted activity sensors (IceTags, IceRobotics, Edinburgh, Scotland, UK). Cows were maintained in the field for an initial adaptation stage of seven days before the trial started to acclimatise to the location and equipment fitted to them. Some visual animal observations were carried out during the adaptation period in order to confirm the absence of adverse reactions to the fence when switched on.

Technology

The Boviguard ® system comprised a series of battery powered receivers attached to leather collars worn by each cow and an induction cable connected to a transformer and 12-volt car battery that provided a low power electromagnetic field. The Boviguard® collars weighed 1450 gr with the receiver housing having dimensions of 150 x 70 x 90 mm. The induction cable was fully sealed, flexible and could be laid on the ground, suspended or buried. In this case, the colour of the cable was blue. A magnetic field was emitted by the cable when powered. In this study, the system was tested with the cable laid on the ground (Fig. 1, inset) forming a boundary around the exclosures (Fig. 2) since it was important to be able to move the cable during the experiment. The technological principle of the system was that if a Boviguard® collar came within a certain distance (depending on the signal strength of the induction cable), the cable’s signal would trigger a warning sound to be emitted from the collar. If the animal continued to approach the cable, an electrical stimulus would be triggered. The electrodes were integrated into the collar in the form of braided wiring in contact with the animal. The distances between the collar and cable required to trigger a warning cue were tested for each collar. All 10 collars showed different triggering distances ranging from 15.2 to 57.2 cm with an average of 36 cm.

In order to accumulate information about the animal responses to the Boviguard® fence, we deployed GPS collars attached to the neck and activity sensors attached to the left hind leg of each cow. The GPS collars were switched on between 20 October and 08 November 2011, inclusively. The GPS collars recorded a usable locational reading every 4.5 min. The collars were originally set to log data every 5 min but due to the specific software the sampling actually took place every 4.5 min. The decision not to log GPS fixes (recordings of cow locations) more frequently was due to energy restrictions imposed by the battery power source. The GPS fixes obtained were not differentially corrected for locational error. The activity sensors operate on integrated accelerometers, with output including step counts, a motion index and the duration of lying bouts. The motion index is a parameter that combines the data of the three accelerometers and, therefore, gives an indication of the degree of movement in three dimensions (no units available). The detailed algorithm of how the three data streams of the accelerometers were combined was not available from the manufacturer. Data from cattle using this equipment and collecting motion index data has been evaluated and reported by Tolkamp et al. (2010). The data were analysed based on 1-min intervals. All cows were fitted with a GPS collar, however, only nine of the animals were fitted with activity sensors as one Angus x Limousin cow proved too aggressive when attempting to attach the sensor and thus was not included in that part of the data collection. In addition, one of the activity sensors and two GPS collars developed technical problems and discontinued working.

Experimental Design

The experiment was divided into five sequential periods (Table 1) after the initial adaptation stage, when the cows became acclimatised to the field and the wearing of the collars and activity sensors.

In the first control period (C1) of three days, cows had full baseline access to the whole area of the field. This was a period when the cattle could show their natural behavioural use of the field. This was followed by the next period, the first Treatment period (T1) when the Invisible Fence induction cable was laid out (as shown in Figure 2) and the unit was power activated, with the cattle having no previous experience of the warning or electrical stimuli. Control period 2 (C2) followed with complete removal of the induction cable to measure any residual effects of the first test period, and to provide a new baseline period, prior to a new rectangular exclosure of Invisible Fence area being installed in Treatment period T2. This was a novel area adjacent, but different to, the exclosure area in T1. This phase was aimed to understand how the cattle behaved in a second period of full use of the Invisible Fence. The last control period (C3) was a period with no power, and thus, no warning or electrical stimuli, but with the visible induction cable remaining laid out. The objective of this period was to identify how cattle responded to residual visual cues.

Data Analysis

Eight GPS collars and eight activity sensors recorded full sets of data throughout the trial with no missing periods or loss of signal from the satellites to the GPS collars. The activity data were analysed with Genstat Version 14 (VSNi 2011), while the GPS locations, used for cow distribution mappings were analysed within ArcGIS 9.3 (ESRI 2008).

GPS location readings of the virtual fence line (location of the induction cable) were taken and plotted within the GIS (Geographic Information System). Then, a polyline boundary was hand digitised through the collected GPS locations forming an enclosed polygon for both treatment exclosures (Fig. 2). Buffer zones at 5 m and 10 m away from the polyline on the outside and inside of each exclosure were calculated since the GPS collar fixes (and multiple GPS fixes to position the fence polyline within the GIS) were both known to have a likely +/-5m margin of locational error. The GPS fixes along with time stamps for each cow could then be inputted to the GIS, allowing for analysis of distribution about the field according to time, as well as position relative to the fence line. To achieve this, the distance of each fix to the nearest edge on the boundary polyline was calculated out to a maximum distance away from the exclosure boundary of 80 m. The distance measurements were then exported from the GIS into Microsoft Excel for further analysis. Considering the large number of GPS fixes obtained, the distribution of distance measurements for each collar were grouped into 5 m frequency intervals (‘bins’) within Microsoft Excel, allowing for graphical plots of the distribution of each cow during the trial periods to be created (Fig. 3).

For analysis purposes, the field was divided into notional north and south section, creating digitised polygons that would allow for the comparison of cow location and presence within the two sections (Fig. 2). This notional boundary was not fenced. The parameter ‘section’ could then be combined with a day-or-night parameter offering more detailed behavioural analysis of the cows. The ‘day’ time period was set as the time between 7 am and 7 pm and ‘night’, therefore, was the remaining period of the 24 h clock. The time points were set according to the analysed activity of the cows (Fig. 4) and were corresponding with nautical twilight during that time of year.

The field was only very slightly undulating and had an easterly aspect. There were trees and shelter outside the western boundary and a public road along the eastern boundary and no other cattle were in adjacent fields.

Statistical Analysis

A Generalized Linear Mixed Model (GLMM) was run with Genstat 14 for the locational data focussing on the number of fixes in the north and south sections of the field. A binomial distribution was chosen and the link function ‘logit’ was set. The model included the fixed effects: treatment, day_or_night and day_within_treatment. The collar ID was included as a random effect. The parameters treatment, day_or_night and collar ID were set as factors, whereas, the parameter day_within_treatment was set as a variate.

The time the cows were in lying bouts were calculated from the sensor data as part of the routine output from the activity sensor software package (IceManager 2010, IceRobotics, Edinburgh, Scotland, UK). However, the presence of a high number of extremely short lying bouts (too short for a cow to lie down and get up again) were identified, and dealt with according to the recommendations of Tolkamp et al. (2010); that is, the inclusion of lying bouts > 4 min only. For the data analysis dealing with the duration of lying bouts, a GLMM with a normal distribution and the link function ‘identity’ was chosen. The response variate was the duration of lying bouts recorded in minutes with the fixed model, including the parameters: treatment, hour_of_day and day_within_treatment. The animal identification code was included in the random model as a random effect.

For the analysis of the Motion Index, a Linear Mixed Model was chosen. The response variate was the log transformed Motion Index with the fixed model, including the parameters: treatment, hour_of_day and date. The animal identification code was included in the random model as a random effect.

RESULTS

The GPS locations in Control period 1 (C1) demonstrated that the cows used the complete area of the field, including the areas marked as exclosures for the subsequent treatment periods (Fig. 5 a, Table 2). By contrast, during the two treatment periods (T1 and T2) the number of recorded GPS fixes within the exclusion areas minus the 10 m inside exclusion area boundary (5 m error of locational cow data plus 5 m error for the GPS fence recording) decreased dramatically (with only one fix recorded during Treatment 1 and one fix recorded during Treatment 2; Fig. 5 b). Fewer GPS fixes in total were recorded during Control period 3 compared to Control period 2 due to only testing that period for two full days rather than three days. The number of GPS recorded locations within the exclusion areas (27 and 19 fixes respectively) during Treatments 1 and 2 remained very low compared to the previous control periods (Table 2). The GPS data further indicated that during Control period 2, the cows used the first exclosure area 59% less (932 fixes; relating to 8.7 h per cow over the Control period 2) than during Control period 1 (1558 fixes; relating to 14.6 h per cow over the Control period 1), even though the cable had been removed and the cows were free to re-enter the area. The exclosure location for Treatment 2 was chosen to cover a nearby area well used by the cows. During Control period 1, prior to any fence being activated, each cow spent on average 4.1 hours within the area that would be the exclosure area during T2. In period C2, when once again there was no activated fence line, the time the cows spent in the area, that was exclosure during T2, increased to 6.1 hours. This suggested that the cows continued to avoid the area used as exclosure area in T1 and, therefore, time in the T2 area increased. During the last control period (Control period 3), cows spent only 30% of their time in Exclosure 1 when compared to the previous Control period 2 (data adjusted to the different length of those two periods). Figure 6 reveals that the animals continued to avoid entering the last exclusion area after power to the fence line was switched off.

To further analyse the overall behaviour of the cattle within the complete field, the GPS location fixes for each collar were counted during both day and night, and during the different experimental periods, separately in the north and south sections of the field.

Table 3 shows the numeric locational data. Results suggest that the north section of the field was less used than south section both during the day and night within Control period 1. This behaviour was reversed during Treatment 1. Overall, the cows spent more time in the south section of the field during control periods than during treatment periods ($P < 0.001$). Cows spent more time ($P < 0.001$) in the north section of the field during the night than in the south section of the field. In terms of activity patterns, both motion index and numbers of steps, were different ($p<0.001$) between days within a treatment period (day_within-treatment parameter), but when comparing these same behaviour data for the greater treatment periods compared with each other, there were no significant differences.

The location data of each cow in relation to the fence line was then analysed to better understand how the animals reacted to the audio and visual cues presented. The distribution graph (Fig. 3) shows the frequency of GPS data points for each cow within each 5 m interval distance away from the nearest part of the fence line during the two treatment periods. The fence line was represented by the origin on the 'x' axis (at 0 m). Any distinct frequency peaks in the graphs corresponded to large clusters of GPS data points recorded at similar distances away from the fence line (e.g. frequently used grazing areas or periods where groups of cows were possibly resting).

During Treatment 1, the majority of cows showed an accumulation of chosen locations at distances between 20 and 60 m (median = 35 m, standard deviation SD = ±23.6). During Treatment 2, the pattern appeared to change with a more even distribution of locations between 0 and 80 m becoming apparent (SD = ±13.5), except for one cow (collar 206) which spent considerably more time in the 10 m zone from the fence line. Overall, there were 42% more GPS observations noted within 80 m of the fence line in Treatment 1 than in Treatment 2.

As mentioned before, the activity data provided three main parameters as output; the number of physical steps taken, a motion index and the duration of lying bouts. We found that the motion index was highly correlated with the number of cow steps ($r = 0.83$).

The activity sensors showed a clear diurnal pattern for all eight cows (Fig. 4) which would be expected for the autumn season in Scotland. The 24-hour behaviour pattern usually shows two peaks during the day (4-5 h before and after noon). This typical pattern was displayed during the complete experiment for all five experimental periods.

Figure 7 shows the average sum of hours during lying bouts per cow per day. The amount of lying time was unaffected by the different treatments. This indication was underpinned by the results from the GLMM on lying bout duration. There was no effect of treatment (P = 0.199). However, hour_of_day showed an effect on behaviour as the activity behaviour in general is changing considerably during the course of the day (P < 0.001; Fig. 4). Day_within_treatment had also an impact on behaviour (P < 0.001) due to activity changes per day. The log transformed Motion Index showed a difference for treatment, time and day (all P < 0.001; Figure 8 original data).

DISCUSSION

This study demonstrates the success of the Boviguard® system as an alternative to a traditional electric fence. In Treatment 1, only one GPS fix (Collar 219) appeared to occur inside the exclosure area, after correcting for GPS locational error. The distance measured for this single data point within the exclosure was 11.86 m from the nearest fence line. Although the data point might indeed indicate that this cow passed into the exclosure area for a short period of time, there was no indication from the remainder of the GPS fixes obtained for collar 219 that this was so. This fix point may have been a larger GPS error. In addition, no cow was visually observed inside the exclosure during either of the two treatment periods. We are confident that the few GPS fixes within the exclosure boundary are compatible with GPS locational error, supported by similar fixes on the non-field side of the field boundary, including apparent locations on the adjacent public road.

The shift in number and density of GPS fixes around the exclosure areas during Control periods C2 and C3 clearly suggested that the cows' normal locational behaviour in that part of the field was affected by the awareness (or memory) of the virtual fence exclosure positions. During C2, the cows showed increased presence in the area away from Exclosure 1 and during C3, the cows tended to cluster in areas away from both exclosures. Our experiment could not test the longevity of this response, but we consider it would be a short period in the absence of further warning or aversive stimuli, especially as some cattle quickly moved into the area previously excluded.

Overall, the results appear to indicate that once acclimatised to the system, the cows tended to use the visual cue of the cable lying on the ground rather than the audio cue; or possibly that the visual cue was a stronger exclusion reinforcement than the audio. When the cable was removed after the first treatment period, the cows immediately returned and entered that exclusion area, though as noted above not as much as prior to the treatment periods. When the cable was not removed after treatment T2, during period C3 the cows stayed outside the exclusion area while the power was switched off. We believe the visual presence of the cable led to this effect. In addition, it was noticed that during the treatment periods, cows spent more time during the night in the north section of the field, furthest away from the exclusion areas, during the night but were prepared to spend time in the south part of the field during the day. This suggests that the visual cue of being able to identify the fence line was most important to them. Limited animal observations and cross-comparison with the GPS results suggested that some cows walked along the fence line, reinforcing the view that they were observing the fence line cable rather than reacting to the audio or electrical cues. Combining the GPS fixes with the activity data, the animals adapted to the presence of the exclosures yet maintained their natural activity pattern as demonstrated by the fact that the duration of lying bouts did not significantly differ between treatment and control periods. The results suggest that after the initial learning period, the cows responded mainly to the visual cue rather than the audio warning cue. There was no evidence from the results of any significant impact on animal welfare. Although the increased presence of cows in the north section of the field at night indicates a possible negative link with the visual cue. It should be noted that the audio signal of the Boviguard® collar was considered rather quiet. If the audio signal was louder and the triggering distance longer, it is possible that the cows would have responded and reacted to the audio signal more strongly, especially in situations when the cable was less visible - such as during the night. Greater triggering distances would also improve the option of burying the cable in the ground. The outcome of an experiment with a buried cable would be uncertain and had nothing to do with the overall technological approach. It would also be helpful if the triggering distances would be more similar between the collars in order to be able to optimise the distance, though in this experiment all collars appeared to be equally effective.

There are many different technical approaches patented which fall under the term ‘Virtual Fence’ (Umstatter 2011). However, to the authors’ knowledge, only the ‘Invisible Fence’ method patented by Peck, is currently available commercially for livestock (i.e. the Boviguard® system). The ‘next stage’ development of a GPS based system is not yet commercially available. The lack of commercial GPS-based virtual fence technologies is largely due to the large power requirements for long term use; an energy issue that has not yet been resolved (Ruiz-Mirazo et al. 2011). Because the induction cable is connected to a separate power source, the actual Boviguard® collar does not need a large amount of energy and can be sufficiently powered by 4 AA batteries which can last, according to the manufacturer, for over one year.

Another potential problem with virtual fencing is the use of electrical stimuli as negative reinforcement. The majority of virtual fence patents include some form of electrical stimuli (Umstatter 2011). Although some research has looked at other options, such as using sound as negative reinforcement (Butler et al. 2004; Umstatter et al. 2009, 2011, 2013), or using only positive reinforcement (Lalor 2005, 2009), there is a strong indication that an electrical stimulus is the most effective form currently available. However, the debate on whether electrical stimuli are considered acceptable for animal welfare reasons is on-going. This is an important issue in some European nations, such as Wales where electric shock collars (e.g. for dogs) are banned (Animal Welfare Regulations 2010) and regulations such as this could potentially influence the future acceptance of virtual fencing as a viable alternative. Our results indicate that the Boviguard® collar rarely activates the electrical impulse, and so, could be compared to traditional electric fences which animals avoid.

Some research has been carried out to ascertain the acceptable levels of electric stimuli use in a virtual fencing environment and their impact on the animals. Tibbs et al. (1995) investigated the influence of electronic diversion away from riparian areas, assessing livestock grazing behaviour, nutritional physiology, stress physiology and performance. The system used ear tags with audio warning cues and electric stimuli. According to the authors, the animals showed no difference in stress levels or in body condition score. However, a higher weight gain was detected in the control groups ($p = 0.02$). They explained this in terms of a higher quality diet because the control animals were able to access the riparian areas. In addition, Lee et al. (2008) studied the effect of low energy electric shock on cortisol, beta-endorphin, heart rate and behaviour of cattle. They found no difference between the stress hormone responses of cattle to three unpredictable electric shocks and common handling procedures (e.g. being held in a crate for weighing and restraint in a head bail).

In the case of this study, due to the fact that the animals could see the cable on the ground and possibly associate it with the electrical stimulus, it was not a significantly different setup to a common electric fence. However, although similar in function, the Boviguard® system still has the positive aspects of being a ‘virtual fence’ in terms of not being a physical and clearly noticeable barrier. This could provide a good alternative option for when electric fencing is not useable, such as in nature conservation areas. For example, fencing is not permitted within much of the Exmoor National Park in the UK. A Boviguard® style approach could offer a cost-effective solution to ensure that managed grazing is feasible but without the visual side effects of solid or electric fencing being noticeable by the public. Invisible fences, therefore, can be especially useful in recreational landscapes. However, warning signs for the presence of livestock would be required in this instance.

Costs of current equipment are high, due to low production numbers. At the moment collars will cost over US $300 each and charger and cable unit will cost over US $500. With small numbers of animals and a relatively small area this could be lower than the costs of standard post and wire or electric fencing, but still high cost for larger herd sizes. The relatively short fence length also limits practicality and increases costs in more extensive grazing locations.

Overall, the development of virtual fencing can provide a management tool which not only can reduce the amount of fencing cost and labour (Umstatter 2011) but also lead to completely novel management strategies. For instance, with climate change, we need adaptation strategies resulting in innovative ways to manage our rangelands across the world (Joyce et al. 2013). Although the Boviguard® system already improves flexibility in terms of fencing, as no fence posts or stakes are required, future developments using different technologies could lead to an even greater management flexibility.

IMPLICATIONS

The experiment presented here has shown that cows can be efficiently prevented from crossing a ‘virtual’ fence line using a combination of visual, audio and electrical stimuli as preventative cues. The installation of an induction cable fence line is much less labour intensive than erecting an electric fence as no fence posts or stakes need to be installed. This technology could provide a beneficial solution for farmers needing to move fences on a frequent basis, such as in strip grazing. Use of virtual fencing for internal subdivision would allow greater variability in allocation of pasture to meet changing feed requirements of a herd. This could greatly improve farm efficiency on intensively managed pastures.

It can also be a useful tool for farmers, nature conservationists or others who wish to restrict livestock access to specific areas (for example, to lessen the impact of poaching, for habitat regeneration or for public access). The study further indicates the potential for virtual fences to be used as effective barriers where traditional fencing options are not possible, although it also highlights the apparent effect that visual cues may play on the behaviour of the animals. The results demonstrate the effectiveness, and the lack of behavioural changes in parameters measured here, of a collar-based electrical stimuli system for cattle. Further research is required to analyse how much the cows rely on the visual warning cue, how a solely audio warning cue based system would fare and a measure of the number of electrical stimuli given would provide data to answer animal welfare issues. This study can provide impetus for the continued development of virtual fencing technologies as a viable alternative and cost-effective option for a wide range of grazing situations.

ACKNOWLEGEMENT

The authors wish to thank Caroline Klutke for her assistance in running the experiment and Marie Haskell for advice on experimental design.

LITERATURE CITED

Animal Welfare Regulations. 2010. Wales, statutory instruments, No. 943 (W. 97). The Animal Welfare (Electronic Collars) (Wales) Regulations 2010.

Butler, Z., P. Corke, R. Peterson, and D. Rus. 2004. Virtual Fences for Controlling cows. Proceedings of the IEEE 2004 International Conference on Robotics and Automation, May, 2004. IEEE Computer Society Press.

[ESRI] Environmental Systems Research Institute. 2007. ArcMap GIS software, edition 9.2. Redlands, CA, USA: Environmental Systems Research Institute, Inc. 528 p.

Fay, P. K, V. T. McElligott, and K. Havstad. 1989. Containment of free-ranging goats using pulsed-radio-wave-activated shock collars. *Applied Animal Science* 23:165–171.

Joyce, L. A., D. D. Briske, J. R. Brown, H. Wayne Polley, B. A. McCarl, and D. W. Bailey. 2013. Climate Change and North American Rangelands: Assessment of Mitigation and Adaptation Strategies. *Rangeland Ecology & Management* 66:512-528.

[VSNi] VSN International. 2011. GenStat *for Windows* 14th Edition, Lawes Agricultural Trust, VSN International Ltd., Oxford, UK

Lalor, T. 2005. Automated Animal Return System. U.S. patent 2005/0235925 A1, publ. date Oct. 27, 12 p., Int. Cl. A01K 3/00 and A01K 15/02.

Lalor, T. 2009. Automated Animal Return System. U.S. patent 2009/0025651 A1, publ. date Jan. 29, 11 p., Int. Cl. A01K 15/04 and A01K 15/00.

Lee C., A. D. Fisher, M. T. Reed, and J. M. Henshall. 2008. The effect of low energy electric shock on cortisol, beta-endorphin, heart rate and behaviour of cattle. *Applied Animal Behaviour Science* 113:32-42.

Monod M. O, P. Faure, L. Moiroux, and P. Rameau. 2009. Stakeless fencing for mountain pastures. *In*: C. Lockhorst and P. W. G. Groot Koerkamp [EDS.]. Precision Livestock Farming ‘09’. Wageningen, The Netherlands: Wageningen Academic Publishers. p. 175-181

Peck, R. M. 1973. Method and apparatus for controlling an animal. U.S. patent 3,753,421, August 21, 6 pp., Int. Cl. A01K 15/00.

Reid, R. S., P. K. Thornton, G. J. McCrabb, R. L. Kruska, F. Atieno, and P. G. Jones. 2004. Is it possible to mitigate greenhouse gas emissions in pastoral ecosystems of the tropics? *Environment, Development and Sustainability* 6:91-109.

Ruiz-Mirazo, J. G. J. Bishop-Hurley, and D. L. Swain. 2011. Automated Animal Control: Can Discontinuous Monitoring and Aversive Stimulation Modify Cattle Grazing Behavior? *Rangeland Ecology & Management* 64:240-248.

Tibbs, T. M., T. DelCurto, M. McInnis, A. R. Tiedemann and T. M. Quigley. 1995. Influence of Electronic Diversion from Riparian Areas on Livestock Grazing Behavior, Nutritional Physiology, Stress Physiology, and Performance. EOARC, Field Day Report, Special Report 951 (June): 7-9A. Available at: URL: http://oregonstate.edu/dept/eoarc/sites/default/files/publication/392a.pdf. Accessed 7th August 2014.

Tolkamp, B. J., M. J. Haskell, F. M. Langford, D. J. Roberts, and C. A. Morgan. 2010. Are cows more likely to lie down the longer they stand? *Applied Animal Behavior Science* 124: 1-10.

Umstatter, C., 2011. The evolution of virtual fences: A review. *Computers & Electronics in Agriculture* 75:10-22.

Umstatter, C., S. Brocklehurst, D. Ross, and M. Haskell. 2013. Can the location of cattle be managed using broadcast audio cues? *Applied Animal Behaviour Science* 147:34-42.

Umstatter, C., D. Ross, and M. J. Haskell. 2011. Audio approaches in Virtual Fencing. *In*: C. Lokhurst, and D. Berckmans. [EDS.]. Precision Livestock Farming '11. Prague, Czech Republic: Czech Centre for Science and Society. p. 177-182.

Umstatter, C., C. Tailleur, D. Ross, and M. J. Haskell. 2009. Could virtual fences work without giving cows electric shocks? *In*: C. Lockhorst, and P. W. G. Groot Koerkamp [EDS.]. Precision Livestock Farming `09. Wageningen, The Netherlands: Wageningen Academic Publishers. p. 161-168.

FIGURE CAPTIONS

Figure 1: Cow equipped with GPS (first collar nearer the head), activity sensor (left hind leg) and Boviguard® collar (second collar). Inset shows induction cable.

Figure 2: Experimental field divided into north and south sections using a hand digitised polygon layer within the GIS. The points indicate GPS fixes of recorded animal locations. The exclosure areas were located in the south section of the field.

Figure 3: Representation of the proximity of all eight cows with GPS data to the virtual fence line during Treatment 2.

Figure 4: Average activity pattern of cows over 24 hour periods for the 5 different experimental periods. The vertical lines indicate the beginning and end of the nautical twilight at the midpoint of the experimental period.

Figure 5: Locational data during control (no virtual fence) C2 (a) and treatments T1 and T2 (b). The treatment exclosures can clearly be seen in the second and third picture.

Figure 6: Locational data during control C3. The power to the cable is switched off but still laid on the ground.

Figure 7: Average amount of lying time per day and cow during the different treatments (n = 8 cows).

Figure 8: Average Motion Index and step data from IceTags per day (n = 8 cows).

TABLES

Table 1: Experimental design. Cows were wearing the equipment during all five test periods. Treatments were grazed sequentially without a break. There was an adaptation phase before the experiment started.

Period	Treatment		Description	No. of measured 24-h-periods
1	Control 1	[C1]	No cable on the ground (7.88 ha)	3
2	Treatment 1	[T1]	Exclusion area no. #1 (approx. 5400 m^2)	3
3	Control 2	[C2]	No cable on the ground (7.88 ha)	3
4	Treatment 2	[T2]	Exclusion area no. #2 (approx. 7900 m^2)	3
5	Control 3	[C3]	Exclusion area no. #2; power off but cable left in situ (7.88 ha)	2

Table 2: Frequency of all GPS proximity fixes to the exclusion areas during the experiment (counts within band intervals of 5 m).

	Number of GPS fixes
Exclusion area 1 during Control 1	1558
Exclusion area 1 during Control 2	932
Exclusion area 1 during Control 3	184
Treatment 1 (within exclusion area)	27
Treatment 1 (within exclusion area minus the 10 m inside exclusion area boundary)	1
Exclusion area 2 during Control 1	435
Exclusion area 2 during Control 2	653
Exclusion area 2 during Control 3	10
Exclusion area 2 during Control 3 (within exclusion area minus the inside 10 m exclusion area boundary)	0
Treatment 2 (within exclusion area)	19
Treatment 2 (within exclusion area minus the inside 10 m exclusion area boundary)	1

Table 3: GPS locations* (%) during day (7 am – 7 pm) and night of a 7.88 ha paddock divided into notional North and South sections.

	Control 1	**Treatment 1**	**Control 2**	**Treatment 2**	**Control 3**
North – night	21.1	60.3	49.2	80.8	45.3
South – night	78.9	39.7	50.8	19.2	54.7
Total night	100	100	100	100	100
North – day	31.4	60.5	29.7	46.2	26.0
South – day	68.6	39.5	70.3	53.8	74.0
Total day	100	100	100	100	100

* GPS locations were counted for day and night within each Control and Treatment period. The counts were then analysed regarding their distribution within the North and the South sections and the percentage of counts in each area, respectively, was then computed.

Figure_1

Figure_2

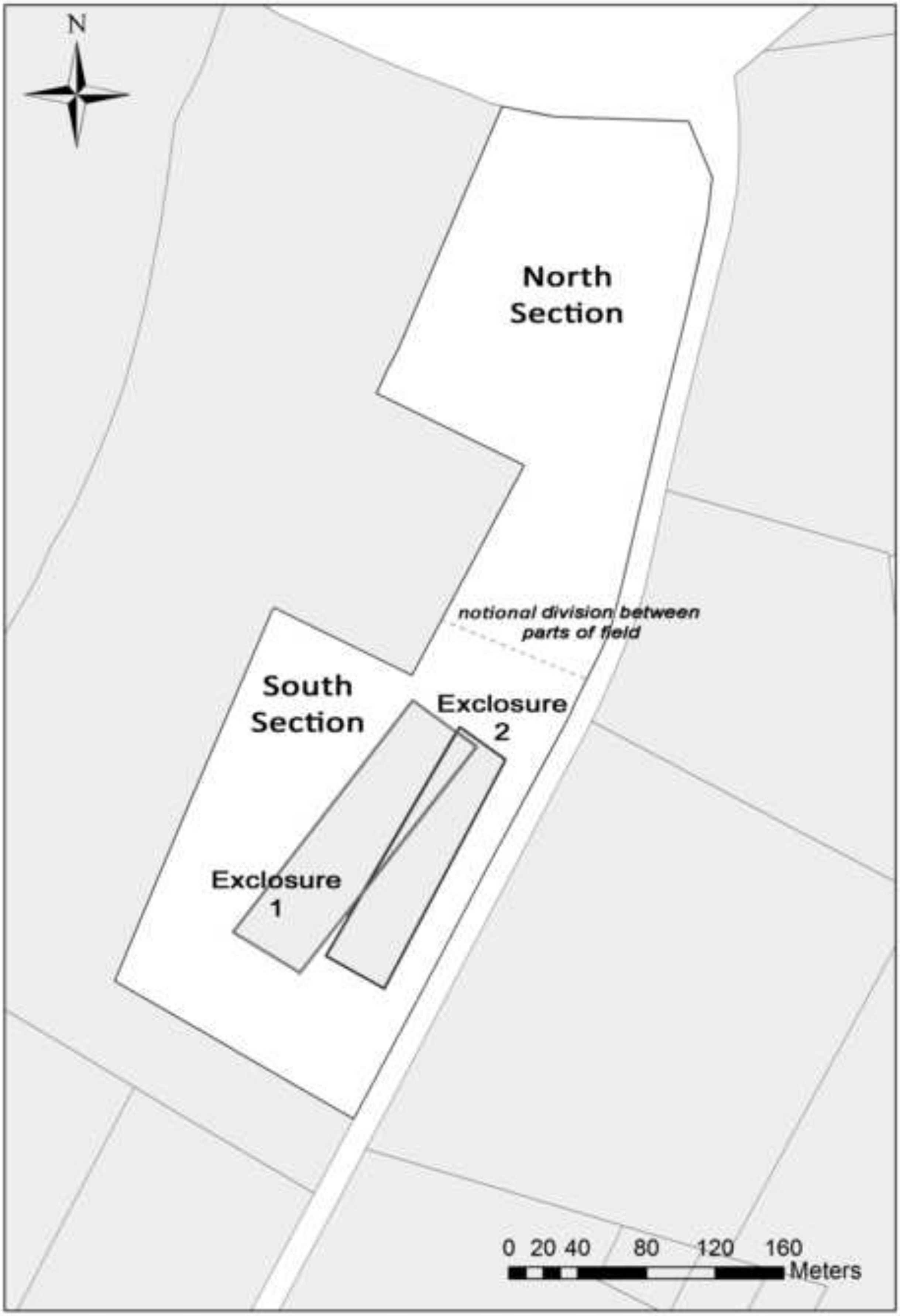
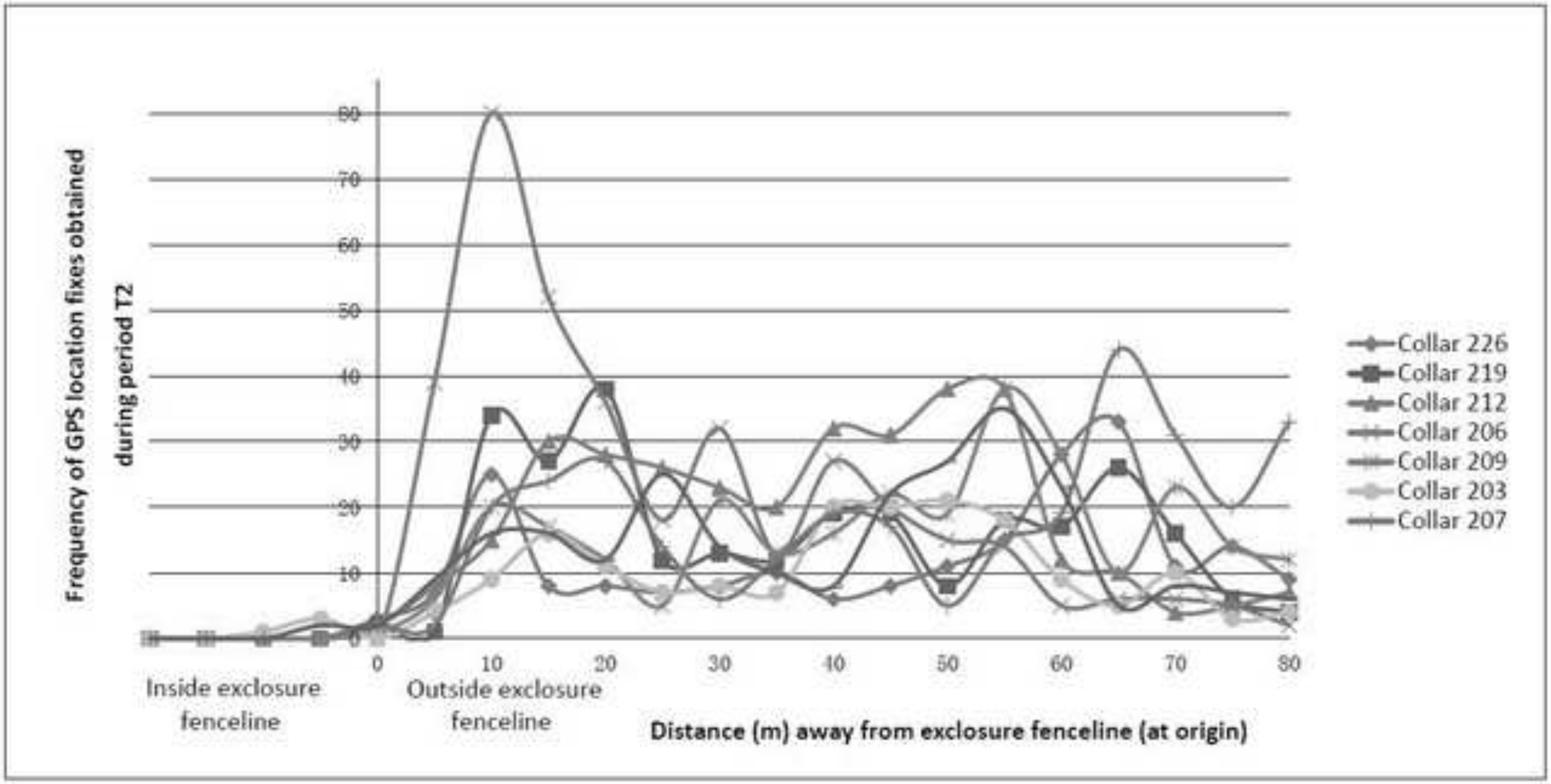

N
North Section
notional division between parts of field
South Section
Exclosure 2
Exclosure 1
0 20 40 80 120 160
Meters

Figure_3



Frequency of GPS location fixes obtained during period T2
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
Inside exclosure fenceline
Outside exclosure fenceline
Distance (m) away from exclosure fenceline (at origin)
Collar 226
Collar 219
Collar 212
Collar 206
Collar 209
Collar 203
Collar 207

Figure_4

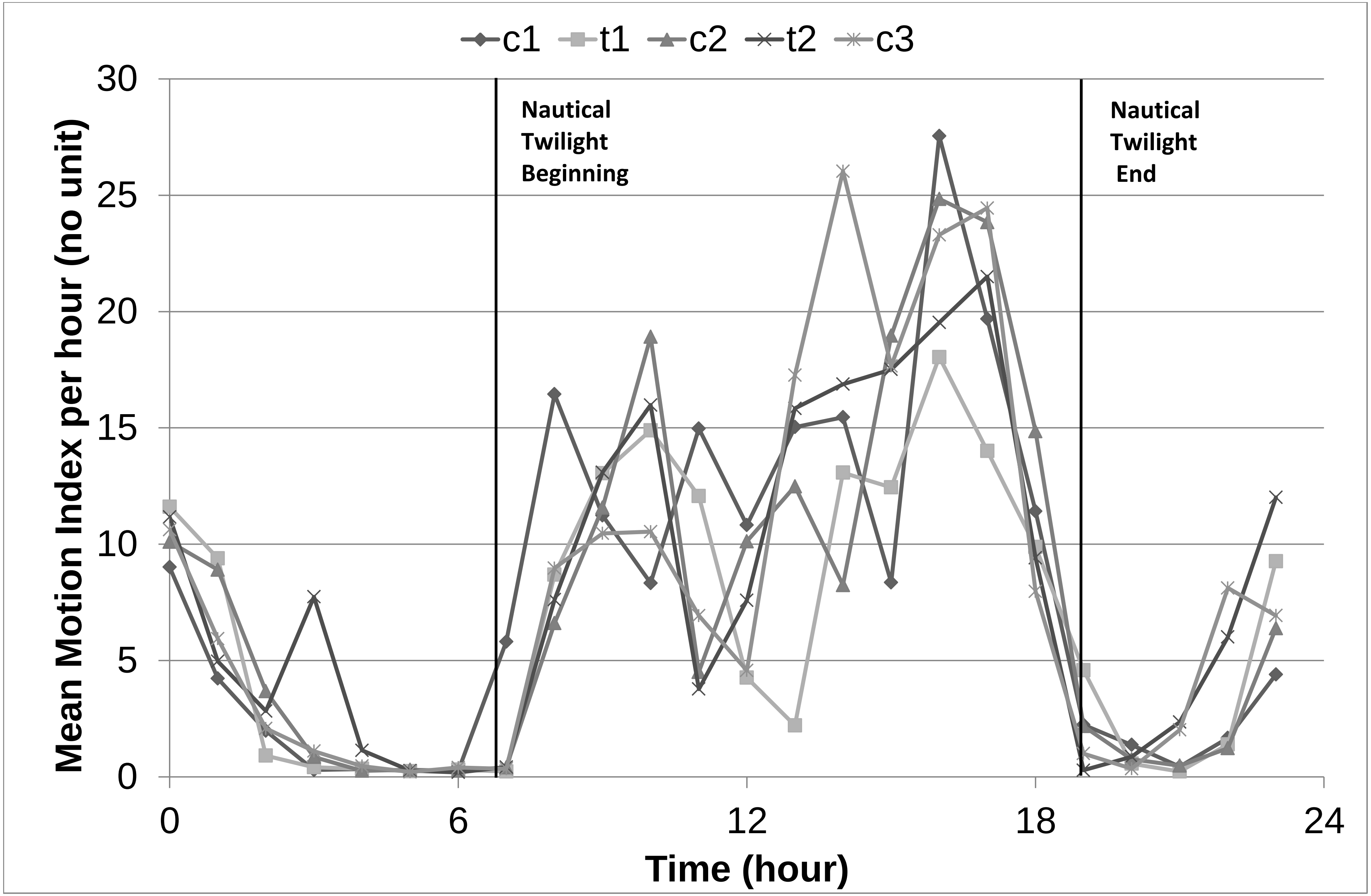

c1
t1
c2
t2
c3
Mean Motion Index per hour (no unit)
0
5
10
15
20
25
30
Nautical
Twilight
Beginning
Nautical
Twilight
End
0
6
12
18
24
Time (hour)

Figure_5a

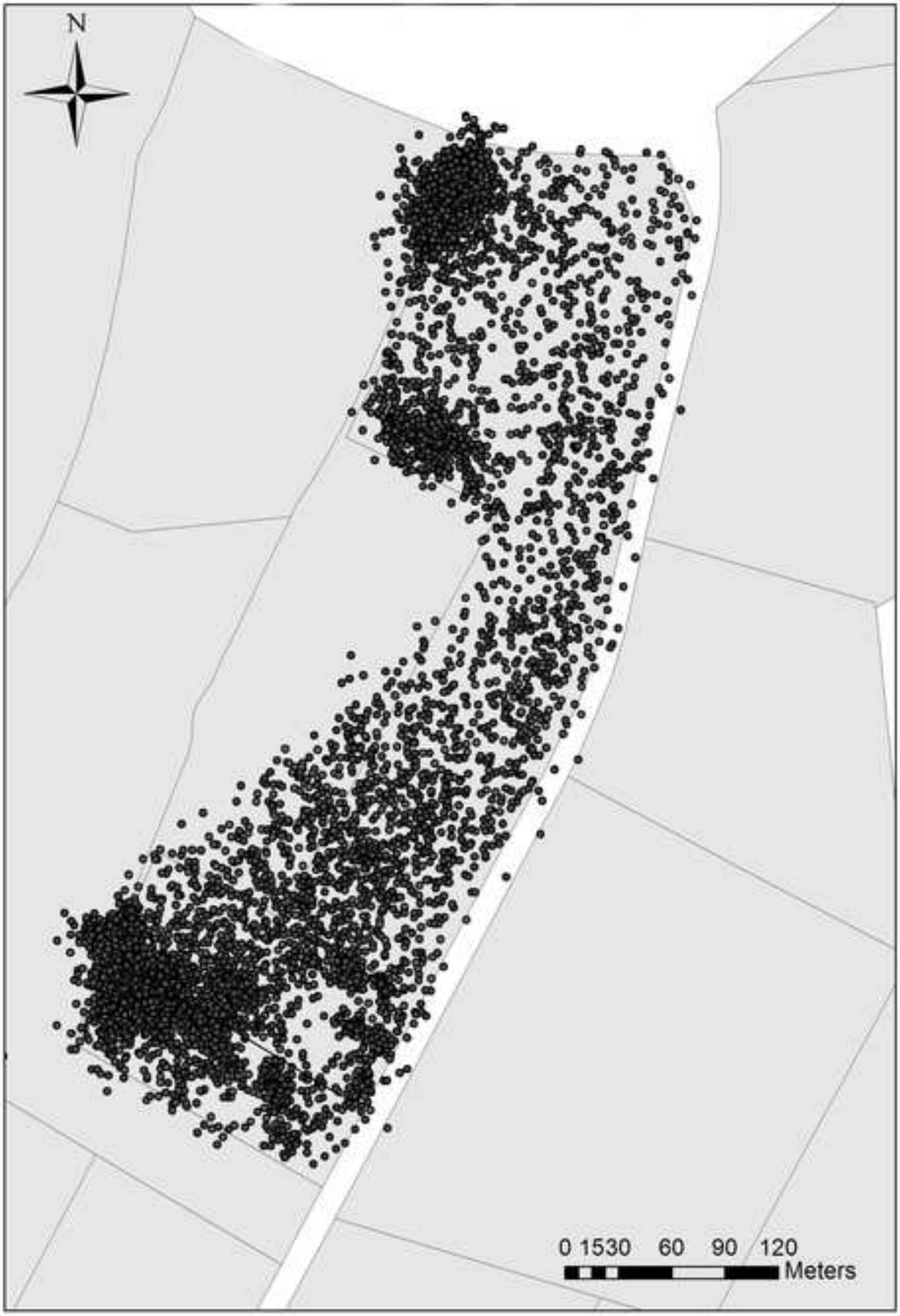


Figure_5b

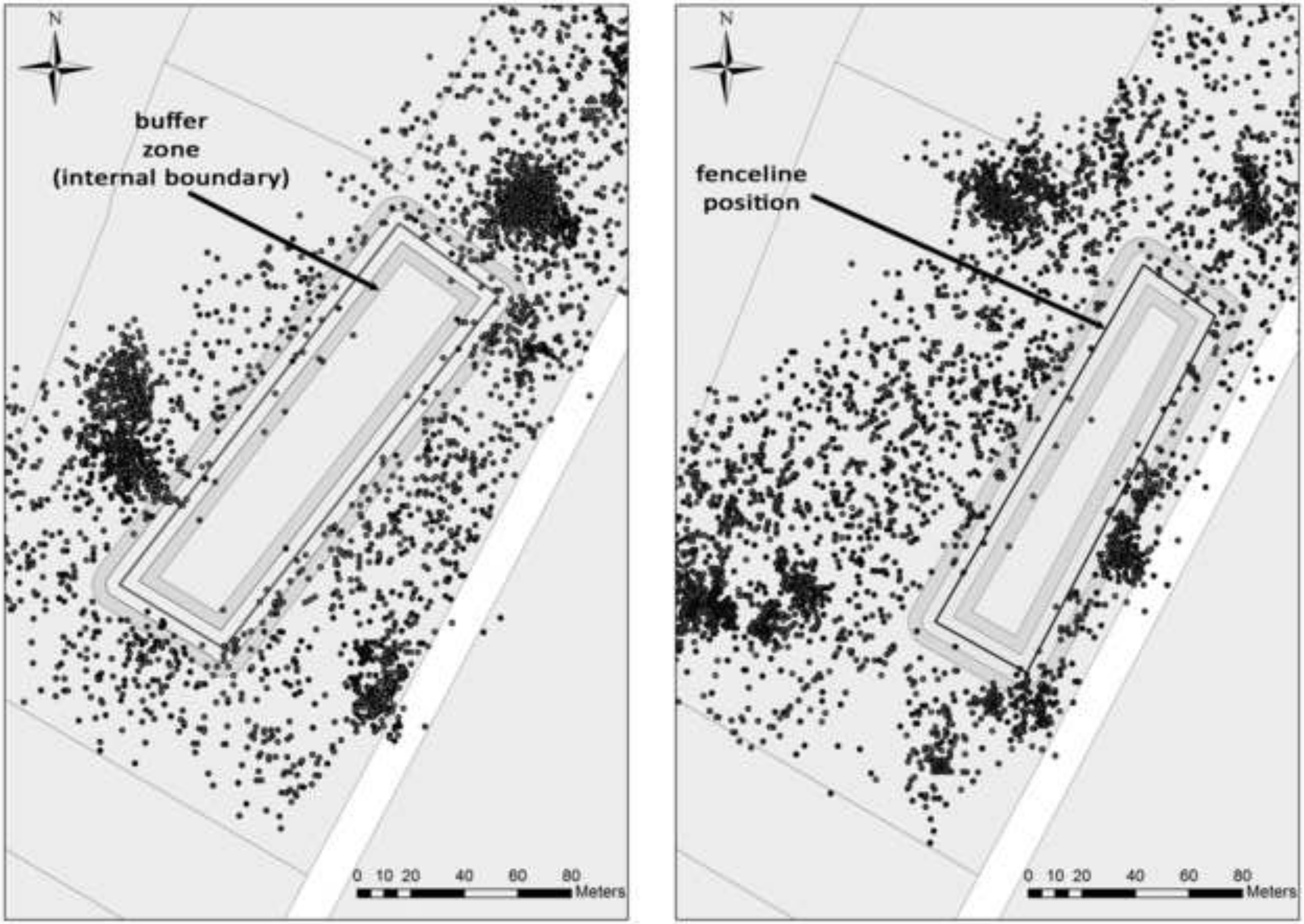

N
buffer
zone
(internal boundary)
0 10 20 40 60 80
Meters
N
fenceline
position
0 10 20 40 60 80
Meters

Figure_6

Figure_7

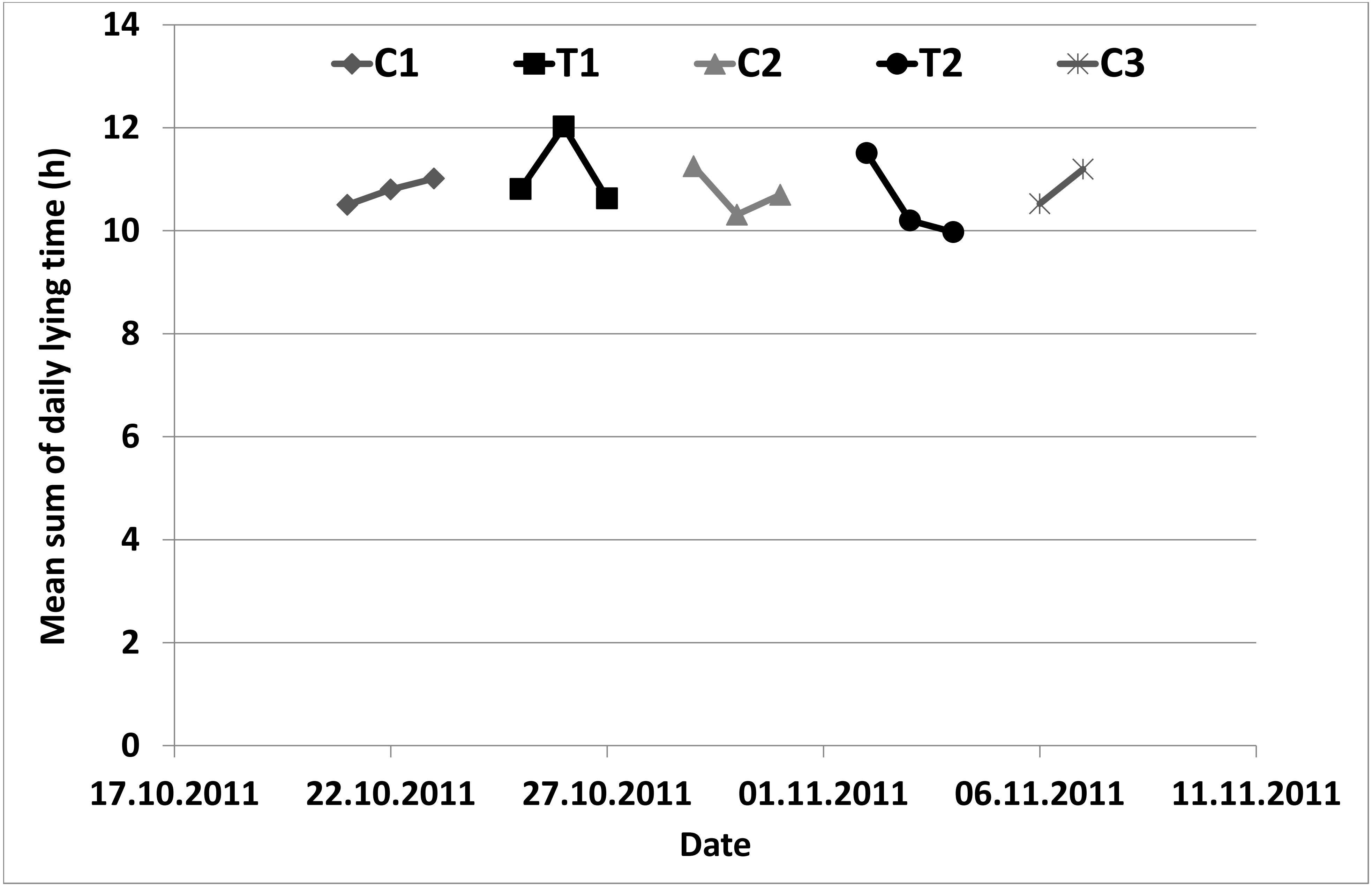
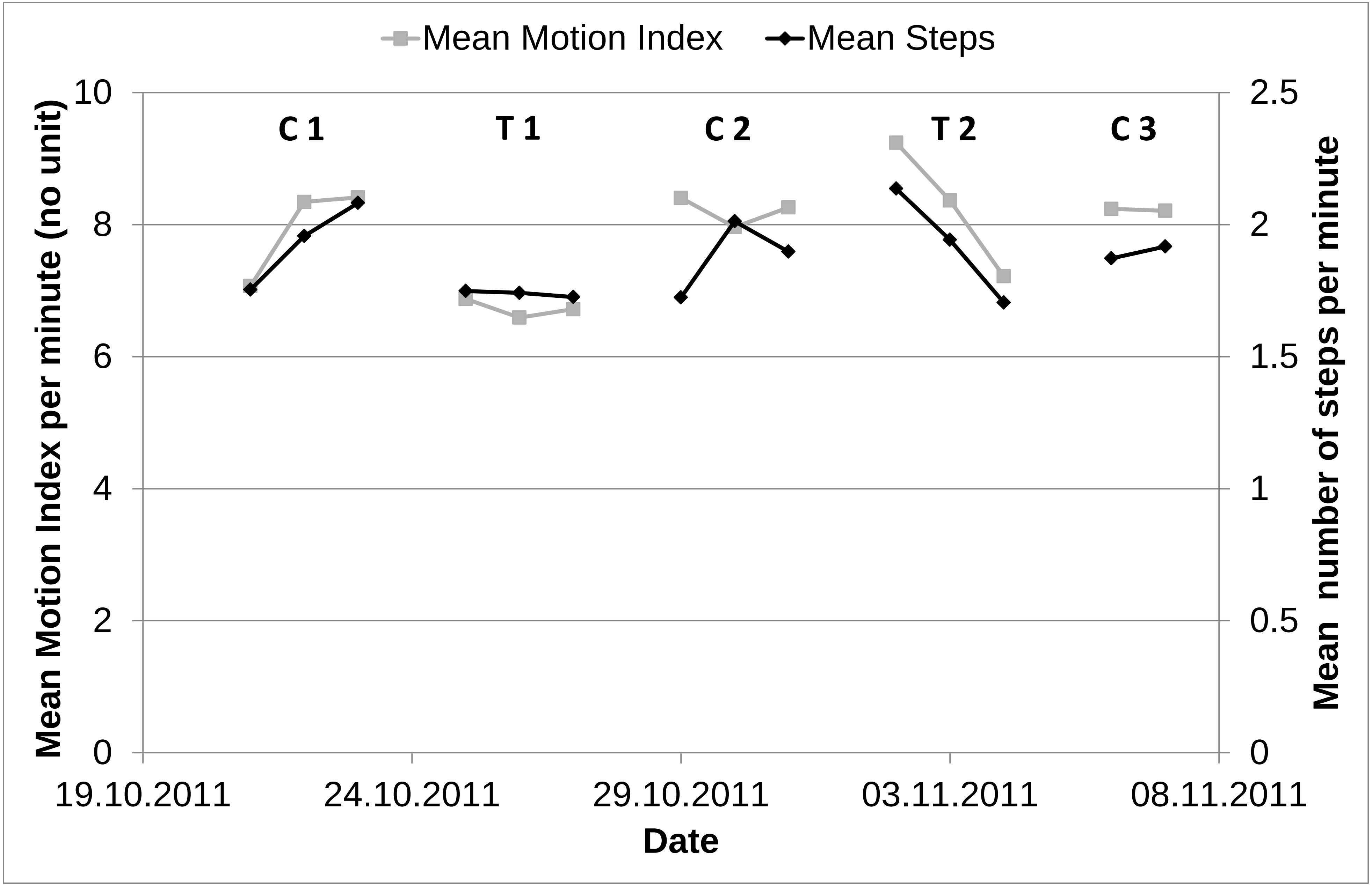

C1
T1
C2
T2
C3
14
12
10
8
6
4
2
0
Mean sum of daily lying time (h)
17.10.2011
22.10.2011
27.10.2011
01.11.2011
06.11.2011
11.11.2011
Date

Figure_8



Mean Motion Index
Mean Steps
C 1
T 1
C 2
T 2
C 3
Mean Motion Index per minute (no unit)
Mean number of steps per minute
10
8
6
4
2
0
2.5
2
1.5
1
0.5
0
19.10.2011
24.10.2011
29.10.2011
03.11.2011
08.11.2011
Date

Figure_1_for online version