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The integration of GPS, vegetation mapping and GIS in ecological and behavioural studies

Steven Mark Rutter

Harper Adams University College, Edgmond, Newport, Shropshire, TF10 8NB United Kingdom. E-mail: smrutter@harper-adams.ac.uk

ABSTRACT - Global Positioning System (GPS) satellite navigation receivers are increasingly being used in ecological and behavioural studies to track the movements of animals in relation to the environments in which they live and forage. Concurrent recording of the animal's foraging behaviour (e.g. from jaw movement recording) allows foraging locations to be determined. By combining the animal GPS movement and foraging data with habitat and vegetation maps using a Geographical Information System (GIS) it is possible to relate animal movement and foraging location to landscape and habitat features and vegetation types. This powerful approach is opening up new opportunities to study the spatial aspects of animal behaviour, especially foraging behaviour, with far greater precision and objectivity than before.

Advances in GPS technology now mean that sub-metre precision systems can be used to track animals, extending the range of application of this technology from landscape and habitat scale to paddock and patch scale studies. As well as allowing ecological hypotheses to be empirically tested at the patch scale, the improvements in precision are also leading to the approach being increasing extended from large scale ecological studies to smaller (paddock) scale agricultural studies.

The use of sub-metre systems brings both new scientific opportunities and new technological challenges. For example, fitting all of the animals in a group with sub-metre precision GPS receivers allows their relative inter-individual distances to be precisely calculated, and their relative orientations can be derived from data from a digital compass fitted to each receiver. These data, analyzed using GIS, could give new insights into the social behaviour of animals. However, the improvements in precision with which the animals are being tracked also needs equivalent improvements in the precision with which habitat and vegetation are mapped. This needs some degree of automation, as vegetation mapping at a fine spatial scale using the traditional manual approach is far too time consuming. This paper explores these issues, discussing new applications as well as approaches to overcoming some of the associated problems.

Key Words: GIS, GPS, spatial behaviour, vegetation mapping

Introduction

Understanding the factors influencing the spatial aspects of the behaviour of domestic and wild animals, and how this spatial behaviour relates to the spatial aspects of the environment, has been and still is an important objective for both behavioural scientists and ecologists alike (Dumont & Gordon, 2003). One of the main features that distinguish the animalia from the other Kingdoms of Life is their active mobility (Starr & Taggart, 2006), which is an important part of their behavioural repertoire as they move about the environment in search of resources, such as food, water, shelter, a mate or other conspecifics. For most animal species for much of their lives, the majority of locomotor behaviour is associated with foraging, as they search for and consume food and water. The spatial distribution of plants has an impact herbivore foraging (Chapman *et al*., 2007), and in turn animal foraging also has a dynamic impact on the abundance and spatial distribution of vegetation (Tallowin *et al*., 2005). Interest in this dynamic interaction has grown since it has been shown that grazing plays an important role in the maintenance of biodiversity in grassland habitats (Rook *et al*., 2004). Consequently, given its importance, this paper will focus on the recording and interpretation of foraging related locomotor behaviour, although

Correspondências devem ser enviadas para: smrutter@harper-adams.ac.uk

other locomotor behaviour will be discussed later in the paper.

In order to study the spatial patterns of foraging, we need three sets of data: at any given point in time, we need to know the location of the animal, whether or not the animal is actively consuming food (or water) at that point in time, and what landscape features are at that location (typically the vegetation type or types if we are studying herbivores).

The combination of automatic satellite navigation based animal tracking, the automatic recording of foraging behaviour and vegetation or habitat maps based on ground survey or aerial and/or satellite images allow these three data sets to be collected, and provide behavioural and ecological scientists and with a powerful tool for analysing spatial foraging behaviour and how it interacts with landscape and habitat features. This paper reviews this approach, discusses some of the limitations and how these might be overcome.

Recording animal location

Initially, animal tracking relied on manual or aerial observation of the animal, with the position of the animal being estimated with reference to landscape features (usually with reference to a map). This approach was of limited value, as unless the animal was continuously followed (which was clearly very expensive in terms of effort), the focal animal would first have to be located before its position could be recorded. Such close tracking of the animal by a human also risked influencing the animal's natural movement patterns, so risked compromising the tracking data. The development of VHF radio tracking collars in the early 1960's for wildlife (Slater, 1963; Macdonald, 1978) provided a far more reliable means of locating animals, and the use of directional receiving antennas allowed the collared animal's position to be estimated using triangulation (White & Garrott, 1990) without the need to approach it. However, this approach was still very time consuming, and small errors in determining the bearing of the collar from the location of the receiver could result in considerable errors in estimating the animal's location (White & Garrott, 1990).

In the 1970s and 1980s the US Department of Defense developed for military navigation purposes a satellite based navigation system called the Navstar Global Positioning System (more commonly know as GPS), and part of the functionality of the system was made available for civilian use. The ease with which GPS delivers precise position information has helped the civilian GPS based satellite navigation market to develop rapidly over the past few years, growing into a multi-billion dollar-a-year industry. GPS has also become the system of choice for those wishing to track animals, with several commercial companies producing wildlife (and more recently domestic animal) tracking collars incorporating GPS receivers. The first commercial GPS animal tracking collars were manufactured by Lotek (Lotek Engineering, Newmarket, Ontario, Canada; http://www.lotek.com) and used in March 1993 to track Caribou (Rogers *et al.*, 1995; 1996; 1997)

The first study to use GPS receivers with domestic animals used Trimble (Trimble Navigation Ltd., Sunnyvale, California, USA; http://www.trimble.com) GPS receivers mounted in purpose built enclosures to track domestic sheep in an upland area in the United Kingdom in August 1993 (Roberts *et al.*, 1995; Rutter *et al.*, 1997a). The system also incorporated a jaw movement sensor allowing the animal's foraging behaviour to be accurately recorded (see the next section). Lotek (Lotek Engineering, Newmarket, Ontario, Canada; http://www.lotek.com) are among a number of companies selling GPS receivers that can be used with domestic livestock. More recently, mapping-grade (*i.e.* sub-metre precision) GPS receivers have been used to record the spatial aspects of the foraging behaviour of domestic cattle. For example, Rutter *et al.* (2006) used a Trimble (Trimble Navigation Ltd., Sunnyvale, California, USA; http://www.trimble.com) GeoXT sub-metre GPS receiver to record the precise location of beef heifers with reference to a vegetation map in order to estimate the diet selected by the animals. Sub-metre GPS receivers incorporate additional features to improve their precision compared with basic GPS receivers, as discussed in the next subsection.

One important point to bear in mind when using GPS to track animals is the choice of an appropriate sampling interval for the GPS position data. The limiting factor with most GPS collars is their battery life, with the batteries capable of achieving a certain number of fixes. The longer the collar is deployed on the animal, the greater the average interval between position samples. The intervals between position samples used in wildlife studies are usually quite long (typically at least several hours), as the deployment (and retrieval) of a tracking collar from a free-ranging wild animal is usually a difficult process, so tracking collars are usually left on the animal for extended periods (usually several months). The animals movements between position samples can only be estimated (usually as a straight line between the two), but this clearly introduces a source of error, with longer intervals being associated with greater errors. Whilst this may not be an issue if the study is only concerned with e.g. the general route taken by an animal as part of a long-distance migration, the error associated with estimating position data between samples is a greater problem if one wishes to study an animals foraging route in detail. One way to overcome this problem is to use a sampling schedule which periodically collects position data with a short sample interval (for use in foraging route analysis) as well as periods of long-interval samples for *e.g.* migration analysis. Fortunately, the fact that domestic animals are kept in captivity makes the deployment of tracking equipment relative straightforward, such that short sampling intervals can be used continuously and the GPS batteries replaced with relative ease when necessary. The use of sub-metre GPS receivers mean that very short sample intervals (*e.g.* one second as used by Rutter *et al.*, 2006) need to be used if the precision benefit is not to be lost due to errors in estimating inter-sample positions.

GPS Precision and accuracy

It is important to distinguish between the precision and accuracy of GPS receivers. Precision refers to the repeatability of a position as recorded by a GPS receiver at a fixed point, whereas as accuracy refers to any discrepancy in the position as calculated by the GPS receiver and the position as determined by reference to a published map. The accuracy of GPS is therefore very much related to the accuracy of the published map, and the precise nature of GPS has shown the limitations of many maps produced before GPS was available. Accuracy is often not an issue as many scientific studies use GPS to generate their own maps (*e.g.* of vegetation), and if all the spatial data are collected using GPS, precision is then the main concern and accuracy can be ignored. However, it is important that users are aware of potential discrepancies between GPS position data and published mapping if that mapping was not generated using GPS. It is also worth noting that GPS precision is usually quoted as 2DRMS, which equates to 95% of the values lying within the stated precision of the true position value. It therefore follows that 5% of the position data has an error greater that the stated precision value, and very occasionally this error can be considerable (in the author's experience it can be several kilometres out!).

The precision of the civilian GPS signals was for a while deliberately reduced by the US Department for Defense to approximately 100m in a programme known as Selective Availability (SA). However, this was removed in May 2000, giving civilian GPS receivers a precision of about 15m. Precision can be further improved using a process known as differential correction (Hulbert & French, 2001). This involves recording the error in the signals received by a GPS receiver at a fixed known location, and then applying these as a correction factor to a mobile receiver in the same part of the world. This can be either real-time, in which case there needs to be a radio link between the fixed and mobile receivers, or post-processed, in which case the error data recorded by the fixed receiver can be subsequently applied to the data recorded by the mobile receiver. Differential correction improves the precision of GPS to between 3 and 5m. Whilst differential correction may sound complicated, in practice it is usually offered as an option on commercial systems, and can be carried out with relative ease. Wide Area Augmentation Systems (WAAS) are also available in some parts of the world (including North America, Europe and parts of Asia). These provide real-time differential correction using correction signals carried on one or more satellites, allowing WAAS enabled GPS receivers carry out real-time differential correction and so the data they store are already differentially corrected. Mapping grade and survey grade GPS receivers use differential correction along with other signal processing techniques to achieve precision of a few centimetres (albeit at a higher cost than standard GPS systems). The details of the additional signal processing techniques used by sub-metre GPS receivers are beyond the scope of this paper, but fortunately the user does not need to understand how they work in order to use them.

Recording foraging behaviour

Just as with recording animal position, the simplest approach to recording the foraging behaviour of animals in by direct observation. However, for studies requiring data to be collected over long periods of time, manual observation is laborious and expensive, so various attempts have been made to develop automatic foraging behaviour recorders (reviewed by Rutter *et al.*, 1997b). Various approaches have been taken, including jaw movement sensor recording (Penning, 1983; Penning *et al.*, 1984; Rutter *et al.*, 1997b) with subsequent processing to determine bites and chews and periods of eating and ruminating (Rutter, 2000). A system based on this approach, known as the 'IGER Behaviour Recorder' is commercially available (Ultra Sound Advice, London, United Kingdom; http://www.ultrasoundadvice.co.uk). An alternative approach is to make acoustic recordings of the sounds associated with grazing from a microphone, usually held against the animals skull, that can be subsequently processed to determine bites and chews from their acoustic signatures (Laca *et al.*, 1992), as well as the potential for estimating bite mass (Laca & Wallis de Vries, 2000). A comparison of the jaw movement and acoustic approaches (Ungar & Rutter, 2006) showed broad correspondence between the two, although each approach had their own limitations leading the authors to conclude that the integrated recoding of both jaw movements and the acoustic signal may be the best line of development in the future.

Mapping vegetation

The final component needed to join the animal based measurements described above is a precise vegetation map. Just as with determining animal position and behaviour, the simplest approach to vegetation mapping is through manual survey. This can be done with reference to features on a map, although precise mapping on featureless terrain requires the use of precision survey equipment (Gooding *et al*., 1997). This approach has been assisted by the development of precise GPS receivers, allowing for more rapid entry of vegetation types into a hand-held GPS receiver that automatically records the observer's location (*e.g.* as used by Rutter *et al.*, 2006). However, if the improvements achieved in the precision with which animals are tracked using sub-meter GPS are to be exploited in full, the vegetation map should have similar precision. The danger of the two not having similar levels of precision was demonstrated by Rutter *et al.* (2006), when the comparatively poor correlation between manual observation and GPS tracking/vegetation map approaches when estimating diet selection was attributed to the vegetation map being based on samples at 4m intervals (the precision of the animal data was sub-metre). Whilst the obvious solution to this problem is to decrease the distance between vegetation samples, we need to do this in two dimensions (x and y) so the increase in the required number of samples increases with a square function (n^2) and so requires a lot more time and effort the extra samples. For example, in the authors experience it takes approximately 30 seconds to determine the location of and record each vegetation sample. So a single 1.5ha paddock which is 152m by 100m (as used by Rutter *et al.*, 2006) sampled in a grid at 4m intervals has 950 sample points and takes approximately 8 hours (one working day) to map if each sample takes 30s. Decreasing the distance between samples to 0.25m gives 240,000 sample points, which, at 30 seconds a sample would take 50 working weeks (8hrs a day, 5 days a week) to map! Whilst such an effort could be expended, the dynamic nature of plant/animal interactions result in changes in the spatial abundance of different plants, and if these changes are to be tracked the vegetation will need to be mapped at least twice, and ideally on an on-going basis.

Clearly, an alternative approach is needed. One possibility is to restrict sampling to the route taken by the animal *e.g*. program the animal's foraging route into a GPS receiver and then follow and sample along the route. This would reduce the amount of vegetation sampling required, but has the significant drawback of sampling the plants that the animal **did not** eat. It is feasible that the animal has consumed entire plants on its route, with little or no visible sign that they existed. Even if preferred plants were not entirely consumed, their relative abundance is likely to be lower along the foraging route after the animal has grazed compared with before, so leading to inaccuracies in the estimation of the vegetation cover that was present before grazing.

The problems associated with the manual survey of vegetation maps can only be overcome by some other form of sampling, and aerial (or possibly even satellite) imagery offers the greatest opportunities. For example, Sickel *et al.* (2004) compared recent coloured infra-red aerial photographs with ~40 year old black-and-white aerial photographs to determine areas that had shown continuity of grazing and to generate geo-rectified vegetation maps. The movements of cattle fitted with GPS collars were then related to the vegetation maps to determine the preferred location of the cattle. Whilst this approach shows great promise, if one is interested in the fine detail of foraging at the patch scale, the aerial images need to be of sufficiently high resolution to allow high precision vegetation maps to be derived. Imagery need not be constrained to the visual spectrum, and a European Union funded project is investigating the use of multi and hyperspectral aerial and satellite imagery in a wide range of applications, including vegetation mapping (Project PIMHAI, http://www.pimhai.ietr. org). Whilst aerial imagery and high resolution satellite imagery are not cheap to obtain, they do provide a rapid way to generate precise vegetation maps, and developments in this field should yield significant benefits to those wishing to combine GPS tracking, foraging behaviour recording and vegetation mapping to understand the spatial dynamics of plant/animal interactions.

Integrating the data

Although of some use of their own, the three sets of data (animal position, foraging behaviour and vegetation maps) need to be combined if we wish to understand the spatial dynamics of foraging behaviour. Fortunately the geosciences have a need for powerful software tools to integrate and analyse spatial data, and consequently Geographical Information Systems (GIS) have been developed for this purpose and are available off-the-shelf. These typically split spatial data into three classes: points, lines and areas. The GIS software can then used to explore the relationships within the data e.g. what proportion of points of a particular type lie within certain types of areas.

One important consideration is which data class (*i.e.* point, line or area) is best associated with the data we import. The track an animal takes is, strictly speaking, a line, although it is usually recorded by the GPS receiver as a series of points. Whilst displaying a line in the GIS package helps visualise the foraging route of the animal (as it makes it easy to see the **sequence** of the positions that form the route), the data were originally recorded on the GPS as discrete points, so should ideally be analysed as such. The vegetation map is best represented by a series of areas, with each area having identical (or at least similar) vegetation properties.

Off-the-shelf solutions are available for the majority of the stages involved in collecting, processing and combining the different sources of data. However, there isn't (to the authors knowledge) yet available an off-the-shelf solution to combining the animals position data with the grazing behaviour data in a form that can be imported into a GIS package, so it is worth describing in some detail the method that has been developed by the author. The first stage is to perform differential correction (if necessary) on both the animal GPS position and any vegetation GPS mapping data, usually using software provided by the manufacturer of the GPS receiver. The animal position data then needs to be combined with the foraging data, and the author uses a spreadsheet program to carry this out, as there are no *off-the-shelf* options for this stage of the process. First process the foraging data, and concatenate eating bouts into meals using sensible intra-meal interval criteria (*e.g.* Yeates *et al.*, 2001). Then load the animal position data into the spreadsheet, including position (typically WGS84 latitude and longitude) along with the time and date that the position was recorded. Ensure the position data are sorted into chronological order (this is not always the case in the raw data generated by differential correction software). In a new column in the spreadsheet, enter a 1 in this column in the row that best corresponds with the start time of the first meal, and a 0 (zero) in the row that best corresponds with the end time of the meal. Repeat this for all the meals. Then use a macro to read down this column and duplicate any value (*i.e. 0* or *1*) it finds into all the empty cells in the rows below it until it encounters a cell with a new value in which case that new value is replicated in the empty cells below it until the last row is reached. The result of this is that all those position fixes that are associated with foraging having a *1* in the new column, and all those positions that are not associated with foraging having a zero. This allows those fixes associated with foraging to be readily identified in the GIS analysis. The vegetation mapping data can usually be read straight into the GIS package (after differential correction if required). If the user has sampled the vegetation at regular intervals, the data will consist of a series of points. These need to be converted from points into areas, typically using thiessen polygons (search for *thiessen* in ArcGIS 9.2 Desktop Help, http://webhelp.esri.com/arcgisdesktop/9.2). The area contained in each polygon is closer to the point on which the polygon is based than to any other point in the dataset.

Once the animal position point data (tagged with the foraging data) and the vegetation map (a series of joined up areas) are loaded into the GIS package, the user can start to generate spatial queries to explore the data. *For example*, the proportion of time an animal spends foraging on a particular vegetation type can be quickly and easily determined by selecting those animal positions that are tagged as foraging AND are located within areas containing the chosen vegetation type. The number of the selected points expressed as a proportion of the total number of positions associated with foraging give the proportion of time the animal spent foraging on a the given vegetation type.

Understanding spatial behaviour

Whilst we have seen considerable technological advances in animal tracking hardware that have transformed the quantity and quality (in terms of precision) of animal and vegetation/habitat spatial data, our understanding of the biological and behavioural factors influencing the spatial aspects of the foraging decisions made by animals is still in its infancy. Studies using artificial distributions of feed patches (typically bowls containing pelleted food) have demonstrated that both sheep (Edwards *et al*., 1996) and cattle (Laca, 1998) have good spatial memory, and can remember the location of preferred food items. Hewitson *et al.* (2005) demonstrated that sheep can switch between using spatial memory and sampling behaviour depending on the spatial scale and predictability of resources. More detailed analysis of foraging paths using fractal analysis in sheep have shown that grazing paths were tortuous in tall swards in summer, but straighter in heterogeneous, well structured swards showing visual cues in autumn (Garcia *et al*., 2005).

Ultimately, the aim will be to develop models of the oriented movement of animals (*e.g.* Nams, 2006) as well as models of herbivore foraging behaviour that are spatially explicit (*e.g.* Farnsworth & Beecham, 1999; Dumont & Hill, 2004) which will allow hypothesis about the behavioural and biological mechanisms underlying foraging to be developed and tested. The precise and objective empirical data provided by the combined animal position, foraging behaviour and vegetation map approach described in this paper will be invaluable in helping to develop and test these hypotheses.

Future opportunites and challenges

The use of sub-metre GPS receivers to track animals opens up new possibilities for recording their patterns of spatial behaviour with increased precision, which should in turn help to improve our understanding the underlying biological principles. As mentioned earlier, if we are to capitalise on the increased precision in our measurement of animal position we also need improvements in the precision and resolution of vegetation maps. Another factor to consider in the use of sub-meter GPS in animal tracking is that the location of the GPS antenna on the animal becomes an issue. With standard GPS receivers (with a precision of several metres), the position of the GPS antenna (*i.e.* the part of the system that has the ‘position’ associated with it) is not really relevant, as the animal's body is small compared with the typical error associated with the GPS position. However, with sub-metre systems, which are capable of a precision of a few centimetres, the antenna might be located a long way from the part of animal which we wish to locate, or we might want to locate two or more parts of the animal *e.g.* the mouth for foraging and the rump for defecation and urination. Clearly, having the antenna located *e.g.* on a saddle on the animal's back will introduce a source of error in our estimation of the position of the animal's mouth. One solution to this problem is to incorporate a digital compass into the system which allows the animals orientation (relative to magnetic North) to be recorded every time a GPS position fix is recorded (Rutter *et al*., 2005). Given a linear measurement between the GPS antenna and the point of interest on the animal (measured directly with *e.g*. a tape measure whilst the animal is restrained), the location of the point of interest relative to the antenna can be calculated using simple trigonometry, given the antenna to point of interest distance and the animal's orientation. Rutter *et al*. (2005) demonstrated that this approach improved the estimation of both foraging and elimination locations compared with using the position of the just the GPS antenna (which was mounted on a saddle of the animals back) without the correction performed using the digital compass data.

The combination of a digital compass and a sub-metre GPS receiver allows the precise location and orientation of the animal to be determined. If all the animals in a group were to be fitted with the equipment, one could record the precise relative positions and orientations of all the animals, and such data could give new insight into the social behaviour of the animals. Whilst the importance of social facilitation (*e.g.* Rook and Huckle, 1995) and the relative spacing of grazing animals (Sibbald and Hooper, 2003) in the foraging behaviour of domestic ruminants have already been demonstrated, the novel approach described here would allow for greater precision and objectivity in the collection of data in future studies.

One final issue to consider in the implementation of this sort of technology is that whilst off-the-shelf solutions are available for the various components that make up such a system (GPS collars, grazing behaviour recorders, GIS software etc.), scientists and their technicians still face a significant technical challenge in integrating these various components. Hopefully a commercial supplier will realise the potential in this market and produce an integrated off-the-shelf solution along with expert technical assistance. Until then, scientists and technicians will need to expend some effort bringing together the various components that make up the system.

Conclusions

Using GIS to integrate and analyse the data from concurrent, automatic GPS animal tracking, automatic foraging behaviour recording and precise vegetation mapping provides a very powerful tool for those investigating the spatial aspects of foraging behaviour in complex, natural environments. Until a commercial supplier develops a fully integrated system, scientists face the technical challenge of integrating the various components that make up the system. However, for those willing to take on the challenge the benefits are considerable.

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