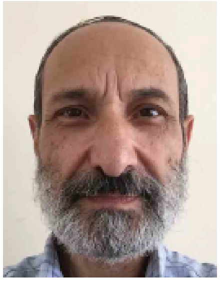

OVERVIEW

The gap between what is "possible-in-principle" and "achievable-in-practice" is large when it comes to the application of precision agriculture to extensive grazing systems. Part of the challenge is that these systems are spread over large and remote areas, and are also spatially heterogeneous, both in primary production and in pattern of utilization by grazing animals. Certain tools associated with precision agriculture that operate in a spatially explicit way – remote sensing, GIS (geographic information system) and GPS (global positioning system) – are being harnessed to study grazing systems. Satellite-based remote sensing holds much promise in terms of which plant characteristics can be inferred. The most important ones are cover classification, and the quantity and quality of plant biomass. Animal-borne GPS-enabled devices can tell us where an animal goes and when, but one has to contend with the fact that herds comprise many individuals. In the case study presented here, a GPS-based herd tracking system was developed to map the cumulative presence of a number of goat herds employed to forage along fire-breaks in the Jerusalem Hills. The combination of utilization maps generated by such wide-scale herd monitoring and remote-sensing of the vegetation should facilitate a quantum leap in the depth at which grazing systems can be studied and managed.

Grazing systems of one kind or another occupy at least a quarter of the land surface of our planet and are of huge economic and ecological importance. However, many of them are extensive, low-input/low-output systems that operate in harsh physical and economic environments into which technology penetrates slowly; thus, the gap between "possible-in-principle" and "achievable-in-practice" is large. Discussion of precision agriculture has been restricted to crops, with no mention of rangelands. However, one might well ask whether precision agriculture could be relevant to grazing systems. One complication in attempting to answer this question would be that, by definition, a grazing system comprises two very different actors.

The first is the vegetation, which in some broad sense resembles a crop, therefore we might expect the tools of precision agriculture to be readily applicable to rangelands. However, rangeland paddocks are relatively large and their value per unit area is low, so that data acquisition and analysis become expensive. Furthermore, the heterogeneity of natural vegetation is far greater than that encountered in crops, and it occurs at a variety of spatial scales, from centimeters to hundreds of meters. In fact, one could justifiably ask: "In this context, what kind of decision support can we expect of precision agriculture, given that these areas are neither cultivated, planted, irrigated, fertilized, sprayed, nor mechanically harvested?" But they are ***grazed***, and the timing and intensity of grazing can have a strong impact on the future productivity of the vegetation. Most importantly, timing and intensity of grazing are also under some degree of management control, so that the ability to map characteristics of the vegetation such as potential productivity, standing biomass, and nutritional quality would constitute a quantum leap in our ability to study and manage grazing systems. Satellite-based remote sensing is an obvious means of progress towards this improvement, although it should be noted that ground-sampling of sufficient scope to enable high-quality calibration of the satellite data presents a major challenge. Nevertheless, as costs of satellite imagery fall and the technology improves in terms of spatial resolution, number of spectral bands, and imaging frequency, precision agriculture will become increasingly relevant for rangelands.

The second factor is the animal, and to balance the crop bias implied by the term precision ***agriculture***, we refer to precision ***livestock farming***. In the case of housed-ruminant production systems, the deployment of a sensor on every animal in a group (primarily for estrus detection) predates the term, but the repertoire of behavioral and physiological signals that can be sensed at the individual level has grown considerably. The nature of housed-animal production systems means that, for some purposes, many individuals can be monitored by a single device, such as a camera positioned strategically in a passageway leading to the milking parlor. However, even if such controlled and standardized measuring conditions could be created on rangelands, seemingly trivial "details" could kill the idea, for example, distances from the electricity grid or the cellular communication network.

Classic examples of the large gap between "possible-in-principle" and "practicable" abound in applications of the global positioning system (GPS). GPS chips have been attached to just about anything that moves, from bicycles to ballistic missiles; from marine mammals to flying insects; also, there must be about 2 billion GPS chips in smartphones around the world today and the unit cost is a few dollars. What could be simpler than slinging a GPS chip around the neck of every animal? Indeed, a major topic of interest in the study and management of grazing systems is the spatial dimension: how uniformly do the animals utilize the area available to them and how does the spatial pattern of animal presence relate to, and even influence, that of landscape heterogeneity?

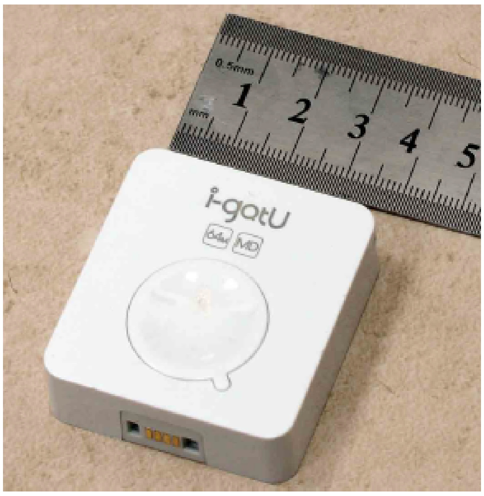

Figure 1. The general-purpose i-gotU GPS logger (Mobile Action Technology, New Taipei City, Taiwan) at the heart of the GPS collars used to map animal location on rangeland. The device weighs 37 g, contains a 750-mAh battery and can store 262,000 locations. A simple-to-use software interface enables the device to be programmed to operate with GPS fix intervals of 1 s to 1 h; the optional power-saving mode can be used for fix intervals ≥7 s. Operation can be scheduled according to starting date and operating hours over a 24-h cycle, with a resolution of 1 h. A third-party external battery can be used in conjunction with the device's data/charging cable to greatly extend operating time.

Answers to these questions would also provide a quantum step forward in the study and management of grazing systems; clearly, the combination of spatially explicit data on primary production and spatially explicit data on its utilization by animals would raise potential benefits to yet another level.

However, incorporation of a chip into a commercial animal-borne GPS collar raises the few dollars cost of the GPS chip to many hundreds or even a few thousands for the finished product. The high cost of a collar is a major limiting constraint on exploitation of this powerful technology, but by working with flocks of sheep or goats, which are accompanied by a herder and are not free-ranging, some of the difficulties can be overcome. Firstly, the fact that the animals move across the landscape as a fairly coherent group means that their location can be well approximated by the position of any one animal, which enables just one collar per group to form a reasonable starting investment. Secondly, such flocks and herds usually spend the night in a corral, from which they emerge and to which they return each day. Thus, the animals do not have to be rounded up and corralled specifically to change the GPS collars; also changing collars on small ruminants is incomparably simpler and safer than doing it on cattle.

However, if the goal was to prepare the way for widespread, routine deployment of GPS collars, even one commercial collar per herd would be expensive. One way to bring down costs considerably would be to build the collars in-house, using basic electronic components such as the cheap GPS chip mentioned earlier; but this would not be practicable outside a research facility. We achieved a compromise solution by using an inexpensive, general-purpose GPS logger intended primarily for sports and leisure use (Figure 1). The i-gotU GPS logger (Mobile Action Technology, New Taipei City, Taiwan) fits into the palm of a hand and offers an impressive set of features; most importantly, it proved robust under field conditions and generated good quality data for our purposes. However, small size means small battery, and small battery means limited operating time between battery recharges, as with all electronic gadgets. This complicates collar construction because now we need an external battery; this necessitates connectors, and one thing leads to another, until we arrived at the rather amateurish-looking GPS collar shown in Figure 2. Nevertheless, the cost of our "cheap-and-nasty" collar is 10–20% of that of commercial ones; it is reliable, can be assembled in about 10 minutes, and can be dismantled quickly after deployment, to access the GPS logger and recharge the battery.

This basic design has been applied in several studies in Israel; they addressed small-ruminant herds in the northern Negev and the Mt. Carmel regions, and cattle herds at three other ↘

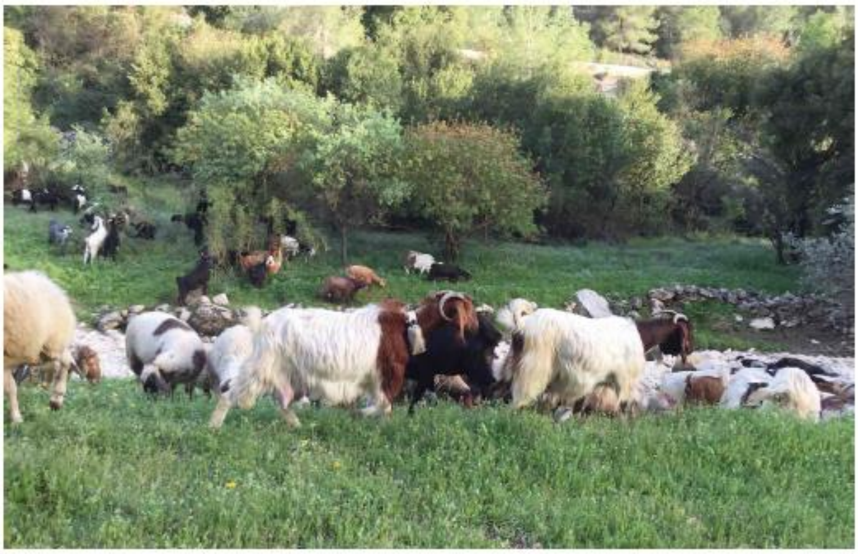

Figure 2. Goat herd grazing along a fire-break corridor in the Judean Hills. The brown-and-white goat in the center is wearing an in-house assembled GPS collar. The picture was taken along the seasonally active Refa'im riverbed in the 'Amminadav Forest. The dry riverbed of whitish pebbles and rocks runs horizontally across the middle of the photo, and goats graze the herbaceous and shrub vegetation along its banks. The edge of the main dirt road that runs parallel to the river bed is in the foreground.

→ sites. In the study described here, our objective was to map, over several annual cycles, the daily foraging routes of goat herds within a 100-km^2 region of the Judean Hills, south-west of Jerusalem. A large proportion of this region is covered by woodlands and planted pine forests managed by the Jewish National Fund; it contains some of the most scenic landscapes in the country and is dotted with sites of cultural importance. However, pines and picnic fires form a combustible mix; arson poses an additional threat, and serious wildfires are not uncommon. The basic idea could not be simpler: every kilogram of undergrowth vegetation consumed by the goats is that much less fuel for a wildfire. However, there are simply not enough goats available to adequately suppress the herbaceous and woody undergrowth vegetation across the entire region. Therefore, the herd "fire power" was focused along designated fire-break corridors, to keep them passable and safe for ground crews who need to operate along them when fighting a wildfire.

That, at least, is the theory. But testing whether this works in practice requires the ability to associate the state of the vegetation at each point with the amount of grazing that had occurred there; and this requirement cannot be addressed seriously without continuous GPS-based mapping of herd presence.

Our low-cost GPS collars for the herds were constructed and deployed, and were refreshed every few weeks throughout the year. For each collar that returned from the field, the data files that were downloaded needed organizing and merging into a cumulative database. Initial processing of this database is required, to create a clean data file, ready for analysis by geographic information system (GIS) software which is designed to process spatially referenced data. The objective is to isolate all GPS locations that represent a position that was logged while the herd traced out its daily foraging route across the landscape, between leaving the corral and returning to it; inclusion of locations logged when the herd was in the corral would create artificial peaks of calculated grazing pressure. The rigor with which this initial processing is performed depends on the context, and it can be crude-but-simple - delete coordinates in the corral area - or, as we chose, based on a computer code that analyzes each daily route to pin-point exit and re-entry times. These approaches yield slightly differing results for reasons related to inherent GPS error.

The resulting dataset - which we sampled at 1-min intervals - is then imported into GIS software to be become a geographic layer, which then can be combined with other geographic layers that describe biotic and abiotic features of the landscape. It is really this application of GIS software that enables us to extract value from the GPS data.

The first and obvious step in examining the collected GPS locations is to simply overlay the entire collection onto an orthophoto (geometrically corrected aerial photograph), as a cumulative cloud, with no regard for the inner structure of the data, as related to daily foraging routes, as shown in Figure 3. This visualizes in one glance where the herd did - and did not - go, and the varied density of GPS points across the landscape gives a clear impression of the relative intensity of animal presence.

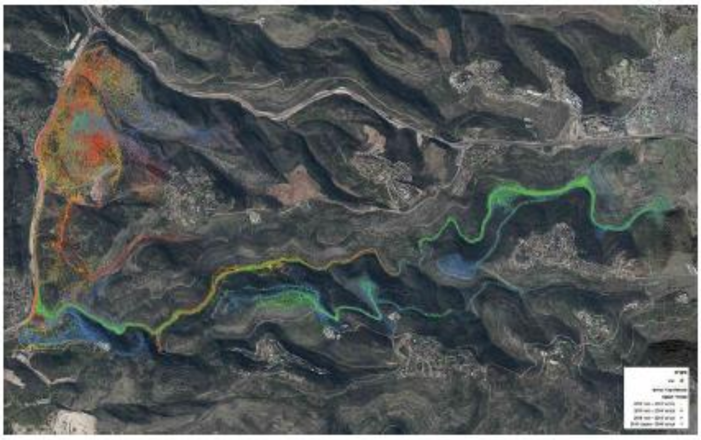

Figure 3. Visualization of the presence of one goat herd that grazed the Qedoshim Forest, in the Judean Hills, over four years. A serious wildfire occurred in this area in 1995, halting traffic on the main Tel Aviv–Jerusalem highway, Route 1 — which runs east-west in the top half of the image — and along Route 38 which runs south from it on the left of the image. Herd presence was determined by a GPS collar assembled in-house and installed on one animal in the herd. Each point represents one minute of presence of a herd of about 200 goats. Note how the spatial dispersion of the herd ranged from tight concentration along the fire-break corridor that follows the seasonally active Kesalon riverbed that runs east–west across the image and along a second fire-break corridor a short distance southward, to being relatively diffuse near the junction of routes 1 and 38. The approximately 520,000 GPS points are color-coded according to year.

The next step is to convert GPS locations to meaningful units as expressed in the language of range management: grazing-days per unit area. The concept of "grazing-days" encompasses both the number of animals and the duration of their presence. For example, 30 animals for 20 days and 15 animals for 40 days both comprise 600 grazing-days. We know that the area occupied by a herd at any point in time is approximately circular and we can estimate that area in various ways. Therefore, conceptually at least, we can draw such a circle around a GPS point and reason that the patch of rangeland under the circle accumulated animal presence (grazing-days) equal to the number of animals in the herd multiplied by the amount of time represented by one GPS point - in our case, 1 minute. If we divide that value by the area of the circle, we express this grazing pressure in standardized units of grazing-days per unit area. By means of suitable GIS tools this reasoning can be applied to the entire collection of GPS points and the result summed across all of them to generate a heat map of grazing-days per unit area. This is shown in Figure 4 at the regional level after one year of monitoring seven herds. Note that herd size is accounted for in this image, which would not be the case for a regional GPS point cloud.

The heat map of grazing pressure - expressed as grazing days per unit area — can be translated to units of herbage mass removed per unit area by assuming some normative value for the daily herbage intake of one animal. Some further assumptions underpin this approach but there is, as yet, no practicable animal sensor to measure the intake rate of grazing animals. Nevertheless, we conducted this exercise to gain a feeling for one of the two fundamental rate processes occurring in this system: herbage production and herbage consumption.

Is more widespread adoption of herd monitoring practicable? Based on our experience in the Judean Hills, we estimated that a land-management agency could scale this procedure up to the order of 100 herds for a total investment of $30,000 for the collars, 3 months labor, and a vehicle. The collars would probably be configured differently from the research mode, by using a power-saving mode in conjunction with a GPS fix interval of about 5 minutes. The power-saving mode would impose some loss of precision, and the relatively long fix interval (compared with our standard 10-s interval) would sacrifice some detail in tracing the meandering foraging route of the herd, but these would be acceptable compromises for a large-scale monitoring scheme, because they would greatly extend the period between col- ↘

→ lar changes. Algorithms have been developed to digest the many millions of data records such a scheme would generate and prepare them for GIS analysis. If land-management agencies see sufficient value in herd-location data to justify the cost of their acquisition, precision agriculture will have made a major entry into the vast and complex world of extensive grazing systems. ❑

ACKNOWLEDGEMENTS

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Areas of interest: primary productivity of rangelands, grazing behaviour and management, applications of remote sensing, GIS and GPS, acoustic monitoring and modeling.

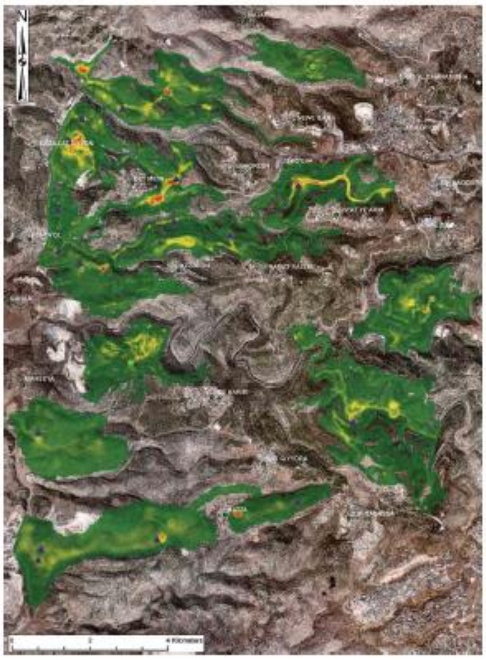

Figure 4. Heat-map of grazing pressure imposed by seven goat herds in the Judean Hills over 1 year, based on approximately 800,000 GPS points, each representing one minute of herd presence. Grazing pressure is expressed as grazing-days per unit area; it was computed from the GPS locations by factoring in: the area occupied by the herd at any given point in time, the number of animals in the herd, and the time interval between GPS fixes. Thus, the resulting values are comparable across the entire region despite differences in herd size. Values range from close to zero (dark green) to almost 500 grazing-days per 1000 m^2 (red). With this kind of information it becomes possible to approach the subject of grazing impacts in a quantitative way. Some of the regions of higher grazing pressure reflect the meandering contours of fuel-break corridors along seasonally active riverbeds, but there also are other patterns of spatial dispersion apparent in this image. Triangles show locations where night corrals are periodically established and populated.