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An increasing number of threats, both natural (e.g. fires, drought) and anthropogenic (e.g. agriculture, infrastructure development), are likely to affect both availability and quality of plants that grouse rely on for cover and food. As such, there is an increasing need to monitor plants and their use by grouse over space and time to better predict how changes in habitat quality influence the behavior of grouse. We use the greater sage-grouse *Centrocercus urophasianus* to showcase how new technology can be used to advance our understanding of the ecology, behavior and conservation of grouse. We demonstrate how laser, spectral and chemical detectors and unmanned aerial systems can be used to measure structural and phytochemical predictors of habitat quality at several spatial scales. We also demonstrate how advanced biotelemetry systems and robotic animals can be used to measure how habitat quality influences fine-scale habitat use, movement and reproductive effort of grouse. Integrating these technologies will allow researchers to better assess and manage the links among habitat quality (safety and food), resource acquisition (foraging behavior) and reproductive behaviors of grouse.

Galliform bird species in the *Tetraonidae* subfamily (grouse and ptarmigan, hereafter grouse) are of critical conservation concern (Storch 2007). Internationally, three of the 18 species of grouse are on the International Union for Conservation of Nature (IUCN) Red List as endangered or critically endangered, five are near-threatened or vulnerable, and an additional 14 grouse species are red-listed in at least one country (IUCN 2014). The perilous condition of many grouse populations can have billion-dollar-effects on local and regional economies because these species are harvested as game and some are sympatric with agriculture, energy development, tourism, recreation, forestry and urban growth. Because of the high economic stakes at play, some of the largest conservation initiatives in history have recently been launched to ensure persistent populations (e.g. <www.sagegrouseinitiative.com>). The success of these efforts will require new approaches for monitoring and mitigating threats to grouse, their habitats and ecosystems. Where can we turn for these crucial insights?

Recent technological developments have emerged that can help evaluate and address the many challenges facing grouse. These technologies can provide more extensive information than ever before about changes in habitat quality and habitat use by grouse and other wildlife. Much of this technology has been adopted to study basic questions in ecology, evolution and behavior and there are few direct examples specifically demonstrating the application of emerging technology in conservation and management. As such, researchers focused on management and conservation may be unaware of how this technology is used and how it could benefit the goals of their organizations and stakeholders. In this paper, we use research conducted primarily on greater sage-grouse *Centrocercus urophasianus* (hereafter, sage-grouse) in the sagebrush steppe ecosystem in the western United States to demonstrate the potential for how new technology can be used to advance our understanding of the ecology, behavior and conservation of grouse. Specifically, we describe 1) how laser, spectral and chemical detectors can be used to measure habitat quality at several spatial scales directly or remotely with unmanned aerial systems (UAS), and 2) how advanced biotelemetry systems and robotic animals can be used to measure how habitat quality influences grouse behavior (Fig. 1). Our goal is to disseminate examples of emerging

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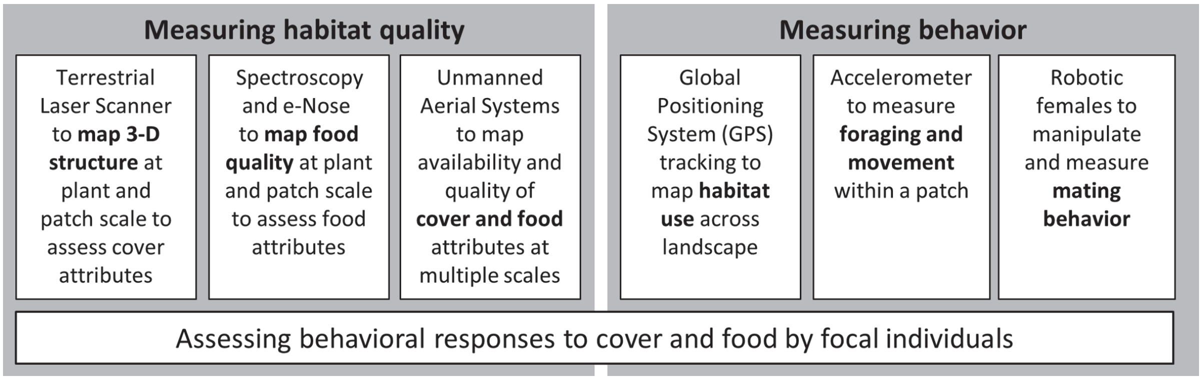

Figure 1. An overview of how data from different technologies can be used to examine the links among the structural features of habitats (cover), diet quality (food) and foraging and mating success in grouse (Tetraonidae subfamily) specifically and wildlife in general.

technology to a wide community of scientists who can best identify if, when, where, and how to apply these techniques in conservation and management of wildlife.

Measuring habitat quality

Habitats offer a range of structural features that influence predation risk and the thermal environment, and chemical features such as nutrients and toxic plant secondary metabolites that influence diet quality for animals. For example, grouse respond to the amount of aerial and terrestrial shrub cover that influences their predation risk (Wiebe and Martin 1998, Stonehouse et al. 2015). In addition, selection of habitats, patches and plants by grouse is influenced by phytochemicals (Guglielmo et al. 1996, Wang et al. 2012, Frye et al. 2013) that constrain energy budgets (Guglielmo et al. 1996), can influence reproductive success (Brittas 1988) and are hypothesized to reduce population stability through bottom–up changes in browsing (Feng et al. 2009, DeAngelis et al. 2015). Moreover, several habitat disturbances including management practices and changes in land use (Niemuth 2000, Signorell et al. 2010, Hancock et al. 2011, Beck et al. 2012, Davies et al. 2016, Bates et al. 2017) and climate change (Forbey et al. 2013, García-González et al. 2016) can change the availability and quality of vegetation used by grouse for cover and food. Consequently, there is an immediate need to develop rapid, predictable tools to measure the quality of vegetative cover and food for wildlife. New advances in remote sensing offer unique opportunities to map the functional quality of habitat for wildlife at the same spatial scales and resolutions as measures of habitat use (Féret and Asner 2014, Li et al. 2015). We illustrate how four emerging techniques, terrestrial laser scanning, spectroscopy, electronic nose and UAS, can expand our capacity to map the amount, quality and distribution of cover and food and to monitor these habitat features over space and time.

Terrestrial laser scanning

The structural characteristics of a landscape influence predation risk and therefore the quality of habitat for grouse. The resolution of most structural data collected from satellite imagery (e.g. vegetation types) or ground-based measures (e.g. line point intercept) often does not encompass all of the scales at which grouse might select habitat (i.e. plant, patch and landscape, Olsoy et al. 2015). High-resolution remote sensing, such as terrestrial laser scanning (TLS), provides scalable data and allows for flexibility in modeling and predicting habitat changes. TLS is a ground-based, active imaging method that rapidly acquires the three-dimensional (3-D) structure of the earth's surface and aboveground features including vegetation and infrastructure (Shan and Toth 2008). In a typical TLS system, a laser pulse is emitted from the scanner and when the pulsed energy hits an object, a fraction of it is returned to the sensor. The location of the point in 3-D space is calculated by knowing the angle of the pulsed energy and the precise time of flight. The TLS point cloud is very dense (~100–1000 points m^{-2}), but typically covers a small area (~0.01–1 km^2), making it ideal for projects requiring high detail at smaller scales for local studies or for use in scaling to larger landscapes (Li et al. 2015) (Fig. 2).

TLS has been used to calculate vegetation metrics and provide 3-D maps of both habitat and static measures of wildlife (Vierling et al. 2008). For example, TLS has been used to measure canopy structure and volume (Moskal and Zheng 2011). Other studies have measured habitat properties that are more directly related to habitat quality, such as terrestrial concealment and visibility across scales and from a range

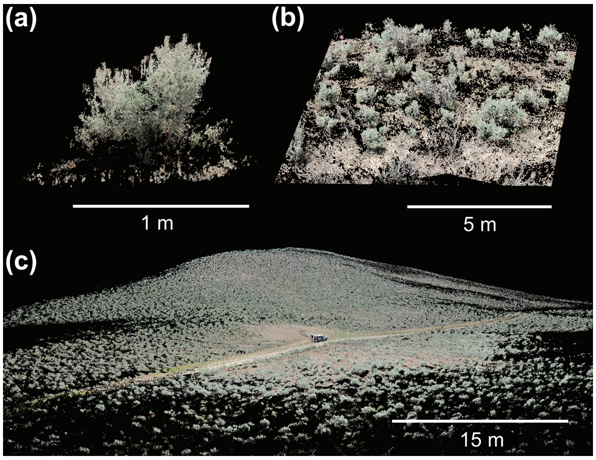

Figure 2. Three-dimensional point clouds from terrestrial laser scanning at multiple scales: plant (a), patch (b) and landscape (c) in the sagebrush (*Artemisia* sp.) steppe ecosystem, USA.

of vantage points representing predator sightlines (Olsoy et al. 2015). Field measures of vegetation cover and TLS-derived data have been demonstrated to be highly correlated and therefore may offer an alternative to time-intensive field methods in some ecosystems (Olsoy et al. 2015).

Although TLS has many advantages, limitations include computational expertise and access to potentially expensive equipment and software. Collaborating with researchers or government agencies with access to the equipment and software or adopting low-cost scanners (Eitel et al. 2013) and open-source software may alleviate the expense. In addition, many surveying companies use and rent TLS equipment, and national programs such as UNAVCO (Boulder, CO, USA) provide TLS support for researchers funded by the National Science Foundation (NSF, USA). Occlusion of objects and logistical challenges associated with areas containing dense vegetation or rugged terrain may be overcome by using the surrounding topography to strategically position the scans. When these challenges are overcome, TLS complements and can replace field methods at scales currently used to monitor habitat features for grouse and other wildlife. For example, TLS data can be used to quantify which lekking territories used by grouse have the largest reach (visual or acoustic) in signaling potential mates or competitors and which territories or nesting locations have the highest detectability by aerial or terrestrial predators. Moreover, TLS data can provide detailed vegetation structures associated with variation in successful territory establishment and maintenance, mating, and nesting, and detect how these features are altered by natural (e.g. fire, snow) or anthropogenic (e.g. logging, grazing) disturbances (Ashcroft et al. 2014, Olsoy et al. 2015).

Spectroscopy

Spectroscopy has contributed to ecological, geological, agricultural and hydrologic fields and is generally used to collect spectral signatures of a variety of targets across the ultraviolet, visible and near infrared portions of the electromagnetic spectrum. By calibrating targets to a known standard, these spectral signatures can be converted to measurements of absolute reflectance across the range of wavelengths collected by the spectrometer. Reflectance is defined as the proportion of light striking an object that is reflected, and it is a characteristic of the object being measured independent of light conditions. Libraries of reflectance spectra can be correlated with any number of chemical or physical characteristics (Mitchell et al. 2012, Couture et al. 2013).

Organic compounds including plant pigments and structural coloration in feathers or air sacs may correlate with portions of the reflectance spectra (Brink and Berg 2004). Birds can see in wavelengths captured by many spectrometers (Cuthill et al. 2000), and consequently, grouse may be able to sense the physiological quality of food and conspecifics they encounter (Hill and Montgomerie 1994). Therefore, spectroscopy has the potential to allow biologists to see the world from the perspective of grouse to understand their behavior relative to visual cues in their environment. We recently demonstrated that spectroscopy can differentiate three subspecies of sagebrush within a common garden (Fig. 3). These subspecies often overlap in range and are difficult to distinguish in the field based on morphological characteristics. However, herbivores including sage-grouse show strong foraging preferences among these subspecies (Frye et al. 2013). Mean spectral values and 95% confidence intervals of replicates within each subspecies identify portions of the spectrum that allow reliable differentiation, which likely reflects different physiological and phytochemical characteristics of the subspecies with the specific environment.

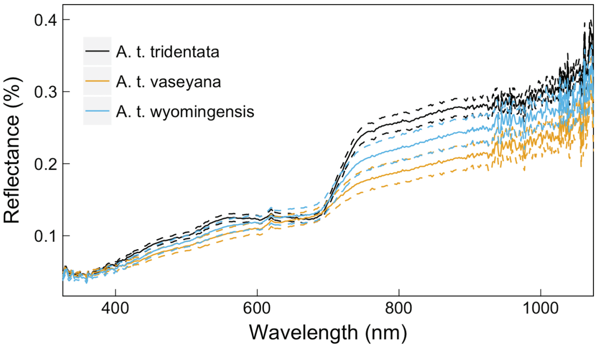

Figure 3. Reflectance (%) across wavelengths (nm) of light among three subspecies of big sagebrush (*Artemisia tridentata wyomingensis* in green, *A. t. tridentata* in red, *A. t. vaseyana* in blue, 95% confidence intervals as dashed lines) in a common garden established at the Orchard Experimental Site, Boise, ID, USA.

Spectroscopy can also map the distribution of plant species with different chemical constituents at larger spatial scales (Clark et al. 2005, Asner et al. 2014). Current laboratory-based instrumentation and supported chemometrics software enable rapid and repeat measurements of plant dietary quality (Mitchell et al. 2012). Expanding these capabilities to larger scales through portable and airborne instruments greatly reduces the time and resources necessary for traditional chemical analyses (Foley et al. 1998). These data can then be used to construct predictive models of plant–animal interactions (e.g. food preference) that can be mapped across larger spatial scales (Moore et al. 2010). Although spectroscopy has the potential to map and quantify countless chemical, physical and biological characteristics of targets, some limitations remain. Constructing reliable predictive models requires large libraries (i.e. hundreds to thousands) of spectral data (Foley et al. 1998). Collecting, storing and analyzing these data sets requires standardized protocols and specialized equipment, software and multivariate analytical techniques. Although instrumentation can be relatively expensive (ranging USD 15 000–150 000 depending on model), opportunities to lease or borrow instruments from manufacturers may offer researchers the chance to incorporate spectroscopy into their investigations without the need to purchase them.

Electronic nose

Volatile organic compounds (VOCs) represent a class of chemicals important for sensing and responding to plant defenses, finding mates or as an indicator of health. Although spectroscopy has been used to predict concentrations of chemicals in plants (Boegh et al. 2002, Tamburini et al. 2015), the ephemeral nature of VOCs may require additional methods for detection. Several electronic instruments have been developed as 'noses' to detect and compare chemical vapors for medical and environmental applications. In general, the 'electronic nose' (hereafter, e-nose) is trained to recognize classes of VOCs, which are cross-validated and used as standards for analysis of unknown samples. Chemical measurements are produced when a sensor recognizes differences in resistance (voltage decreases) produced by the volatile gases. Each sensor is unique, and therefore responds differently to particular VOCs, creating a chemical fingerprint, or 'smell print'. The patterns produced by sensors are analyzed using principal components analysis or other multivariate analyses for pattern recognition. The instrument compares the unknown samples to the 'smell library' in its memory and provides a qualitative assessment of the VOCs associated with the sample.

Although not commonly applied in wildlife studies, the electronic nose has been developed to detect volatile chemicals in several areas that could benefit grouse research. We recently tested the potential for the e-nose to differentiate species of sagebrush browsed by sage-grouse in Idaho, USA. We exposed the e-nose (Cyranose 320 by Sensigent Technologies, Baldwin Park, California, USA) to a training set of two species of sagebrush (*A. t. wyomingensis* and *A. tripartita*), then cross-validated the training set using additional samples from that site. The classification accuracy for identifying each sagebrush species (n = 2) was 100% at each site (n = 2, Fig. 4). The e-nose may be a valuable tool to easily and accurately verify the identity of morphologically similar species in the field. Moreover, the e-nose has the potential to classify fruit maturity and predict the nutritional quality of food (Pathange et al. 2006), which may help explain selective foraging observed by several species of grouse (Guglielmo et al. 1996, Wang et al. 2012, Frye et al. 2013). The e-nose may also be a valuable new tool to identify, diagnose and monitor infections in animals by analyzing breath, saliva or blood (Dutta et al. 2002, Cheng et al. 2009). In addition, the e-nose can be used to monitor air quality (Sironi et al. 2014) and exposure to heavy metals, herbicides and pesticides (Canhoto and Magan 2003) that may persist in soil that is ingested as grit. Finally, the e-nose could be used to study sexual selection and signaling, because the major histocompatibility complex markers that affect mate selection can be detected through olfaction and have previously been classified with an e-nose (Montag et al. 2001).

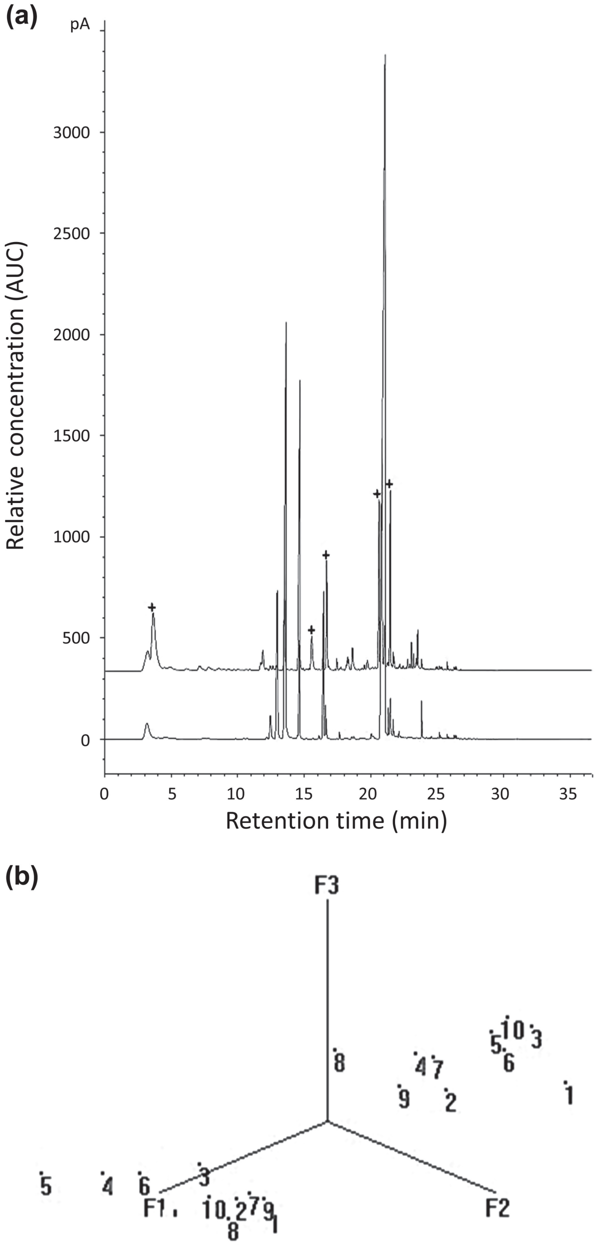

Figure 4. Sagebrush species (*Artemisia tridentata wyomingensis* (top) and *A. tripartita* (bottom)) have unique monoterpene (a class of volatile organic compounds) profiles, with unique compounds indicated by '+' (a). The e-nose automatically creates a principal components analysis (PCA) diagram of samples in the training set (b), which allows for quick visual comparisons of the unknown samples to training sets. In this example, the two species from the chromatogram (a) distinctly separate into two groups in the PCA (b). *Artemisia tripartita* groups together in the bottom left, and *A. tridentata wyomingensis* groups in the upper right.

The application of the e-nose to benefit our understanding of grouse will require several components that may be difficult to meet in some systems. First, an ideal training and cross-validation set consists of at least 20 samples per category and may be difficult to obtain for sensitive or rare species. Validation often requires analyses using more advanced bioanalytical techniques such as gas chromatography, which can be both costly and time-consuming. Additionally, the complexity of plant chemicals and biological samples from grouse may make the resolution of the e-nose limited in certain seasons or locations. The potential for high geographic variation in chemical profiles such as those observed in plants (Peñuelas and Llusià 2004, Fig. 4) make it necessary to train the e-nose for each population separately. Additionally, the e-nose is not capable of quantitative analysis and therefore cannot be used to identify mixed diets without analysis and validation of samples of known composition, further limiting use in the field. These limitations highlight the importance of strategically selected training sets and cross-validating data sets, and starting with a simple study design to learn the limitations of the instrument for each application. With this in mind, the e-nose has the potential to be an effective instrument for a wide variety of studies related to the chemical ecology of grouse.

Unmanned aerial systems

Unmanned aerial systems (UAS) provide increased opportunities to remotely assess both structural and phytochemical habitat features at increasing spatial scales across diverse ecological systems (Anderson and Gaston 2013). UAS is a promising platform for light-weight lidar sensors to provide intermediate to fine-scale 3-D point clouds to assess structural attributes of habitats. The fine-scale point clouds derived from emerging lidar technology on UAS platforms provide the height metrics that can characterize the understory and canopy in forest ecosystems and grasses and shrubs in temperate, alpine and arctic ecosystems. In addition, imaging spectroscopy (hyperspectral, typically visible to shortwave infrared wavelengths) with UAS enable assessment of biodiversity and plant function (Zarco-Tejada et al. 2013). Because the spectral fingerprints obtained from imaging spectroscopy reflect phytochemicals (Foley et al. 1998, Moore et al. 2010), these images have the potential to not only map availability and distribution of plant species, but also provide information about the dietary quality of forage for grouse. Further, thermal and shortwave infrared sensors on UAS and other aerial platforms have been successfully used to survey wildlife populations (Linchant et al. 2015) as an alternative to conventional, ground-based observations.

One of the primary advantages of UAS remote sensing is the ability to collect fine-scale habitat data over relatively large areas. For example, we captured high-resolution digital images using true color, multispectral and infrared sensors which we classified using object-based image analysis similar to Laliberte et al. (2010) (Fig. 5). We are expanding this initiative to include hyperspectral sensors to scan shrubs and patches with known intensity of use by sage-grouse and other wildlife based on telemetry or on-ground measures of use. In addition, UAS with onboard wildlife tracking systems can reduce human effort required to acquire signals from directional antennae over complex terrain.

Application of UAS for wildlife research requires consideration of a number of issues. First, choosing the UAS platform (multi-rotor or fixed-wing) that is capable of carrying the required sensor and covering the study area necessitates a balance between time spent collecting and processing data versus cost. Multi-rotor UAS are a lower cost platform, yet they lack the extended flight time of fixed-wing systems because of payload limits and battery capacity. Second, choice of mission-specific sensors depends on the research questions or management goals, necessitating a clear rationale for what data are required. Third, weather conditions can require repeated flights and increase expense, especially if a study site is at high elevation or subject to high winds. Fourth, processing high-resolution imagery and performing geo-referencing requires sufficient computational power and access to appropriate software (e.g. Agisoft's Photoscan (St. Petersburg, Russia) or Pix4D (Lausanne, Switzerland)), and analysis of the processed UAS imagery requires expertise in GIS and remote sensing. Finally, scientists need to understand and address regulatory constraints of UAS use. In the United States, the Federal Aviation Administration (FAA) requires either Certificates of Authorization or a Section 333 Exemption before flights are conducted. Permission to conduct UAS flights can take several months to obtain, and the presence of a qualified pilot and ground observer may be needed to comply with national airspace requirements. Further, UAS platforms may have special certification and registration requirements, and many academic institutions and government agencies require additional insurance policies to cover liability of UAS operated by researchers. UAS-based sensors offer the opportunity to collect data related to habitat quality and animal behavior at scales and resolutions that are revolutionary for wildlife research.

Management applications of technology for measuring habitat quality

Managers require reliable information about the quality of habitat features to restore and conserve habitats (Beck et al. 2014), select suitable habitat for reintroductions (Marshall and Edwards-Jones 1998), and predict occupancy and performance of wildlife populations (Holloran et al. 2005). This information must be relevant to the scale of management, which is often entire landscapes, and it must reflect the functional value of the habitat to the population. However, measuring important habitat features such as food and cover in ways that are meaningful for management often is difficult, expensive and labour-intensive. For example, even accurately characterizing the concealment provided by a specific plant species in a study plot or measuring the nutrient and chemical properties of one plant species over a landscape

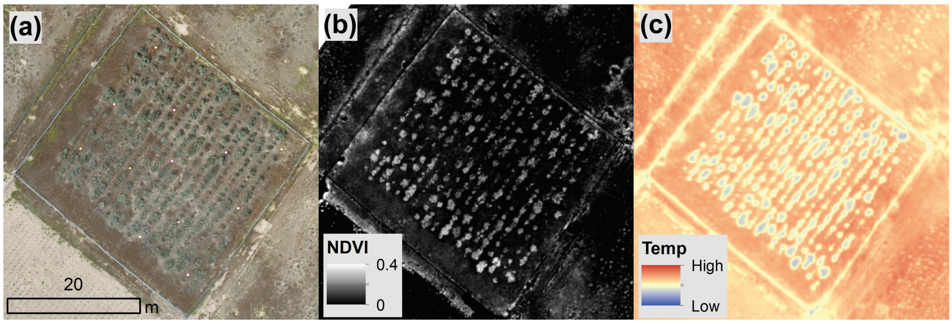

Figure 5. Example of images obtained using an unmanned aerial system (ebee, Empire Unmanned, Advanced Aviation Solutions, LLC, < www.adavso.com >) at a common garden near Boise, ID, USA containing three subspecies of sagebrush (*Artemisia* sp.). Images from true color sensors (a) can reveal morphological attributes (e.g. estimate crown cover). Images from multispectral sensors (b) can reveal physiological or chemical attributes (e.g. gradient of normalized difference vegetation index (NDVI)). Images from infrared sensors (c) can reveal gradients of temperatures (Temp). Individual images from UAS data capture are seamlessly stitched together using structure-from-motion photogrammetry to generate an orthomosaic and digital elevation model. An object-orientated approach is used to segment the image based on feature boundaries and topography. A rule set can be developed using area, shape, texture or reflectance to produce a classification specific to vegetation.

often is beyond the budget of management agencies. As a consequence, wildlife managers often rely on surrogate variables that are easy to measure in the field or can be obtained from databases, but are only indirectly related to animal behavior and fitness parameters, such as tree height or basic land cover categories. However, with proper calibration, the technologies we have described can increase the speed and scale, and reduce the cost, of assessing habitat features of functional value to grouse and other wildlife. The technologies reviewed here have been applied successfully in shrubland ecosystems and also can be applied in other habitat types used by grouse (e.g. prairie, forest or tundra). Integrating information and insights gained using newer technologies with traditional knowledge and assessment of habitat status can help to make management more effective, efficient and responsive to environmental changes.

Measuring animal behavior

Answers to many questions in wildlife ecology and management require not only knowing where animals spend their time, but also how they use different habitats. Animals select features of their habitat at a variety of spatial and temporal scales, and they often trade off habitat features across scales (Godvik et al. 2009). For example, increased perception of predation risk can reduce intake through increased antipredator behavior (Watson et al. 2007) and may result in decreased reproductive success (Zanette et al. 2011). The tradeoffs animals make among foraging, mating, predation risk and the abiotic environment can therefore have important fitness consequences. Understanding those tradeoffs at the appropriate spatial scale(s) will increase our capacity to conserve and manage for higher quality habitats. We illustrate how advanced telemetry systems can be used to assess specific foraging and mating behaviors of grouse and how biomimetic robots can be used to measure the mating behavior of grouse.

Advanced telemetry systems

Understanding the consequences of habitat quality requires measuring where and how animals use cover, food and other resources within habitats. Characterizing behavior and space use via traditional radiotelemetry is not always practical because of time and logistical constraints, whereas newer satellite technologies can be prohibitively expensive. Moreover, radio tags that combine low weight, long battery life, and sufficient transmitting power may not be available. Fortunately, recent advances in the next generation of telemetry systems are opening up a ‘golden age’ for studies of movement, behavior and habitat use of animals (Kays et al. 2015, Wilmers et al. 2015). Telemetry devices are becoming both smaller and more powerful, allowing for collection of a variety of environmental (e.g. light levels, magnetic field strength, audio and video recordings), behavioral (e.g. proximity logging, acceleration and posture) and physiological data (e.g. body temperature and heart rate) at extremely fine temporal and spatial scales (Kays et al. 2015, Wilmers et al. 2015).

As an example, we are investigating the relationship between on-lek courtship dynamics and off-lek foraging behavior of male sage-grouse. We recently pioneered the use of an encounternet telemetry system (Mennill et al. 2012) to obtain detailed movement data from free-living grouse. This system consists of rump-mounted tags containing both a GPS and 3-axis accelerometer sensor modules. Data are stored locally on tags until remotely downloaded by hand-held receivers or stationary logging stations placed near male territories on the lek. The series of GPS locations provide a detailed map of where lekking male sage-grouse travel when away from the breeding grounds (Fig. 6). Additionally, collecting video of focal individuals engaging in known behaviors allows classifying samples of accelerometer data to common behavioral categories (Fig. 7). These classification rules then can be applied to off-lek samples to estimate the behaviors, such as roosting or foraging, that occurred at the time of each GPS fix (Nathan et al. 2012). In our study, we use encounternet telemetry systems to evaluate how diet quality across the landscape and within patches influences off-lek movement distances and patch level movements. These insights may explain how males vary in their energy budgets (Vehrencamp et al. 1989), thereby making sense of critical variation in courtship effort and the tactical decisions made by males on the lek (Patricelli and Krakauer 2010).

The combination of these data sources allows us to link fine-scale maps of grouse activity with high-resolution patch-scale measurements of habitat quality (e.g. TLS and UAS described above) and courtship. However, next generation telemetry may not be a panacea, because the technology may be constrained by both existing and new limitations for animal tracking studies. For example, because downloading data stored on tags requires placement of a receiving device relatively close to transmitters, the ability to retrieve data is easiest when movements are predictable, as would be the case for birds using the same lek, breeding territory or winter resource. For species with less predictable patterns of space use, collecting data may require combining traditional radio

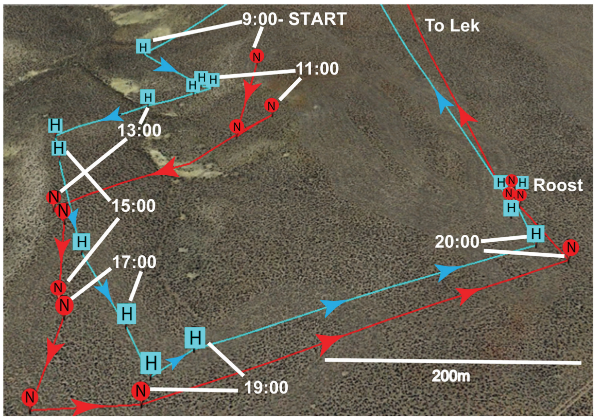

Figure 6. A day in the life of two male sage-grouse *Centrocercus urophasianus*, as revealed by the GPS logging function of encounternet tags. Male N (red circles) and male H (blue squares) departed the lek (out of top of frame) before 9:00 h. Squares and circles represent GPS fixes recorded at approximately 1h intervals. Movement of both birds was characterized by a combination of longer movement lengths and shorter inter-fix distances that may represent periods of resting or foraging. At dusk (~19:00 h), the two birds appeared to move together towards a roosting site at the right side of the map, remaining there until returning to the lek before sunrise the following morning.

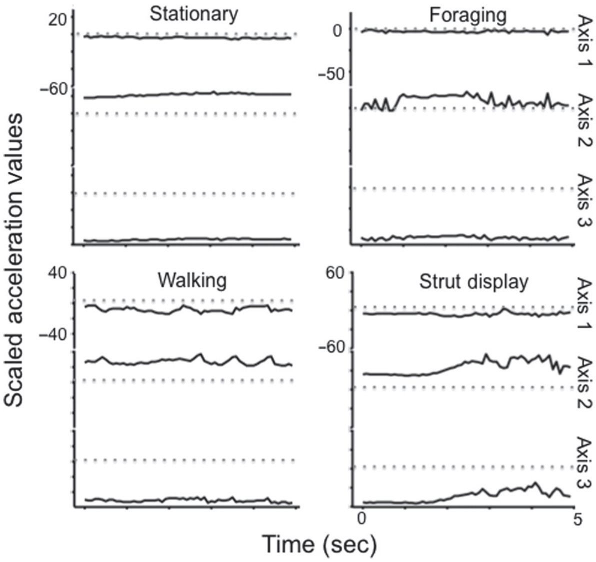

Figure 7. Examples of three-axis accelerometer traces of four common behaviors of male sage-grouse *Centrocercus urophasianus*: standing stationary, foraging, walking and strutting with scaled measures of acceleration on the vertical axis. The vertical scales are the same for each behavior, with the zero indicated by a dotted line. These data were obtained from males directly observed on the lek. A library of such samples can be used to train algorithms to classify unknown samples.

and cellular technology, along with aerial retrieval of data using manned or unmanned aircraft (Williams et al. 2014, Gonzalez et al. 2016). Moreover, tags that transmit large amounts of data may operate on higher radio frequencies than traditional VHF telemetry, which can limit transmission distance. The large amounts of information recorded also require dedicated workflows to manage and analyze the rich and varied sources of data. An additional consideration is that the flexibility in sampling schedules typical of custom-made devices can make them more difficult to optimize under field conditions compared with off-the-shelf solutions. Researchers should budget for that time when planning their research. Finally, as with any type of telemetry, care should be taken that the transmitter weight, visibility and attachment do not negatively affect the behavior of the organism.

Biomimetic robots

Biomimetic robots – machines designed to emulate actions performed by humans or animals – can be a powerful tool for studying behavioral interactions in wild or captive animals (Webb 2008, Patricelli 2010, Krause et al. 2011). Robots enable a 3-D version of one of the oldest tools in the animal behaviorist's kit, the playback experiment, where simulated signals or behaviors are played back to elicit a response from other animals. Robotic playbacks allow the manipulation and experimental control of animal characteristics such as movements, plumage patterns or vocalizations, in isolation or in combination. For example, robots can be used to assay individual differences in animals' responses to a controlled conspecific or predator stimuli across different contexts or levels of anthropogenic disturbance, allowing comparisons of traits such as fearfulness, aggressiveness and vigor (Patricelli et al. 2002, Patricelli and Krakauer 2010). Simple robots have also been used to stimulate conspecific cueing, attracting animals into unused but suitable habitat (Ackerman et al. 2006, Patricelli 2010); combined with acoustic playback, this might be especially useful for establishing new grouse leks after restoration or reintroduction. Robots with embedded sensors have also recently been used to minimize the stress of collecting long-term demographic data on animals wary of humans (Le Maho et al. 2014).

We have used remote-controlled robotic female sage-grouse to imitate female behaviors of interest and collect audio and video data from the perspective of females on the lek. The first-generation robotic female (Fig. 8a) could pivot to face target males and rotate the head from side to side to simulate looking around. Second-generation robotic females can perform similar behaviors, as well as imitate foraging behaviors by tilting the body and neck towards the ground (Fig. 8b). Both robots are covered in the skin and feathers of real female sage-grouse, donated by wildlife agencies. These

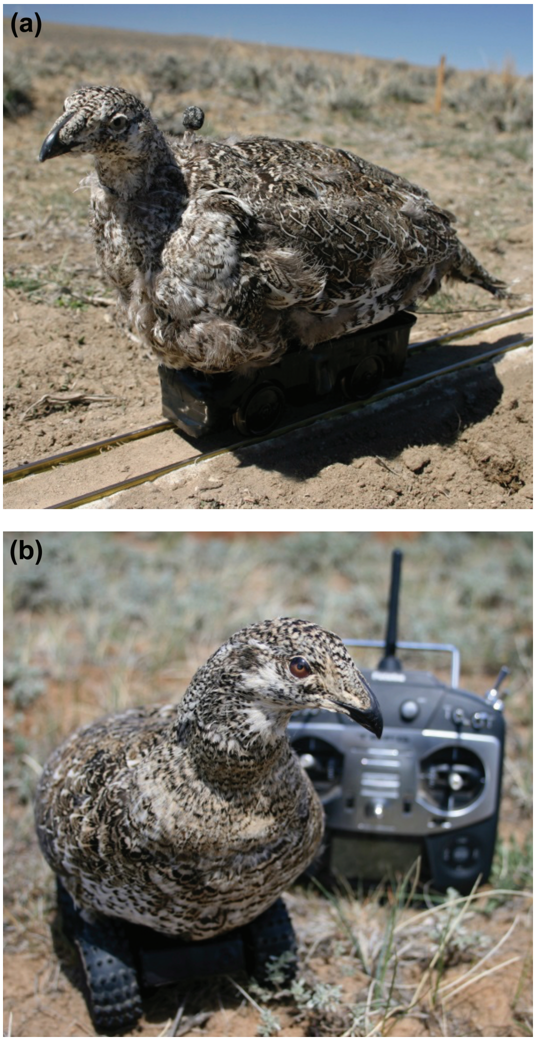

Figure 8. The first-generation robotic female sage-grouse is shown on model train tracks which allow the robot to traverse the lek and approach courting males (a). The second-generation robot, which can move on four independently-rotating wheels and imitate female behaviors, is shown with the remote controller used to manipulate movements during experimental courtship interactions (b).

robots have been used to address the function of female behaviors during courtship and elicit male display behaviors in controlled experiments on free-living male sage-grouse on leks in Wyoming, USA. Robotic female stimuli provide an effective assay of male courtship behavior in sage-grouse – males responded similarly to the first generation robot and real females (Patricelli and Krakauer 2010), and there is a strong correlation between individual males' estimated tendencies to continue a display bout with the second-generation robot and real females (Fig. 9). Robots also permit the collection of courtship data from targeted males on the lek, including peripheral or juvenile males that real females may avoid. This allows the study of how selection acts on male display behavior, by allowing researchers to investigate links between measures of display behaviors and measures collected using other methods, such as foraging behaviors, demographic information and mating success on the lek.

Although robots open new possibilities for studying grouse behavior, they may be challenging to use in some situations. Some mobile robots may have difficulty with rough or wet terrain. More importantly, robots built with current technology will typically succeed in mimicking only the simplest behaviors. Robots that can imitate the complex breeding displays of male grouse – and which can fool highly-discerning females – are likely outside the budget of most research projects, if possible at all. Despite these challenges, robots have been adapted to work in a diverse array of species (Patricelli 2010). With the addition of biologgers and spectral or VOC sensors to existing audio and video sensors, robots may help us to reveal new acoustic, visual and olfactory interactions among grouse and add a new dimension to the study of grouse behavior, ecology and conservation.

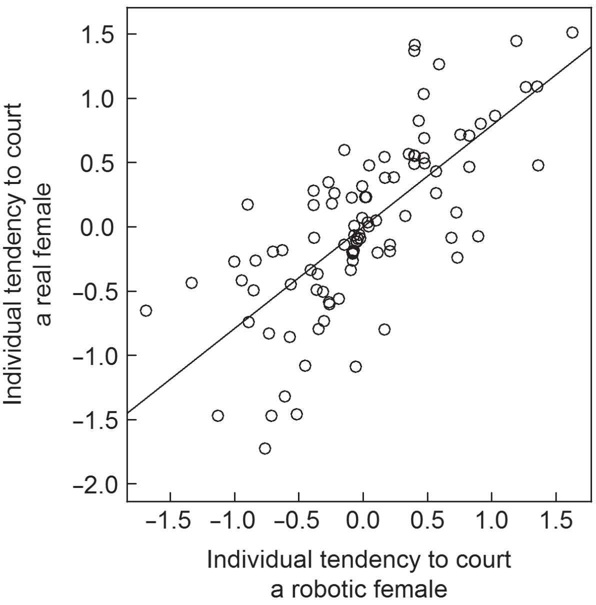

Figure 9. Relationship between courting behavior of males with a second-generation robot versus a real female. Each point represents the posterior mean for an individual male's log odds of continuing a bout of active strutting in response to the second-generation robot and a real female (generated using a hidden Markov model). Males' individual relative tendency to continue a display bout with the robot correlated strongly with their estimated relative tendency to do so with a real female sage-grouse ($r^2 = 0.72$, $t = 10$, $df = 94$, $p < 0.001$). Strut data were collected from 96 males across three leks during interactions with either a robotic or real female in 2012 (10 observation days per type of stimulus).

Management applications of technology for measuring behaviors

Animal behavior is an important aspect of conservation biology, influencing habitat use, reproductive success, and interactions among individuals. The technologies discussed here can help to identify and measure management-relevant behaviors for a wide variety of grouse species in almost any habitat. Advanced telemetry systems may be useful for measuring habitat use and movements, which can be used in resource selection functions and multi-scale habitat assessments. Managers will be familiar with spatial data from these methods as telemetry data on animal locations have long formed the backbone of autecological studies. In at least some cases, ready integration of these additional data types is available from existing software platforms (e.g. AcceleRater for accelerometer data, <www.accapp.move-ecol-minerva.huji.ac.il/>), and platforms for storage and sharing of rich animal movement data already exist (e.g. MoveBank, <www.movebank.org>). Additionally, Encounternet and similar systems can provide information about contact among individuals, which is valuable for studying group dynamics, disease transmission and territory use. Biomimetic robots may also allow data collection when animals are difficult to approach (Le Maho et al. 2014). Video sensors in robots can be used to target specific individuals under specific social conditions, collecting data on variation in behavioral traits of individuals (e.g. 'shyness' or 'boldness') that may be difficult to evaluate from trail cameras or other sources. There is increasing evidence that understanding the variation of these traits can help explain reproductive success and survival in a variety of species (Both et al. 2005, Smith and Blumstein 2008, Cole and Quinn 2014, Madden and Whiteside 2014). In addition, behavioral data obtained from biomimetics could be used to target collection of individuals with specific traits that are associated with more successful captive breeding (Fox and Millam 2014) or translocation efforts (Bremner-Harrison et al. 2004). Thus, technologies developed for basic research on animal behavior may facilitate or complement applied research by elucidating links between habitat use, reproductive behaviors, and other measures, such as survival and/or disease transmission.

Conclusion

The technologies we have described that were primarily developed for sage-grouse offer new approaches for the conservation of grouse and other herbivores under variable management regimes and across changing habitats. The combination of structural and phytochemical predictors of habitat quality that can be measured with new technologies, paired with current monitoring of habitat use, movement and reproductive effort, could significantly expand our understanding of the ecology of grouse (Fig. 1). For example, the radio-tracking system can be used to link movement patterns of grouse with structural (from TLS and UAS) and phytochemical (from sensors on UAS, spectroscopy or e-nose) quality of plants and patches used by grouse to identify which habitat features best predict habitat use at a variety of spatial scales. Combining an understanding of the quality of habitats used by grouse with variation in male display behaviors, as measured and manipulated with female robots, allows us to examine the ecological links among off-lek foraging and roosting behavior, topography and vegetation cover, diet quality, display behaviors and ultimately fitness.

The decision to take advantage of these newer forms of monitoring will depend on the value of answers to questions that cannot be addressed using more traditional methods alone. For example, the following questions may be examined by assessing behavior from telemetry, accelerometers and biomimetics, and by assessing habitat features using TLS, UAS, spectroscopy and e-nose:

- Which fitness-critical behaviors occur in different areas, and what physical and phytochemical characteristics of the habitat explain these patterns?
- How do individuals of different reproductive value (e.g. juveniles versus adults) differ in their habitat use?
- How does the quality and level of disturbance in a habitat relate to foraging, anti-predator and reproductive behaviors of individuals?
- How much variation is there in the behavior and movement of individuals, and how important is this variation for understanding population processes?

Not all management decisions will require answers to these questions. However, as the use of these technologies become more commonplace, it will become easier to incorporate additional levels of complexity and realism in to conservation models. Moreover, these technologies create important opportunities to integrate basic scientific research into management decisions. In all cases, we urge the scientists developing these technologies to collaborate with the managers who might benefit from these technologies to identify research objectives and clear rationale for what data are required, how it can be gathered, and how it will be used.

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