Spatial and environmental patterns of off-road vehicle recreation in a semi-arid woodland

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Abstract

Outdoor recreation is a widely recognized cultural ecosystem service. Ensuring that appropriate, high quality recreation opportunities are available requires, among other factors, knowledge of the environmental preferences of recreation users and spatial indicators of where those environmental features exist on the landscape and offer the potential to meet recreation goals. Diverse types of outdoor recreation exist, and different forms of recreation may be associated with different environmental features. The focus of this study is off-road vehicle (ORV) recreation. We demonstrate how readily available spatial environmental datasets, including high resolution image data provided within GoogleEarth, can be used to develop a cost-effective, objective indicator of ORV recreation across a landscape, which can inform management to provide desired recreation opportunities while protecting ecologically sensitive areas.

ORV recreational tracks were delineated from GoogleEarth imagery throughout our study area in the Great Western Woodlands of Western Australia. In this region, ORV use is a popular recreation activity and a growing concern of conservation organizations, but is not yet actively managed. Most recreational ORV tracks in the study area are informal and user-created. Mapped ORV recreation tracks were used to model and map the environmental associations of ORV recreation. The pattern of existing tracks indicated associations between recreation and noteworthy environmental amenities in the study area such as the shores of salt lakes and rock outcrops with high ecological and cultural value. However, one of the most important determinants of ORV track presence was accessibility, especially proximity to a road. Access infrastructure, such as proximity to roads, is often used to proxy demand and use in expert-based spatial assessments of ecosystem services. The results of our empirical model underscore the importance of incorporating patterns of both supply (i.e., desired natural amenities) and demand (i.e., access) into ecosystem service assessments. In addition, when integrated with maps of environmental sensitivity and more detailed information about human use, the predictive map of areas providing potential recreation experiences can be used for comprehensive spatial planning of sustainable ORV recreation. One possibility suggested by our results is that careful planning and management of access routes may be an effective means to achieve sustainable ORV recreation.

1. Introduction

Ecosystem services are expanding the range of motivations and funding sources for conservation (Goldman and Tallis, 2009) and highlight the importance of integrated land use planning (e.g., Goldstein et al., 2012). Ecosystem services are the benefits that species and the environment provide to human societies, including the supply of such entities as natural resources, cultural resources, and fresh air and water (Millennium Ecosystem Assessment, 2005). Of these benefits, cultural ecosystem services are readily identifiable by the broader public because they involve direct engagement with the environment (e.g., Raymond et al., 2009). Despite this conceptual advantage, the complexity of social systems and cultural preferences has caused them to receive relatively less study to date than other, more tangible ecosystem services, and has limited the development of the spatial indicators of cultural services for use in planning and management (Balmford et al., 2008; Daniel et al., 2012; Hernández-Morcillo et al., 2013; Martínez-Harms and Balvanera, 2012).

1.1. Spatial indicators of recreation services

Recreation and tourism are among the most studied and operational cultural ecosystem services (Hernández-Morcillo et al., 2013; Martínez-Harms and Balvanera, 2012; Pleininger et al., 2013; Seppelt et al., 2011). Nevertheless, there is substantial need for continued research into the spatial distribution of recreation services and the environmental features that meet recreation goals. Although many protected areas monitor aggregate visitor numbers, less is known about the specific locations of recreational activities (Buckley, 2003, 2008; Hadwen et al., 2007) or impacts (Cole, 2004; Ouren et al., 2007). Instead, spatial planning exercises typically rely on expert judgment to relate recreation values to environmental variables and map the distribution of recreation services (e.g., Chan et al., 2006; Lautenbach et al., 2011; Haines-Young et al., 2006; van Oudenhoven et al., 2012; Willemen et al., 2008). Yet expert-based maps are essentially untested hypotheses of the environmental associations of the ecosystem service of interest (Carpenter et al., 2009; de Groot et al., 2010; Haines-Young et al., 2012). Further, this practice has been criticized because it does not explicitly consider actual recreation use preferences (Kliskey, 2000). Indeed, participatory exercises have revealed that expert and user groups differ in their identification of the relative importance of various environmental contributors to recreation value and the resulting maps of recreation services (Nahuelhual et al., 2013).

Alternatively, environmental preferences of recreationists can be directly determined with user surveys or participatory research methods. Such preferences may be linked to spatial data layers to map recreation preferences across a landscape (e.g., Albritton and Stein, 2011; Goossen and Langers, 2000; Kliskey, 2000; Oishi, 2013; Snyder et al., 2008). This type of research may demonstrate that recreation preferences may not be accommodated by the existing opportunities (Oishi, 2013), which may lead to reduced visitor satisfaction (Boers and Cottrell, 2007) or problematic unmanaged recreation (Brooks and Champ, 2006; Snyder et al., 2008; Turton, 2005; Wimpey and Marion, 2011).

Finally, recreation services have been empirically modeled by relating observed patterns of visitor use to spatial environmental variables. Locations of recreation activities can be determined from surveys (Bateman et al., 1999; Termansen et al., 2013), participatory mapping (Sherrouse et al., 2011), or evidence of free-ranging recreation activities such as tracks or informal trails (Braunisch et al., 2011; Coppes and Braunisch, 2013; Matchett et al., 2004; Wimpey and Marion, 2011). Empirical recreation indicators avoid uncertainties in how to represent user preferences or expert opinion with existing spatial data layers and explicitly test relationships between environmental characteristics and recreation occurrences. However, they are correlative models of the environmental associations of recreation and do not explicitly determine causal mechanisms such as personal recreation preferences.

1.2. Off-road vehicle recreation

Another reason for the incompleteness of our understanding of recreation services is the heterogeneity of recreation activities that are possible, with correspondingly diverse preferences (Albritton and Stein, 2011; Bagstad et al., 2011; Goossen and Langers, 2000; Sherrouse et al., 2011). Consequently, different forms of recreation are unlikely to be well represented by a collective recreation indicator. Such heterogeneity continues to grow as new technologies stimulate novel forms of outdoor recreation (Burgin and Hardiman, 2012). One relatively recently developed recreation activity that continues to grow in popularity is off-road vehicle (ORV) use (Burgin and Hardiman, 2012; Cordell et al., 2005). Much of the existing research of ORV recreation is restricted both geographically and environmentally (Buckley, 2004; Stokowski and LaPointe, 2000) to desert (Ouren et al., 2007) and coastal (Priskin, 2003) settings. Considerable basic research remains to be done on the preferences, patterns, and impacts of ORV recreation (Monz et al., 2010; Pickering and Hill, 2007). Given the potential for social and environmental conflicts in areas where ORV recreation overlaps with other types of recreational use or with ecologically sensitive areas (Brooks and Champ, 2006; Shilling et al., 2012), a spatial perspective should be brought to the planning, monitoring, and management of ORV recreation. Rigorous spatial indicators of ORV recreation can also contribute to our understanding of the environmental preferences of recreationists.

This study characterizes the spatial and environmental patterns of recreational ORV tracks in a semi-arid woodland of Western Australia where ORV recreation is largely unmanaged and occurs on informal tracks created by the recreation users. The objectives of this project were to (1) develop a spatial inventory of ORV tracks throughout the study area and (2) use predictive modeling to identify the environmental associations of ORV recreation and to map other locations of potential recreation opportunities. Because much of the ORV recreation in this region occurs on informal tracks created by the recreation users themselves, it is assumed that they occur in environments that provide desired recreation experiences (Coppes and Braunisch, 2013; Wimpey and Marion, 2011). Thus, the modeled environmental associations can suggest inferences into the environmental preferences of ORV recreationists and these and the resulting maps of observed and predicted recreation occurrence can inform effective management to balance recreational use and conservation.

2. Methods

2.1. Study area

The study area is a 1,700 km^2 area surrounding Lake Johnston within the Great Western Woodlands (GWW) of Western Australia (32.3°S, 120.8°E; Figure 1). The GWW is a remnant of formerly widespread semi-arid woodlands and is considered to be the largest intact Mediterranean-type climate woodland in the world (Department of Environment and Conservation, 2010). Notable environmental features of the GWW include numerous rock outcrops and ephemeral salt lake playas. The rock outcrops have high conservation and cultural value (Main, 1997, 2007). ORV recreation is popular in Western Australian woodlands but has not yet been researched in these systems (Buckley, 2004).

The study area is ~100 km from the nearest settlement (Norseman). It contains two maintained roads, several tourist facilities, and a network of tracks normally only accessible by four-wheel drive. These tracks are used for transportation, mineral exploration, recreation, or a combination of uses. There is no comprehensive inventory of tracks in the study area; few are included in regional maps (typically the longest tracks that provide shortcuts to surrounding roads). The study area is representative of the large tracts of unallocated crown lands in the GWW. It is monitored but not actively managed by the Department of Parks and Wildlife and portions of it have been proposed for protection (Department of Conservation and Land Management, 1991). There are concerns that rock outcrops are subject to degradation by unmanaged ORV recreation in this area.

2.2. Mapping ORV tracks

Tracks were mapped by manual photointerpretation of high resolution image data available within GoogleEarth (Google Inc., Mountain View, CA). One limitation to the operational use of high spatial resolution satellite imagery in environmental management and monitoring is that such data can be quite expensive to purchase. The image sets targeted by this research are freely available, offering great potential for environmental science and management, which has not yet been widely harnessed. Thus, one of the goals of this study is to demonstrate a rigorous application of such resources.

At the time of our study, GoogleEarth provided high resolution true colour image mosaics with full coverage of the study area acquired by the SPOT, QuickBird, and/or WorldView-2 sensors (with native resolutions of 2.5 m, 2.4 m, and 1.85 m, respectively, although the latter two image sources have been pan-sharpened to sub-meter resolution). It can be difficult to determine the acquisition parameters of any given location within a GoogleEarth mosaic (Monkkonen, 2008), but imagery of our study area seems to have been acquired over 2006-2012.

Visible linear features were digitized within GoogleEarth, and exported to ArcMap (ESRI Inc., Redlands, CA) for further analyses. We restricted our focus to 4-wheel drive (4WD) vehicle tracks as they are easier to distinguish than single-track routes (such as for motorbikes) and a dominant mode of access and recreation in the study area. Although trail bikes may be common for localized exploration, they are generally brought into specific areas on 4WD vehicles, which are more practical for reaching remote areas with equipment and supplies. Digitized tracks were placed into three categories using spatial characteristics and auxiliary information: (1) *Gazetted roads* were those identified on maps of the area. (2) *Mineral exploration tracks* were short, straight, and occurred in grids that did not deviate around landscape features. (3) *Multipurpose/recreational tracks* were less regular than exploration tracks and their lengths were quite variable. Longer multipurpose tracks may be included in regional maps, but if so they are unnamed. Some of the motivations of recreation track creation can also be deduced from track spatial pattern. In addition to seeking access to new areas, views, or environmental features, informal tracks may be instituted to avoid undesirable or non-navigable conditions (Wimpey and Marion, 2011), resulting in a braided pattern of tracks evident in high resolution image data (e.g., Priskin, 2003). Because our interest was in the environmental associations of recreational tracks, we digitized what appeared to be the main routes in an area and did not consider very short detours or braiding as independent tracks. The accuracy of the digitized tracks was assessed against a limited set of ground reference points of track presence/absence using a confusion matrix (Congalton, 1991).

2.3. Modeling environmental associations of ORV recreation

An empirical model of the environmental associations of ORV recreation was developed from a random sample of multipurpose/recreational track locations (n = 461, split into 231 training and 230 test locations) and spatial environmental data layers of the study area.

2.3.1. Environmental variables

The expected motivations for ORV recreation in the study area are scenic vistas, solitude, skill-testing terrain, and travel to other recreation opportunities (Taylor and Prideaux, 2008). Six environmental variables were chosen to represent these factors, as well as site accessibility. The first four variables describe the main environmental amenities in the study area: the locations of salt lakes, rock outcrops, sites of high elevation relative to their surroundings, and characteristics of the land cover. The remaining two variables describe road access and the presence of tourist infrastructure. The expected links between each of these variables and the primary motivations for ORV recreation are elaborated in Table 1.

The data sources used and details of how they were processed to develop the final variables included in spatial models of ORV recreation are listed in Table 2. Briefly, lakes, rock outcrops, roads, and tourist facilities (such as camp sites and rest areas) were all parameterized with distance-to surfaces (at 30 m resolution). This representation recognizes that these features serve as attractors or sources of recreationists, and thus may influence the distribution of ORV in their vicinity, but does not require the specific distance of that effect to be specified *a priori*. However, all distance surfaces were capped to a maximum value of 5 km as any patterns observed between the occurrence of tracks and distances greater than 5 km are likely to be due to an underlying spatial correlation, rather than a direct effect of these distant features on ORV recreation. Topography was represented by an 'elevated terrain' variable, which estimates the relative elevation of a pixel with respect to its surroundings and is expected to be more closely related to recreation use than the absolute elevation above sea level (see Table 1).

There is no extant land cover classification of the study area beyond coarse global products and a generalized mapping of pre-European Vegetation (Shepherd, 2003), which do not provide the needed level of spatial detail or currency. Instead, we represented functional attributes of the vegetation following the logic of the Dynamic Habitat Index (DHI; Berry et al., 2007). The DHI contains three components calculated from an annual time series of vegetation activity derived from remotely sensed image data. These axes are (1) total amount of vegetation activity, calculated by summing the vegetation index values over a year; (2) the minimum amount of active vegetation at any given point in the year; and (3) the seasonality of the vegetation activity, calculated as the coefficient of variation (CV) of vegetation index values in a year. These three axes encapsulate many of the functional differences between land cover categories, but with continuous variables. They have been shown to capture ecologically relevant variation that is related to bird (Coops et al., 2009) and butterfly (Andrew et al., 2011, 2012) biodiversity, and it is also likely that they will successfully represent environmental variation that is related to recreational use. For this study, a time series of seasonal Landsat 5 TM images were used to calculate the DHI, with two different vegetation indexes (Table 2). The widely used normalized difference vegetation index (NDVI; Tucker, 1979) was used to estimate total and minimum vegetation activity. These two metrics were highly correlated, so minimum NDVI was not considered further. The CV of NDVI showed little spatial variation over the study area, likely because of the evergreen character of the dominant vegetation. Instead, vegetation seasonality was represented by the CV of the normalized burn ratio (NBR; Lopez-Garcia and Caselles, 1991). Because the NBR is calculated using reflectance in the shortwave infrared, it is more sensitive to variation in plant moisture content and does not saturate as rapidly as the NDVI. However, NBR could not be used for the other two components of the DHI because it is also sensitive to soil moisture and un-vegetated pixels in the lakes received high values of this index. In contrast, the CV of NBR did not confound lakes and vegetation.

2.3.2. Statistical analyses

Maximum entropy (MaxEnt) models were used to determine the associations between tracks and the environment and to predictively map other areas with high probability of ORV recreation. MaxEnt is among the best available algorithms for classifying species distributions (Elith et al., 2006), but has rarely been used to model distributions of outdoor recreation (see Braunisch et al., 2011; Coppes and Braunisch, 2013). MaxEnt is a machine learning technique to model the statistical distribution of the response variable along the predictor variables (Phillips et al., 2008) using presence records and a random sample of background locations. It minimizes the assumptions (i.e., maximizes the entropy) made about the modeled probability distribution function by requiring it to be as similar as possible to that of the study area overall while still capturing the mean values of the training set (Elith et al., 2011). Both categorical and continuous predictor variables are supported and a variety of transformations, capturing nonlinearities and interactions between variables, are used (Phillips et al., 2006; Phillips and Dudík, 2008). The mapped outputs of MaxEnt include the predicted value of the probability density function and the transformed logistic output which is proportional to the probability of presence at each pixel (Phillips and Dudík, 2008). The continuous MaxEnt output was thresholded into a binary classification of ORV recreation using the probability value that maximized the sum of model sensitivity and specificity for the test set (Liu et al., 2005).

We evaluated the predictive track model's performance with the area under the receiving operator characteristic curve (AUC) relative to the test set of track points. AUC is a measure of accuracy based on the sensitivity and specificity of model predictions. An AUC greater than 0.5 indicates that the model performs better than random. Inferences about the environmental preferences of ORV recreationists were interpreted from the importance scores and response curves of each predictor variable. Variable importance was estimated by the percent decrease in model performance when a given variable is randomly permuted, termed the permutation importance. Marginal response curves were used to identify the relationship between each variable and ORV recreation occurrence. These curves plot the predicted probability of track presence against the range of values of the predictor variable when holding all other covariates at their mean values.

3. Results

3.1. Mapping ORV tracks

A total of 93 multipurpose/recreational tracks spanning 263 km were digitized from the GoogleEarth imagery (Figure 2), giving a recreational track density of 0.15 km/km^2. The greatest density of recreation tracks occurred in the northern portion of the study area, near the roads. Longer tracks tended to extend to the lake where they either terminated or continued along the shore. Generally few rock outcrops were directly accessed by tracks, especially those distant from the roads and tourist facilities. Several other long tracks traversed the study area (Figure 2). The accuracy of the GoogleEarth-digitized tracks, when assessed against the ground reference data, was reasonable (overall accuracy = 73%; Table 3).

3.2. Modeling ORV tracks

The MaxEnt model predicted the distribution of tracks with very good accuracy (AUC = 0.82). Overall, 19% of the study area was predicted as containing environments associated with ORV recreation (Figure 2). The most important variable to the MaxEnt model was the proximity of rock outcrops, followed by the distances to roads and lakes, and the total annual vegetation activity. The latter three variables made roughly equal contributions to the model (Table 4). The almost complete unimportance of tourist facilities is likely due to the fact that all tourist facilities occurred along the road, and most were adjacent to rock outcrops. Because tracks also accessed roadside locations and outcrops in addition to those served by tourist facilities, the latter variable made no independent contribution to the model.

The variable response curves (Figure 3) underscore the importance of road access. When holding all other variables at their mean values, there was a 80% probability of track presence immediately adjacent to the roads (Figure 3a). ORV track probability declined rapidly and plateaued around 1.5 km from the roads and established tourist sites (Figure 3a, c). There were also strikingly high probabilities of track presence near rock outcrops, and these remained relatively high to a distance of ~1 km (Figure 3b). However, tracks were less likely to occur on the rock outcrops themselves (i.e., at a distance of 0 km), although this may also be a function of tracks being less detectable on the outcrops than on soil. Track probability was also enhanced within approximately 0.5 km of lakes (Figure 3d) and for intermediate levels of total annual vegetation activity (Figure 3e). There was a slight tendency for increasing probability of track occurrence at sites that were elevated above their surroundings (Figure 3f), but this variable was unimportant to the model (Table 4).

4. Discussion

4.1. Mapping ORV recreation with high resolution image data

Our study provides the first inventory of recreational tracks within the study area. Moreover, we demonstrate that high resolution satellite image data can be an appropriate source of information on recreational tracks, despite the presence of a tree canopy. Previously, aerial photography has been used to map recreation in treeless environments (coastal areas: Priskin, 2003; deserts: Matchett et al., 2004; alpine systems: Braunisch et al., 2011). Moreover, the accuracy assessment of the tracks digitized from GoogleEarth against ground reference data (Table 3) is likely conservative: (1) The field sample disproportionately sampled track presences over absences; thus, true absences, which were accurately detected from the image data (Table 3) are underrepresented in the accuracy assessment. (2) The digitizing focused on recreational/multipurpose type tracks, while the ground reference sample did not distinguish between track purposes, partly explaining the relatively large number of false absences observed (Table 3). Finally, the majority of omitted tracks occurred in areas modeled to have a high probability of track occurrence, and thus will not influence the predictive modeling component of this study or its conclusions.

There are a number of potential challenges to using GoogleEarth data for environmental research or monitoring. Most important are the combination of images from different dates and sensors into a seamless mosaic and uncertainties surrounding image acquisition parameters and the image processing steps that have been applied (Potere, 2008; Yu and Gong, 2012). In addition, it is not possible to create alternative colour composites, despite the measurement of additional spectral bands (e.g., infrared) by many of the sensors that provide data to GoogleEarth, or to adjust the contrast of the images (Potere, 2008; Yu and Gong, 2012). Both of these enhancements are valuable strategies for photointerpretation that may improve the detectability of tracks. Nevertheless, the sheer bulk of the high resolution data freely available in GoogleEarth is a tremendous asset. Further, continued updates to GoogleEarth increase its value and may ultimately remove some of these limitations. For example, the GoogleEarth archive now includes historic image dates and vector boundaries annotated with acquisition dates and sensors that delineate source images. (Although it is still not always clear which image is visible in areas of overlap between multiple source images.)

4.2. Environmental associations of ORV recreation

The observed environmental associations of tracks generally agree with the patterns expected under the scenic vistas and skill-testing terrain motivations for ORV use (Table 1). In particular, tracks were found to access views of/from rock outcrops and across the lakes, as well as challenging driving conditions near the lakes. These associations can be seen in the halos of ORV recreation around the rock outcrops, and to a lesser extent the lakes, in the predictive model output (Figure 2), and also in the response curves for the distances to lakes and rocks variables (Figure 3b, d). In general, there appears to be a preference for recreation associated with rock outcrops over lakes. The rock outcrop variable made the most important contributions to the predictive models of track distributions (Table 4), and the response curves indicate greater probability of track presence adjacent to rocks than to lakes (Figure 3b, d). Investigating the associations of tracks with rock outcrops in more detail reveals that 16% of outcrops have been accessed directly by ORV tracks, but half of all outcrops in the study area are approached by tracks (i.e., have a track within 0.5 km). Our results support the concerns of regional conservation groups that rock outcrops are potentially under threat from ORV recreation, but suggest that a number of outcrops are as yet un-impacted and may present opportunities for pro-active protection. More direct, on-the-ground investigation is required to assess if the spatial co-occurrence of ORV tracks and rock outcrops is causing environmental degradation at these sites.

Many of the accessed outcrops occur in the dense cluster of outcrops between the main road and the lake in the northwest corner of the study area (Figure 2). This portion of the study area has the densest existing track network and also the most extensive area of predicted track occurrences (Figure 2). It may be particularly appealing given the variety of proximate recreation opportunities (both rocks and lakes) and its accessibility from roads and existing tourist facilities. Previous researchers have also found access and views of water features to be preferred by ORV recreationists (Albritton and Stein, 2011) or to be associated with informal track networks (Wimpey and Marion, 2011). These are not directly comparable to the ephemeral lakes of our study area, however, which are predominantly dry during times of recreational use. The attractions of lakes here are related to their provisioning of wide, scenic vistas and large, flat expanses for ORV use.

We also observed a unimodal relationship between track occurrence and the total amount of vegetation. This pattern suggests that people prefer to recreate near vegetation, but not if the vegetation is too dense. The avoidance of the highest amounts of vegetation may be related to several mechanisms. Dense vegetation may impede scenic views (Table 1), and may also provide physical impediments to travel. It is not clear which, if either, of these mechanisms operate here as the remotely sensed vegetation index provides no information about the vertical structure of vegetation and, specifically, the density of vegetation at ground level. The seasonality of vegetation, which is likely to be more related to components of the understory, was not related to the occurrence of ORV tracks.

4.3. The role of accessibility

One of the strongest determinants of ORV track presence was accessibility, as represented by the road buffer (Table 4; Figure 3b). Although remoteness is often favored for outdoor recreation (e.g., Kliskey, 2000) and is related to the solitude motivation (Table 1), the strong association here of recreation with roads is not unexpected. Because of their anthropocentric definition, ecosystem services cannot exist independently of the human societies that use them (Cowling et al., 2008; Tallis and Polasky, 2009, 2011). Although the use of some ecosystem services can be quite distant from their supply (Fisher et al., 2009), this is not the case for recreation services, which are enjoyed on site, thus requiring access and, for many types of recreation, infrastructure (Adamowicz et al., 2011; De Groot et al., 2010). The distribution of roads and human populations is widely used to proxy the demand and use of ecosystem services in mapping exercises (Andrew et al., *in press*). However, most current spatial indicators of ecosystem services identify the biophysical conditions that enable the supply of a service, but often do not connect service supply to whether demand exists or the service is actually used (Andrew et al., *in press*). Although the distribution of access infrastructure is a very simple indicator of demand – it provides no indication of use rates and, thus, is perhaps best considered to represent the *potential* for demand – it clearly provides useful refinements of spatial assessments based on supply alone.

Our empirical model of ORV recreation presents a composite indicator of supply and demand. The supply of recreation opportunities is included in our identification of the environmental associations of ORV recreation and the sites that meet them. Demand is represented by accessibility from roads and tourist facilities and, thus, the ability of users to attain recreation experiences at those sites. Other empirical studies have also highlighted the importance of demand (proxied by accessibility, population density) to recreation and tourism services. For example, recreation value is strongly related to the size (Eigenbrod et al., 2009; Holland et al., 2011; Vejre et al., 2010) and proximity (Bateman et al., 1999; Ghermandi and Nunes, 2013) of surrounding populations, and presence of infrastructure such as ski lifts, trails, or car parks (Braunisch et al., 2011; Coppes and Braunisch, 2013; Termansen et al., 2013). In the context of ORV recreation, Matchett et al. (2004) found that track density was greatest near linear features that channel recreation users across a landscape. Further, surveys of ORV recreationists demonstrate preferences for ease of access and tourist facilities such as car parks, toilets, and signage at trailheads (Hallo et al., 2009; Snyder et al., 2008). These studies, and our own, confirm the continued use of demand proxies in spatial indicators of recreation services (e.g., the rule-based indicators of: Chan et al., 2006, 2011; Haines-Young et al., 2006; Lautenbach et al., 2011; Schulp et al., 2012; Willemen et al., 2008), although greater work is needed to develop spatial datasets that provide more nuanced information about demand and recreation use than simple proxies based on access infrastructure alone.

4.4. Management implications

There are concerns about the impacts of ORV recreation to natural systems and other recreational users. Such impacts may be direct, such as physical damage to soils or vegetation, and collisions with wildlife; or indirect, mediated by noise pollution, air and water contamination, and habitat fragmentation, among others (reviewed by Buckley, 2004; Ouren, 2007). The objectives of many protected areas worldwide include both provisioning of recreational experiences and conservation of natural areas. In such settings, managers must minimize the adverse impacts of ORV recreation, while providing desired recreation experiences. Spatial planning provides powerful tools to help balance these needs. Our study, which focuses on the spatial distribution of recreation across a study area, provides one essential component to effective recreation planning. Modeled patterns of desired recreation opportunities can be integrated with maps of vulnerability to recreation use (e.g., Tomczyk, 2011; Tomczyk and Ewertowski, 2013) to identify locations where recreation activities will be sustainable. The resulting maps of potential recreation opportunities that integrate user preferences with environmental impacts can be combined with route planning tools (i.e., least cost distance modeling) to optimize trail networks (e.g., Boers and Cottrell, 2007; Shilling et al., 2012; Snyder et al., 2008; Tomczyk and Ewertowski, 2013).

The strong association we observed between ORV tracks and access presents an opportunity for management. Roads are a considerable source of disturbance themselves (Forman and Alexander, 1998), impacting ecosystems via many of the same mechanisms as ORV recreation. The disturbance zone of roads can extend hundreds of meters, and even several kilometers, into surrounding habitats (Benítez-López et al., 2010; Forman, 2000). These road disturbances encompass much of the area of predicted ORV track occurrences modeled in our study, suggesting that one way to balance recreation and conservation may be to concentrate the majority of recreation within the broad road-effect zone, thereby meeting recreation needs for access while avoiding disturbance and further fragmentation of intact habitat. This recommendation is in keeping with a spatial containment strategy of recreation management, which assumes that cumulative impacts are minimized when use occurs over a relatively small spatial footprint, but at potentially high levels in those areas (Leung and Marion, 1999). However, alternative approaches to recreation management exist, such as allowing extensive but diffuse use over a broad area (Leung and Marion, 1999). Given the relatively large impact of vehicle passage and the sensitivity of semi-arid systems (Lei, 2009), we believe a containment strategy is reasonable, but greater consideration of the specific ecological processes and sensitivity of the region is necessary before making definitive recommendations.

There is currently no formal management of ORV recreation within our study area. In the greater GWW, stakeholder groups conduct track management in areas outside the clear jurisdiction of local and state government authorities. Four-wheel drive clubs perform track upkeep and undertake some environmental protection activities, such as installing bollards or other deterrents to driving over environmentally sensitive areas (Macbeth, 1998; Toyota Land Cruiser Club, 2013). Such actions, in combination with controlled and properly signed access points, may effectively concentrate recreation activities to suitable locations.

5. Conclusions

Outdoor recreation and natural areas tourism have great economic and social value. To maximize the benefits provided by these, and other ecosystem services, recreation opportunities should be provided that meet user preferences for satisfying recreation experiences while also minimizing the potentially adverse ecological impacts of recreation. Spatial planning tools provide excellent resources to meet this goal. This study demonstrates how spatial data and predictive models can determine the spatial and environmental patterns of ORV recreation, for use in environmental and recreation management. Studies of ORV recreation are currently biased to coastal and desert environments, and do not effectively represent the range of ecosystems in which these activities are enjoyed. Our study makes a valuable contribution to our developing understanding of ORV recreation across a broader range of ecosystems.

We also present an approach to develop empirical spatial indicators of recreation patterns based on evidence of recreation use across a landscape. This modeling method is time and cost effective, requiring only high resolution image data, such as that freely available from GoogleEarth, and other commonly accessible spatial data layers. It also avoids potential subjectivities associated with deriving indicators from expert judgment or user-reported preferences, though complementary social data on track use and desired recreation features will be needed to more definitively link the observed patterns of tracks to preferred recreation experiences. Our spatial model of ORV recreation reveals that, although ORV tracks are associated with the natural amenities in the study area (salt lakes and rock outcrops), they are constrained by patterns of accessibility via the existing road network. These findings suggest that an effective management strategy to maintain sustainable ORV recreation in the study area may be to provide desired recreation activities with a spatially optimized, maintained track network near the roads and to limit access and the proliferation of unmanaged tracks into undisturbed areas.

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Table 1. Hypotheses relating the expected motivations of off-road vehicle (ORV) recreation to the spatial variables used to predictively model the environmental associations of ORV tracks.

Motivation	Expected relationship to environmental variables
Scenic vistas	Scenic vistas are provided by expansive areas of low to no vegetation and terrain that is elevated relative to its surroundings. Thus, recreationists seeking views may be associated with the lake shore (ie, open views across the lake), rock outcrops (ie, outcrops are open areas with little vegetation and also slightly elevated), sites that are elevated relative to the surrounding terrain, or areas with little vegetation (low values for the total vegetation component of DHI) or vegetation that is not persistent (high values for the vegetation variability component of DHI).
Solitude	Solitude is expected to be achieved by getting away from human infrastructure. Thus, recreationists seeking solitude may be associated with greater distances from roads or tourist facilities.
Skill-testing terrain	The Lake Johnston study area does not have areas of sharp relief. Thus, in this region, skill-testing terrain is not likely to be associated with steep slopes or heterogeneous elevations. Instead, ORV recreationists test their skill in the boggy conditions in the drying lake bed. Thus, recreationists seeking challenging terrain may be associated with the lake shore.
Transit	ORV use in this category largely uses tracks as short-cuts across the region. Recreationists merely transiting through are not expected to be associated with any particular environmental conditions.

Table 2. Description of the independent variables used in the model and the data sources from which they were derived. The scales of the original data sources are also provided.

Variable	Notes	Source	Scale
Lakes	Represented as a distance-to surface, with values capped at 5km	Lake boundaries taken from GEODATA TOPO 250K Vector Data (Geoscience Australia, 2006)	1:250,000
Rock outcrops	Represented as a distance-to surface, with values capped at 5km	Outcrop boundaries taken from GEODATA TOPO 250K Vector Data (Geoscience Australia, 2006)	1:250,000
Elevated terrain	The difference between a pixel's elevation and the average elevation in a 990m moving window centered on the pixel	Source DEM: SRTM (Rabus et al., 2003) DEM of Australia (Gallant et al., 2011)	1 second (~30m) pixels
Land cover	Two components of the Dynamic Habitat Index capturing intra-annual patterns of vegetation dynamics related to land cover: *Total vegetation:* The sum of seasonal NDVI (normalized difference vegetation index, $[R_{nir} – R_{red}]/[R_{nir} + R_{red}]$) values in a year *Vegetation variability:* The coefficient of variation of seasonal NBR (normalized burn ratio, $[R_{nir} – R_{swir2}]/[R_{nir} + R_{swir2}]$) values in a year	Cloudfree Landsat TM surface reflectance data (Masek et al., 2006) acquired on 8 Feb 2009, 15 May 2009, 3 Aug 2009, and 23 Nov 2009	30m pixels
Roads	Represented as a distance-to surface, with values capped at 5km	Outcrop boundaries taken from GEODATA TOPO 250K Vector Data (Geoscience Australia, 2006)	1:250,000
Tourist facilities	Represented as a distance-to surface, with values capped at 5km	Point locations provided by the Department of Parks and Wildlife and local government authorities	-

Table 3. Contingency table of locations of track presence and absence as observed in the sample of field validation points (rows) and as digitized from the GoogleEarth imagery (columns). Standard accuracy statistics (omission error, commission error, and overall accuracy) have also been calculated.

		GoogleEarth imagery			
		Track	**Non-track**	**Total**	**Omission error (GE)**
Ground reference data	**Track**	27	17	44	39%
	Non-track	1	22	23	
	Total	28	39	67	
	Commission error (GE)	4%			
	Overall agreement	73%			

Table 4. Importance of environmental variables to predictive models of ORV recreational track occurrence. Permutation importance is the percent reduction in model performance when a given variable is randomized.

Variable	**Permutation importance (%)**
Distance to road	21.8
Distance to rock outcrop	34.6
Distance to tourist facility	1.1
Distance to lake	18.7
DHI – total veg, sum(NDVI)	21.5
DHI – veg variability, cv(NBR)	1.2
Elevated terrain	1.1

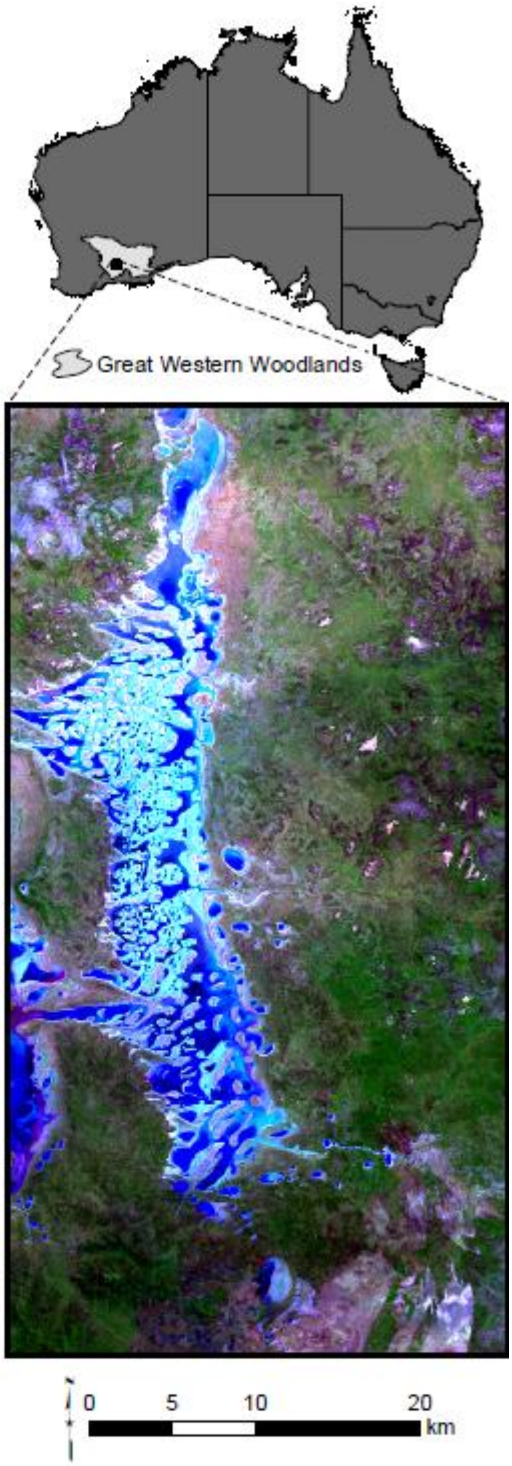

Figure 1. Locator map of the study area within the Great Western Woodlands of Western Australia. The bottom panel presents a "near natural" colour composite image of Landsat 8 image data of the study area (displaying band 6 [shortwave infrared] in red, band 5 [near infrared] in green, and band 4 [red] in blue). Imagery was acquired in the wintertime (14 August 2013), when portions of the lake contained water. In this representation, water appears blue; vegetation is green; and bare ground is displayed in white and shades of orange or purple. (Please refer to the electronic version of this article for references to colour.)

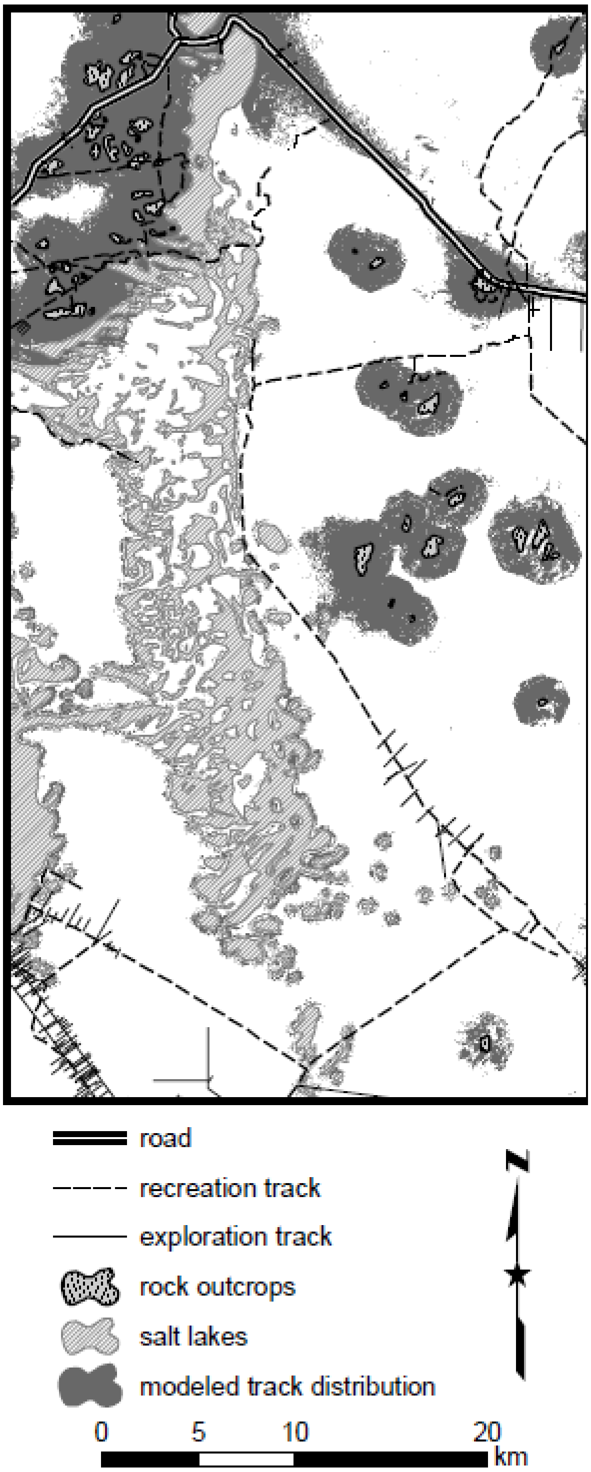

Figure 2. Map of the off-road vehicle (ORV) tracks digitized from GoogleEarth image data and areas predicted to have a high probability of recreational track occurrence by the MaxEnt model of recreation tracks. For reference, the locations of spatial and environmental variables associated with the distribution of tracks (roads, salt lakes, and rock outcrops) are also depicted.

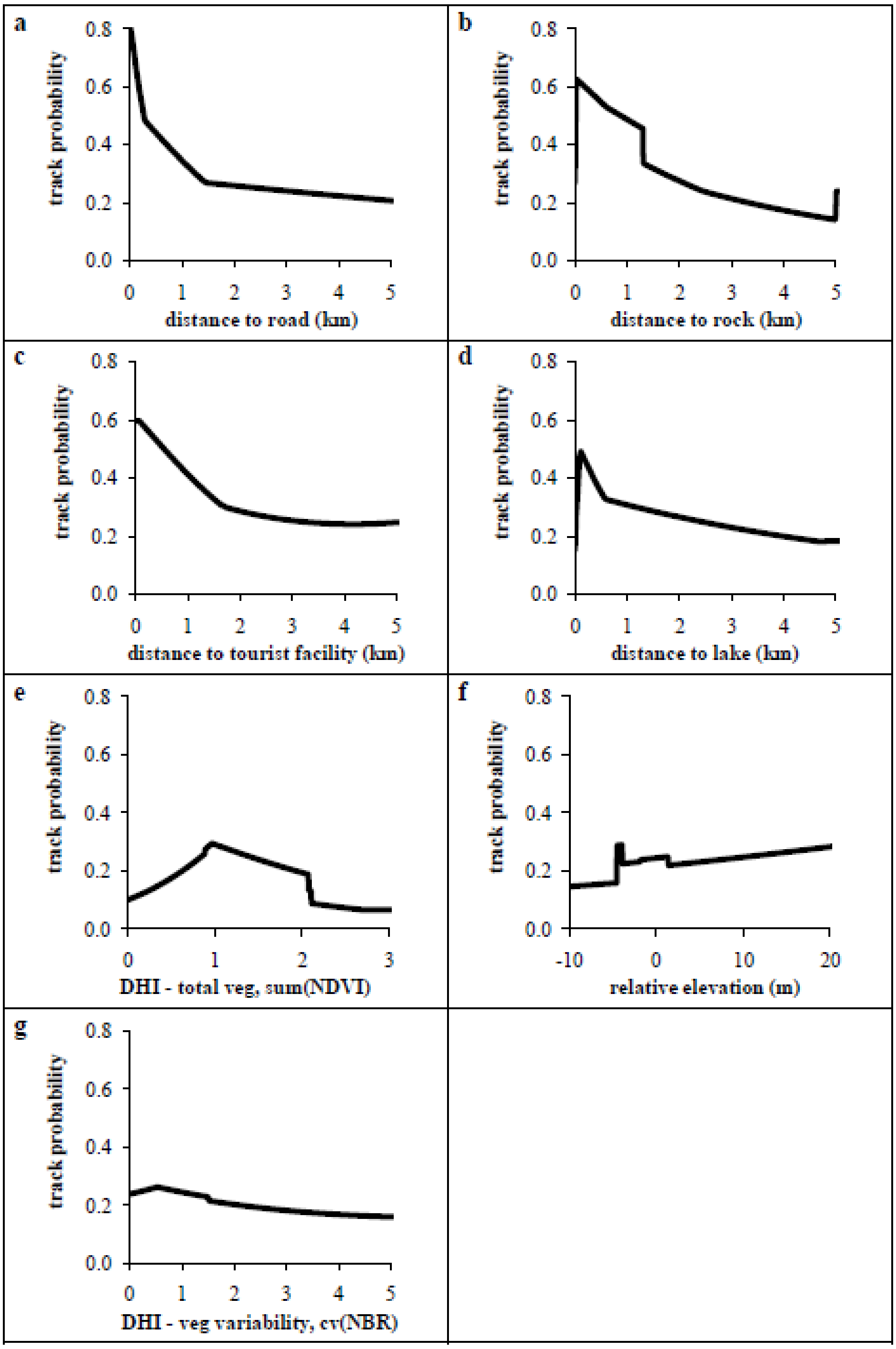

Figure 3. Marginal response curves from the MaxEnt model showing the relationship between each environmental predictor variable and the probability of off-road vehicle recreational track occurrence, when holding all other variables at their mean values.