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Keeping it wild: Mapping wilderness character in the United States

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ABSTRACT

A GIS-based approach is developed to identify the state of wilderness character in US wilderness areas using Death Valley National Park (DEVA) as a case study. A set of indicators and measures are identified by DEVA staff and used as the basis for developing a flexible and broadly applicable framework to map wilderness character using data inputs selected by park staff. Spatial data and GIS methods are used to map the condition of four qualities of wilderness character: natural, untrammelled, undeveloped, and solitude or primitive and unconfined recreation. These four qualities are derived from the US 1964 Wilderness Act and later developed by Landres et al. (2008a) in "Keeping it Wild: An Interagency Strategy to Monitor Trends in Wilderness Character Across the National Wilderness Preservation System." Data inputs are weighted to reflect their importance in relation to other data inputs and the model is used to generate maps of each of the four qualities of wilderness character. The combined map delineates the range of quality of wilderness character in the DEVA wilderness revealing the majority of wilderness character to be optimal quality with the best areas in the northern section of the park. This map will serve as a baseline for monitoring change in wilderness character and for evaluating the spatial impacts of planning alternatives for wilderness and backcountry stewardship plans. The approach developed could be applied to any wilderness area, either in the USA or elsewhere in the world.

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1. Introduction

In the United States, designated wilderness confers the greatest degree of protection from anthropogenic development and increasingly is considered the core for landscape-scale conservation efforts in the face of climate change. At nearly 110 million acres, all designated wilderness is managed under the 1964 Wilderness Act with the legal mandate to the agencies that administer wilderness to ensure the "preservation of wilderness character" in these areas (Section 2a, Public Law 88-577). Despite this mandate, wilderness character is not defined in the Wilderness Act (see Box 1), leading some to define wilderness in its broadest form. Nash (2001), for example, concludes that "Wilderness is what men think it is" (Nash, 2001, p1). While allowing plenty of room for philosophical discourse, such definitions are not helpful when it comes to managing those forces that threaten wilderness or to providing tangible management guideposts to inform decisions and actions to preserve wilderness character.

The Wilderness Act created a single National Wilderness Preservation System (NWPS) and each wilderness is managed by one or more federal agencies: Bureau of Land Management, National Park Service, U.S. Fish and Wildlife Service, and U.S. Forest Service. Representatives from these managing agencies, along with the U.S. Geological Survey, recently published "Keeping it Wild," a conceptual framework that defines wilderness character in tangible terms to link management actions directly to the statutory language of the Wilderness Act (Landres et al., 2008a, b). This conceptual framework was subsequently reaffirmed and refined by additional agency efforts (Landres et al., 2012, 2013), and applies to every wilderness in the NWPS regardless of its size, geographic location, ecological systems, or managing agency. The framework is based on a hierarchical structure that decomposes wilderness character into four "qualities," namely natural, untrammelled, undeveloped, and solitude or primitive and unconfined recreation, that are themselves divided into one or more "indicators." The qualities are derived directly from the definition used in the 1964 Wilderness Act (see Box 1), while the component indicators refer to those individual components that together make up the overall characteristics of the wilderness qualities being described.

As originally developed, this framework of qualities and indicators is non-spatial, ignoring what may be substantial spatial

Box 1

The definition of wilderness used in Section 2c of the 1964 Wilderness Act (with qualities of wilderness character underlined for emphasis).

> "A wilderness, in contrast with those areas where man and his own works dominate the landscape, is hereby recognized as an area where the earth and its community of life are <u>untrammeled</u> by man, where man himself is a visitor who does not remain. An area of wilderness is further defined to mean in this Act an area of <u>undeveloped</u> Federal land retaining its primeval character and influence, without permanent improvements or human habitation, which is protected and managed so as to preserve its <u>natural</u> conditions and which (1) generally appears to have been affected primarily by the forces of nature, with the imprint of man's work substantially unnoticeable; (2) has outstanding <u>opportunities for solitude or a primitive and unconfined type of recreation</u>; (3) has at least five thousand acres of land or is of sufficient size as to make practicable its preservation and use in an unimpaired condition; and (4) may also contain ecological, geological, or other features of scientific, educational, scenic, or historical value."

variability within the boundaries of a designated wilderness area. For example, management tends to focus on the threats to wilderness from such pressures as external sources of pollution and recreational use. It is widely recognised that these pressures vary spatially across a landscape so they will have varying impacts on wilderness character depending on the magnitude of the threat and the resilience or carrying capacity of the landscape. A spatial model showing how wilderness character varies across a wilderness would provide several significant and substantive benefits for wilderness stewardship, including:

- Providing a baseline assessment of current conditions from which future change can be monitored.
- Identifying specific areas where actions could be taken inside the wilderness to improve wilderness character or areas where actions should not be taken because they would degrade wilderness character.
- Helping identify specific areas outside the wilderness where actions might pose a significant risk of degrading wilderness character within the wilderness.
- Performing "What if?" analyses of management decisions and alternatives to show their effect on the spatial distribution, pattern, and condition of wilderness character.

This paper develops an approach that uses spatial data to map patterns in the variability and distribution of wilderness character across a specified wilderness area. Specifically, this paper:

1. Reviews the concept of wilderness character and previous work on mapping wilderness quality.
2. Identifies spatial data inputs that are consistent with the wilderness character conceptual framework as defined by Landres et al. (2008a).
3. Develops an approach for standardizing and combining data inputs to create spatially explicit maps for each of the qualities of wilderness character.
4. Demonstrates this approach using Death Valley National Park in creating an overall wilderness character map.

5. Analyses the robustness of this approach by applying sensitivity analyses to data inputs/indicators to test overall model sensitivity to data inputs and weights.
6. Examines the utility of the approach as a coherent framework for spatial modelling of wilderness character that could be rolled out across the NWPS.

2. Methods

Knowing the location and extent of wilderness areas at multiple spatial scales is important for wildlife conservation (Noss et al., 1996; Mittermeier et al., 1998), biodiversity mapping (Myers et al., 2000; Dymond et al., 2003), development of protected area networks (Zimmerer et al., 2004; Locke and Dearden, 2005), designing wildlife corridors (Beier and Noss, 1998; Beier et al., 2011) and protecting ecosystem services (Turner et al., 2007). Previous work on wilderness mapping has focused almost entirely on modelling indices of wilderness quality at a variety of spatial scales from local (e.g. Carver et al., 2012) and national (e.g. Lesslie and Taylor, 1985; Aplet et al., 2000) to continental (e.g. Carver, 2010) and global (e.g. McCloskey and Spalding, 1989; Sanderson et al., 2002). These analyses go beyond the concept of biophysical or ecological "naturalness" (i.e. land and ecological systems that are ecologically intact and largely undisturbed by human activity) by the inclusion of human concerns such as remoteness (distance from nearest form of mechanised access) and "apparent" naturalness of the land cover and lack of obvious forms of human intrusion within the wider landscape such as roads, railways, power lines, dams, airstrips, harbours and other engineering works. These two aspects of wilderness are closely related and most mapping approaches acknowledge both an ecological and a perceptual aspect to the wilderness definition.

Spatial models of wilderness quality generally use a range of indicator variables describing geographical measures of naturalness and remoteness. These are based on available spatial databases on land cover, population patterns, transportation, infrastructure and terrain which are then combined by map overlay techniques to depict how wilderness quality varies across a spectrum of human environmental modification from least wild to most wild. This is the wilderness continuum concept and is described by Nash (1993) as the "paved to the primeval" (see Fig. 1). This model was first implemented within a GIS framework by Lesslie and Taylor (1985) in developing the Australian National Wilderness Inventory (ANWI). Subsequent wilderness mapping projects have followed a similar approach to the ANWI though with methodological differences such as the introduction of multi-criteria evaluation (Carver, 1996), simple Boolean inventories (McCloskey and Spalding, 1989), fuzzy methods (Fritz et al., 2000; Comber et al., 2009), preference studies (Habron, 1998) and participatory approaches (Carver et al., 2002).

If we recognise areas designated under the NWPS as being at the wilderness end of Nash's continuum, then the next logical step is to apply similar methods to represent and analyse the internal spatial variation in wilderness character within a spatially contiguous and designated wilderness area using the qualities of wilderness character derived from the 1964 Wilderness Act and the U.S. interagency effort to explicitly describe wilderness character (Landres et al., 2008a and Landres et al., 2012).

2.1. Study area

The approach developed here is applied to mapping wilderness character in the 3.1 million acre Death Valley National Park (DEVA) in California and Nevada (see Fig. 2). The park is the hottest, driest,
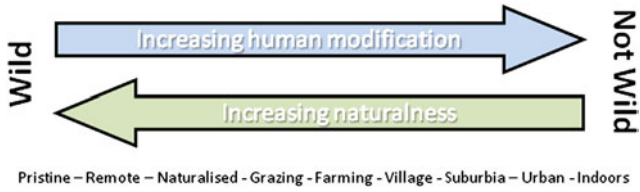
Fig. 1. The wilderness continuum (After Nash, 1993).

lowest place in North America and is the largest national park in the lower 48 US states. A total 91% of the park was designated by the U.S. Congress as the Death Valley Wilderness in 1994 and is the largest named wilderness area in the USA outside of Alaska. The park consists of high mountains surrounding low desert basins containing flat playas and sand dunes. The highest point in the park is Telescope Peak (11,049 feet above sea level) in the Panamint Mountains and the lowest point is Badwater (282 feet below sea level) only 15 miles away.

2.2. Model development

Mapping wilderness character is based on a hierarchical framework (Landres et al., 2008a) that splits wilderness character into four "qualities" that are in turn divided into their component "indicators." The qualities of wilderness character, and their brief definition, used in mapping are:
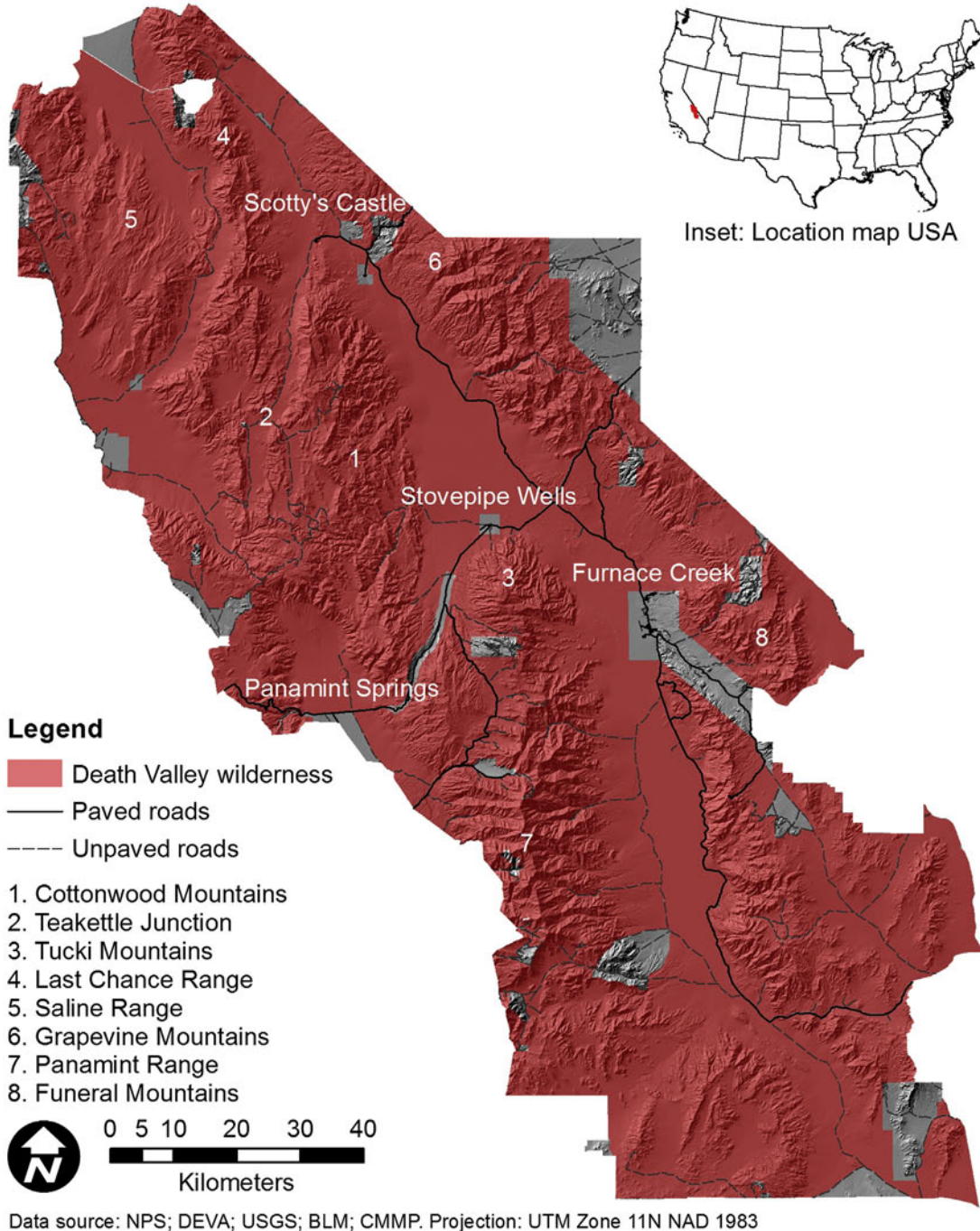
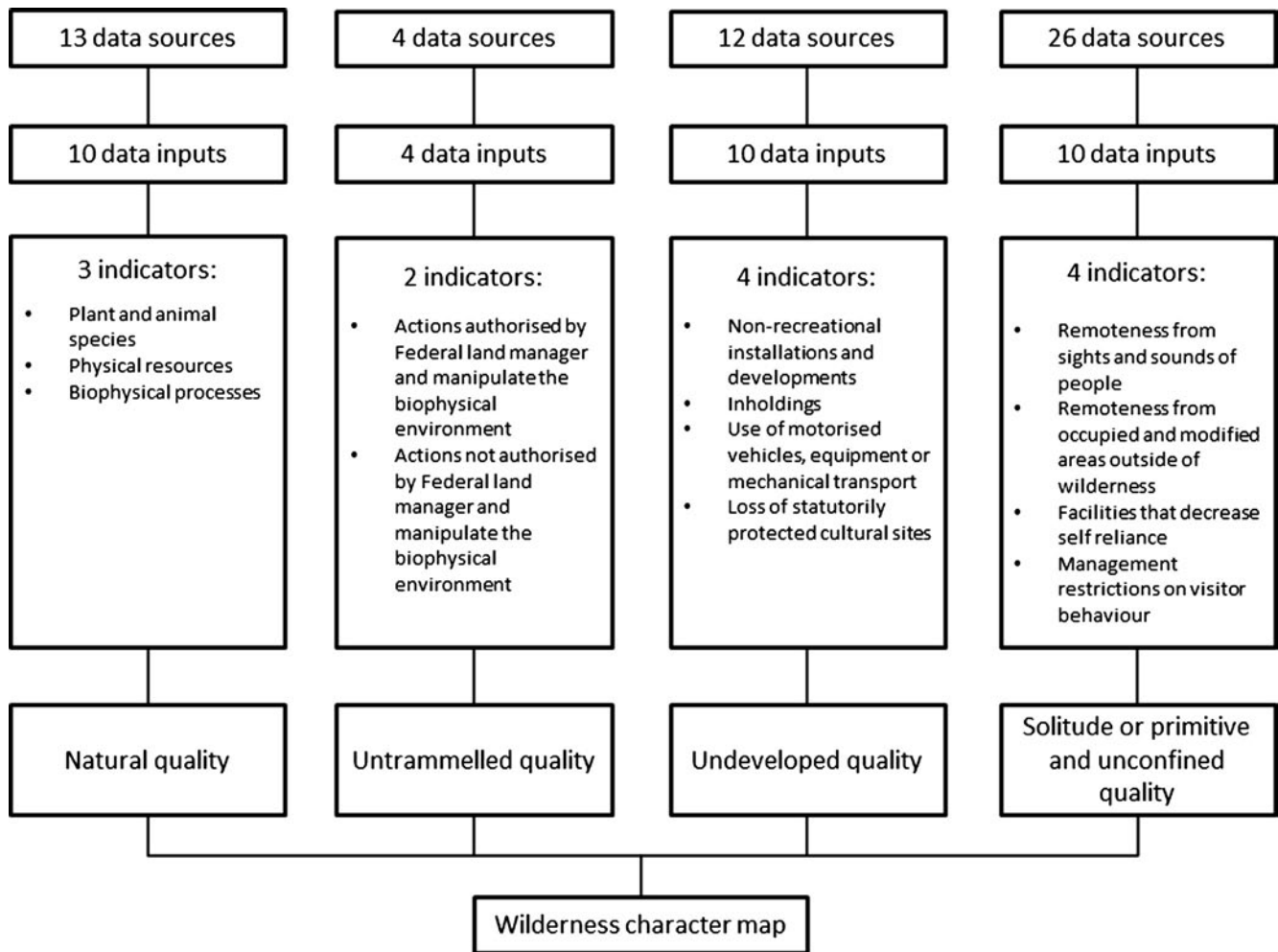**Fig. 2.** Death Valley National Park.

Fig. 3. Flow chart depicting model progression.

- *Natural* — wilderness ecosystems are substantially free from the effects of modern civilization.
- *Untrammelled* — wilderness is essentially unhindered and free from modern actions that intentionally manipulate or control the biophysical environment.
- *Undeveloped* — wilderness is essentially without permanent improvements or modern human occupation.

- *Solitude or primitive and unconfined recreation* — Wilderness provides outstanding opportunities for people to experience solitude or primitive and unconfined recreation, including the values of inspiration and physical and mental challenge.

Each of the above qualities is composed of one or more indicators as defined by Landres et al. (2008a), which are themselves

Table 1
Natural quality indicators, data inputs, weights and rationale.

Indicator	Input	Weight	Rationale	Source	Scale	Accuracy
Plant and animal species and communities	Land cover	50	Overriding descriptor of the landscape	Central Mojave Mapping Project and USGS NVC	5 ha/30 m	High
	Exotic plants	25	Equally weighted because they are equally issues	NPS APCAM	100 m	High
	Exotic animals	25	of concern in that exotic species degrade habitat	DEVA	100 m	High
Physical resources	Ozone (air quality)	5	Minor issue in the desert due to relatively low concentrations and a lack of ozone sensitive species	Air Resources Division, NPS	12 km	Medium
	Wet deposited nitrate and ammonium (air quality)	10	Important due to correlation with increased red brome invasion and altered fire regimes			
	Mining sites	30	Pervasive impacts across the park	NPS AML, USGS and DEVA	100 m	High
	Springs	35	Very important resource for sustaining desert life	DEVA	10 m	High
	Night sky — deviation from natural	20	Important issue to DEVA and degradation may impact nocturnal species, but time limited in that the impact is only felt during night time hours	Night Sky Team, NPS	1 km	High
Biophysical processes	Grazing	67	Important and long term issue that has known detrimental impacts to desert soils and plants	DEVA	100 m	High
	Guzzlers	33	Localised impact			

composed of quantifiable measures that are selected by park staff. Spatial data showing the degradation of each measure are combined and mapped using Geographical Information Systems (GIS) software. In some cases, sub-models are used to generate the required data inputs. For example, a viewshed sub-model is used to calculate the visual impact from anthropogenic features in the park while a travel-time sub-model is used to calculate remoteness from mechanised access. The measures within an indicator are weighted relative to one another, with the combined weighting totalling 100% within each indicator. Indicator layers are then combined to produce a map describing the spatial variation in each of the qualities of wilderness character. Finally, the quality maps are combined to create an overall map showing the degradation of wilderness character and how this varies across the wilderness. This hierarchical process is best visualised as a flow chart (Fig. 3).

2.3. Data inputs and indicators

A total of 51 different datasets are used in mapping wilderness character in the DEVA case study, with each data set describing features, conditions, or actions that could potentially degrade wilderness character (Tricker et al., 2012). The model is therefore a negative one in that the study area is assumed to have a baseline of optimal quality wilderness character and the data inputs are used to record where each of the indicators and, by combination of the indicators, where each of the qualities has been degraded or are deteriorated in some manner. Data inputs are acquired in vector or raster (gridded) formats. Many data record the presence (or absence) of key features affecting wilderness character such as human infrastructure (roads, buildings, mines, etc.) or management actions while other data types record continuous variables
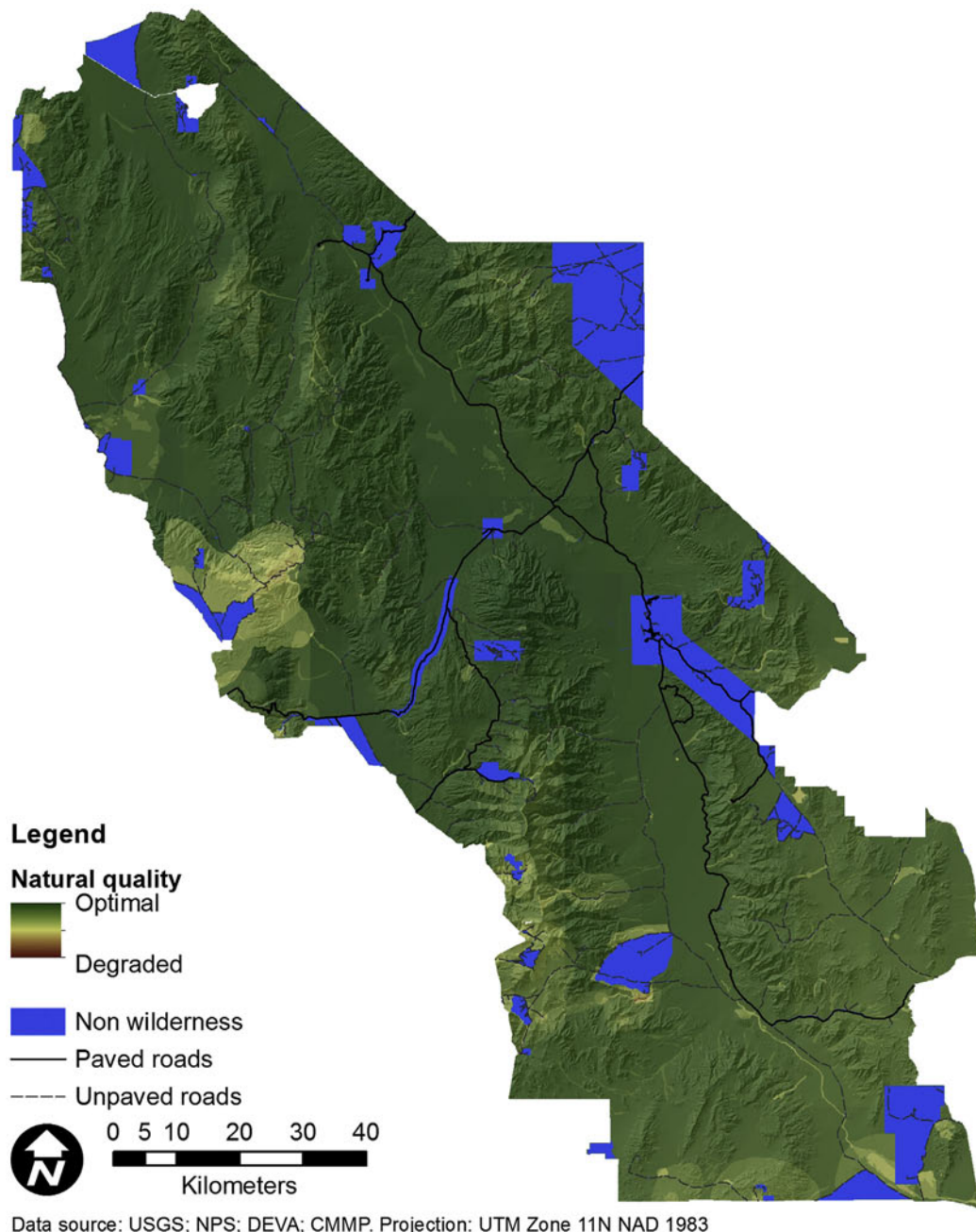

Fig. 4. Natural quality of wilderness character in DEVA.

Table 2
Untrammelled quality indicators, data inputs, weights and rationale.

Indicator	Input	Weight	Rationale	Source	Scale	Accuracy
Authorised actions	Suppressed fires (natural ignitions)	25	Equal weights for all data inputs because all trammelling actions have the same effect on the untrammelled quality	DEVA	100 m	High
	Weed treatments	25		NPS APCAM	100 m	High
	Burro removals	25		DEVA	100 m	High
	Installation of mine closures/ bat gates	25		DEVA	100 m	High

such air pollution or night sky luminosity. Some data require interpolation before being used within the model (e.g. remoteness from mechanised access in the travel-time sub-model) to create ratio scale data inputs while other data types are simply input into the model as present/absent or classified according to likely level of impact (e.g. class of trail and amount of usage). All input data are gridded before being normalised onto a common relative 0–255 scale, where 0 indicates a baseline of optimal wilderness character and 255 indicates degraded wilderness character. For example, the baseline for exotic species is zero where they are absent (optimal wilderness character) and where the data records the presence of exotic species the value is set at 255 (degraded wilderness character). Normalisation of the gridded data is achieved in ArcGIS using equal interval classes so as to retain the shape/distribution of values in the data range.

Legend

Untrammelled quality

Optimal

Degraded

Non wilderness

—— Paved roads

----- Unpaved roads

0 5 10   20   30   40
Kilometers

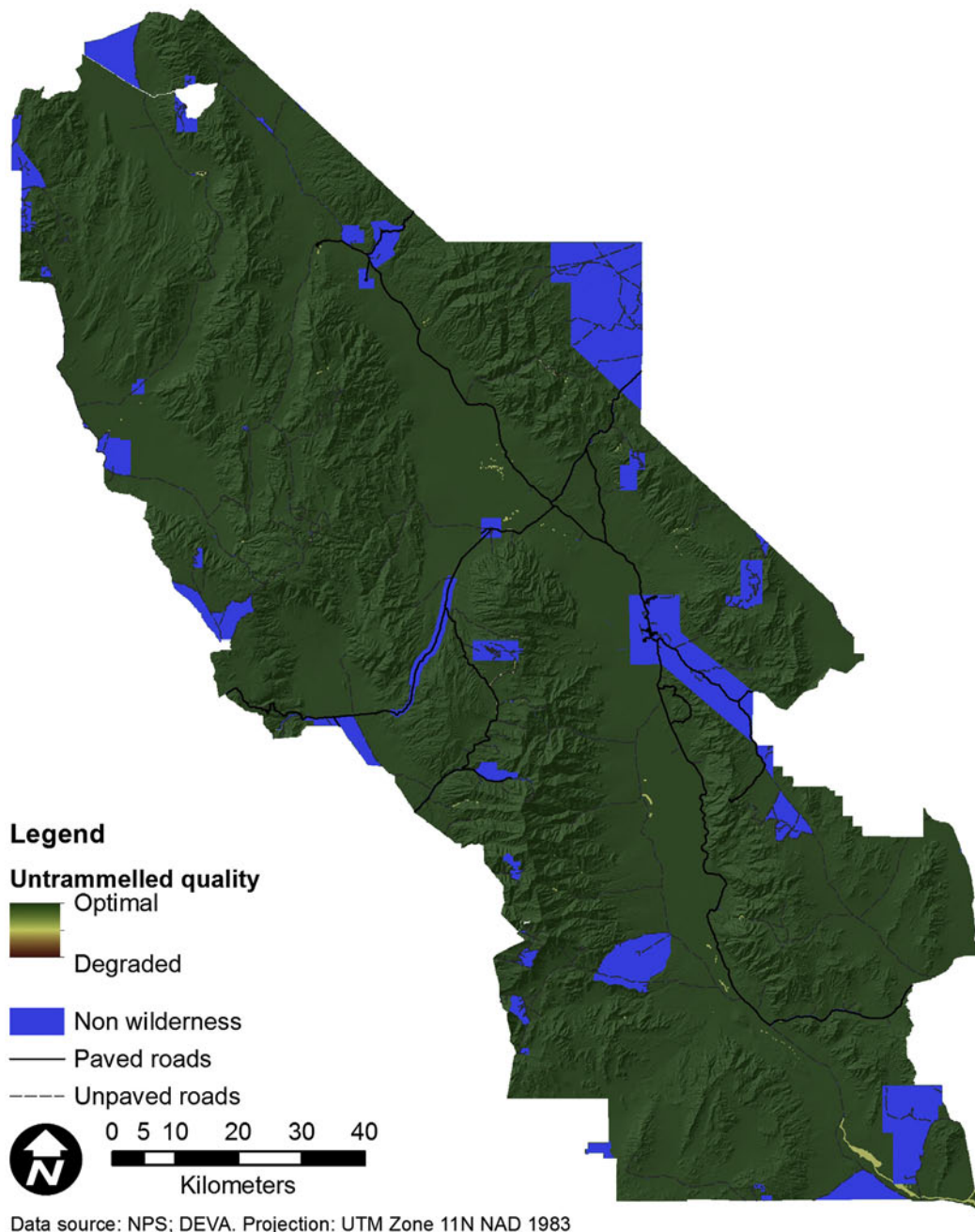Data source: NPS; DEVA. Projection: UTM Zone 11N NAD 1983

Fig. 5. Untrammelled quality of wilderness character in DEVA.

The nominal resolution of the grid conversion process used for the DEVA case study is 100 m, although some data sources (e.g. air quality and night sky luminosity) have significantly lower native resolutions, some as low as 12 km. Although this is not ideal, these coarser resolution datasets are the best that are currently available and constitute important inputs to the model. These datasets therefore need to be included but only after careful discussion with the park staff. While the nominal resolution of 100 m may seem coarse for accurately modelling some features, the huge size of DEVA makes this a suitable compromise between resolution and the size of datasets. However, the travel time and viewshed sub-models make use of 30 m resolution terrain data and rely on the greater accuracy concomitant with these to produce accurate and meaningful results. These variations in the source data have the potential to reduce the overall integrity of the model, but this can be accommodated with careful recording of metadata and the use of uncertainty analyses.

A team approach using the knowledge and experience of park staff was used to identify and weight the measures within each indicator. An iterative process is used to refine all weightings by asking park staff to review the map outputs, modifying the weighting scheme as needed, and then rerunning and reviewing the maps until results are deemed satisfactory by overall consensus. Weights were also provided for missing measures should the data they require become available in the future. This approach allowed substantive discussion among park staff when iteratively refining all decisions. Criteria used in selecting measures and data inputs were: relevance to understanding change in wilderness character, data quality, and data availability (i.e., whether there was coverage for the entire area). Iteratively discussing measures that fit these criteria and coming to a team consensus on the measures to be used, and their relative weighting, was essential to maintaining robustness and reliability in the mapping process and is best done by park staff who are intimately familiar with the area, its landscape and potential pressures on wilderness character. This familiarity with the area is critical for mapping wilderness character because there is no way to test the validity or "truth" of the final map product other than checking with local staff, although uncertainty analyses were conducted to validate variability in our weighting procedures, as described below. Guidance on the technical issues regarding data and modelling operations was provided to park staff throughout this process by the authors.

Data inputs are combined within an indicator using simple weighted linear summation (Malczewski, 2006). Park staffs were asked to review and validate the initial maps. If the maps did not fit

with staff experience and knowledge of the area, the team re-evaluated the measures, data inputs, and weights assigned to the measures. This process was repeated as necessary until the maps reflected a consensus view. Selection of measures, data inputs, weighting, and validating the map based on staff experience and knowledge, inevitably introduces an element of bias into the model. However, this approach also allows necessary local flexibility to incorporate measures and data that are most relevant to the particular area. This approach captures the "rich picture" associated with local conditions and peculiarities that would otherwise be lost if employing a fixed weighting strategy across all wilderness areas. This has substantive implications for cross-wilderness comparisons that are discussed later in the paper.

2.4. Qualities of wilderness character

The data sources, data inputs and indicators used for each of the qualities of wilderness character are described below.

2.4.1. Natural quality

The natural quality of a wilderness area is degraded by the intended or unintended effects of modern people on the composition, structure, and functions of the ecosystems inside the wilderness area (Landres et al., 2008a). Three indicators are recommended in the interagency wilderness character framework: plant and animal species and communities, physical resources, and biophysical resources. Each indicator is mapped based on the weighted combination of data inputs. Table 1 shows the various data sources, scale, nominal accuracy, their combination into the indicators, and the weights applied in this step together with the rationale behind the inclusion and weighting of each data input.

A simple percentage weight is assigned to each data input that describes its contribution to the indicator. For example, the plant and animal species and communities indicator in Table 1 is made up of three data inputs: land cover, exotic plants, and exotic animals. Land cover is the overriding descriptor of the landscape in this instance and receives a weight of 50%, while exotic plants and animals are each assigned a weight of 25% since they are each deemed to equally degrade habitat quality. These weights were determined using an iterative team approach rather than resorting to methods such as the Analytic Hierarchy Process (AHP) common in poorly structured decision problems (Saaty, 1986) because here there is sufficient local knowledge and experience within DEVA park staff to assign priorities via direct weighting.

Table 3
Undeveloped quality indicators, data inputs, weights and rationale.

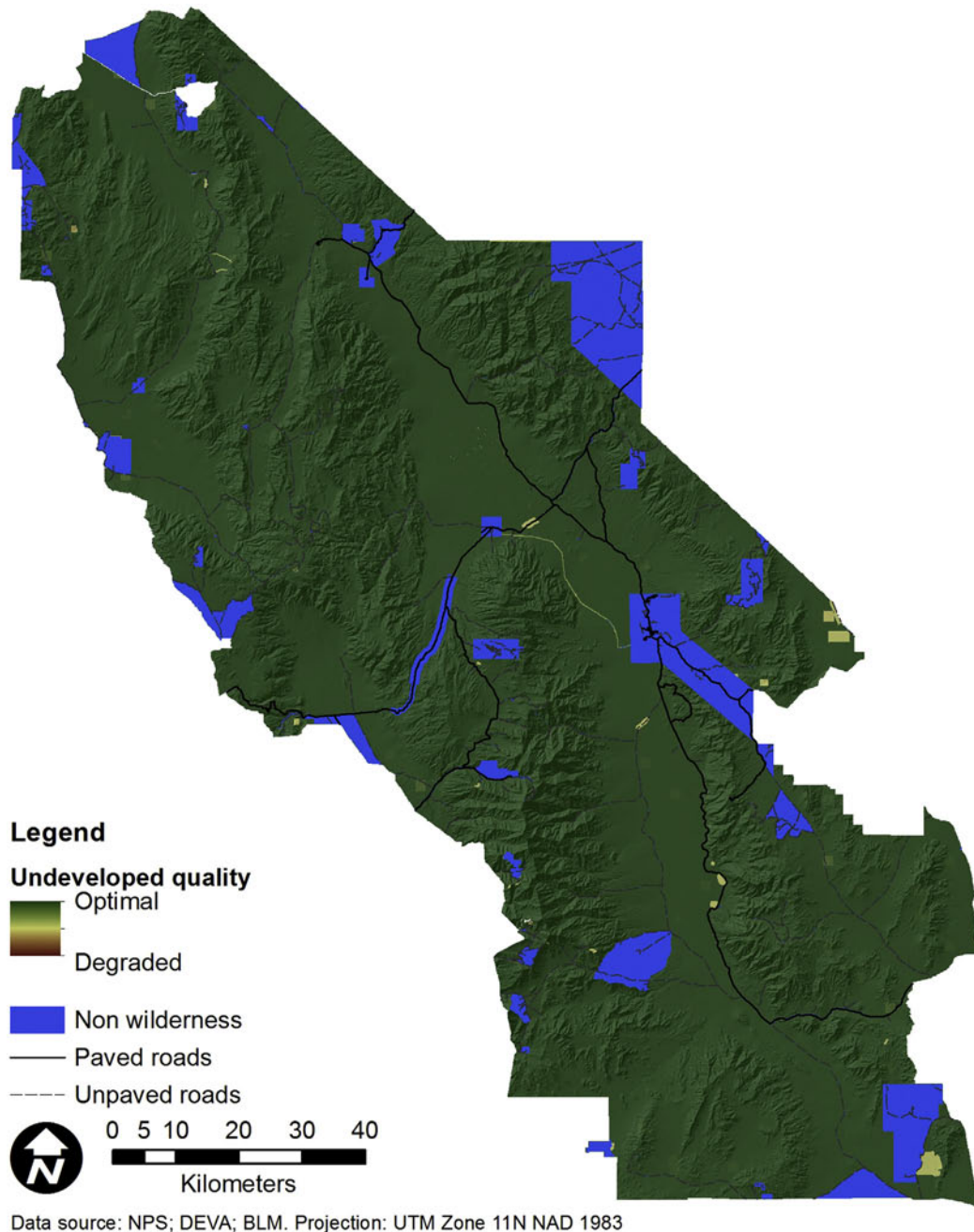| Indicator	Input	Weight	Rationale	Source	Scale	Accuracy
Non-recreational structures, installations, and developments	Installations (including guzzlers and fences)	55	Big footprints and large areas of impact	DEVA, NPS ASMIS	100 m	Moderate - High
	Unauthorised installation and debris	10	Small footprints, scattered	DEVA	100 m	Moderate
	Borrow pits	35	Big footprints, but few	DEVA	100 m	High
Inholdings	State inholdings with road access	15	Limited potential for development	BLM	100 m	High
	State inholdings with no road access or held for wildlife	5	Least likely to be developed	GCDB		
	Private inholdings	60	Most likely to be developed			
	Unpatented inholdings	20	Limited potential for development but more than state inholdings with road access			
Use of motor vehicles, motorised equipment, mechanical transport	ORV trespass	60	Frequent occurrence with potential for long lasting impacts	DEVA	100 m	Moderate
	Administrative uses	40	Point data, limited in space, time and effect on land			
Loss of statutorily protected cultural resources	Damaged or destroyed cabins	100	Important cultural resource and valued by park visitors. Destroyed ranked higher than damaged cabins	NPS ASMIS	100 m	High

Legend

Undeveloped quality
Optimal

Degraded

Non wilderness

—— Paved roads

----- Unpaved roads

0 5 10 20 30 40
Kilometers

Data source: NPS; DEVA; BLM. Projection: UTM Zone 11N NAD 1983

Fig. 6. Undeveloped quality of wilderness character in DEVA.

The weighted data inputs are combined via weighted linear summation to create separate maps for each of the three indicators before these are themselves added together to create the final natural quality map (Fig. 4).

2.4.2. Untrammelled quality

The untrammelled quality is degraded by management or actions that intentionally manipulate or control ecological systems, whereas the natural quality described above is degraded by intentional or unintentional effects from actions taken inside wilderness as well as from external forces on these systems (Landres et al., 2008a). Two indicators under this quality are: actions authorised by the Federal land manager that manipulate the biophysical environment such as fire suppression and invasive weed treatments, and similar actions that are not authorised by the Federal land manager which in this case only concerns poaching. As before, each indicator is derived from the weighted combination of a range of data inputs as described in Table 2.

In the DEVA case study no information was available on unauthorised actions (i.e. poaching), therefore these data and the associated indictor are left out of the model in this instance. The untrammelled quality map is shown in Fig. 5.

2.4.3. Undeveloped quality

The undeveloped quality is degraded by the presence of non-recreation structures and installations, habitations, and by the use

of motor vehicles, motorised equipment, or mechanical transport that increases people's ability to occupy or modify the environment (Landres et al., 2008a). Four indicators under this quality are: Non-recreational structures, installations and developments; in-holdings; and use of motor vehicles, motorised equipment or mechanical transport; and loss of statutorily protected cultural resources (Table 3 and Fig. 6).

2.4.4. Solitude or primitive and unconfined quality

The solitude or primitive and unconfined quality is degraded by settings that reduce these opportunities (Landres et al., 2004). Four indicators under this quality are: remoteness from sights and sounds of people inside the wilderness, remoteness from occupied and modified areas outside the wilderness, facilities that decrease self-reliant recreation, and management restrictions on visitor behaviour (Table 4).

Two sub-models are required for this quality to generate data inputs that quantify remoteness from the sights and sounds of people inside the wilderness. These are a travel-time sub-model and a viewshed sub-model. The travel time sub-model is based on a GIS implementation of Naismith's Rule incorporating Langmuir's Correction (Carver and Fritz, 1999). This allows remoteness from the nearest point of mechanised access to be calculated using terrain and land cover data, taking horizontal distance, relative slope, ground cover and barrier features into account. This approach has been successfully used in previous studies to map remoteness and on-foot travel times in wilderness and wild land areas (Fritz et al., 2000; Carver and Wrightham, 2003; Carver et al., 2012). The output from the travel time sub-model for the DEVA case study is shown in Fig. 7.

The viewshed sub-model utilises custom software (Viewshed Explorer Beta 1.0) and terrain and feature data to calculate where human features located either within or adjacent to the wilderness are visible from within the wilderness, and estimates their relative visual impact taking distance, size and the intervening terrain surface into account (Carver et al., 2012). Previous work on the effects of human features on perceptions of wilderness has tended to focus on simple distance measures because of the computational difficulties associated with calculating line of sight and relative impact measures using proprietary GIS software (Lesslie and Taylor, 1985; Carver, 1996; Sanderson et al., 2002). More recent work at local scales has used measures of visibility of human features using GIS and digital terrain models (Fritz et al., 2000; Carver and Wrightham, 2003; Ode et al., 2009; Ólafsdóttir and Runnström, 2011). Nonetheless, these models can still take weeks and even months to process even relatively small datasets when calculating

the combined distance and size weighted visibility of every human feature in the area. We used the Viewshed Explorer software to calculate the visual impact of all human features in the DEVA case study up to a maximum distance of 15 and 30 km depending on the size of the object or feature in question. The output from the viewshed sub-model for the DEVA case study is shown in Fig. 8. The combined indicator maps for the solitude quality are shown in Fig. 9.

2.5. The wilderness character map

The final wilderness character map is generated by combining the four quality maps using simple addition. All four qualities of wilderness character are of equal importance (Landres et al., 2008a), so no weighting of the individual quality maps is applied at this stage. Non-wilderness areas within the DEVA example are clipped out and represented as null (NoData) values. The final wilderness character map for the DEVA example is shown in Fig. 10.

2.6. Uncertainty analysis

The wilderness character map developed here is likely to be sensitive to various sources of uncertainty. The main source of uncertainty is that associated with the weights assigned to each of the data inputs used to define the indicators that are then used in each of the four wilderness quality maps. This is a common source of uncertainty in spatial multi-criteria decision models of the type developed here (Carver, 1991; Malczewski, 2006; Feick and Hall, 2004). To test the robustness of the overall model of wilderness character to weighting uncertainty, a Monte Carlo simulation (bootstrapping) approach is applied. This approach simulates the effect of errors associated with model inputs (in this case the model weights) by adding random "noise" to the initial inputs based on probable range of their value based on their likely statistical distribution and repeating the model a large number of times. This is commonly used to simulate the effects of GIS model inputs (Fisher, 1991; Emmi and Horton, 1995) and has previously been used to model uncertainty due to user-specified weights (Feick and Hall, 2004). In modelling weight uncertainty, the model weights which are applied to the input data when defining indicators are randomised by ±10% and then rescaled before being used to generate the wilderness character map. This process is repeated 100 times and a composite model created (Fig. 11). Mean and standard deviation of all of the 100 iterations are calculated to demonstrate the overall sensitivity of the model and identify any areas of localised sensitivity. Areas of high standard deviation

Table 4
Solitude or primitive and unconfined quality indicators, data inputs, weights and rationale.

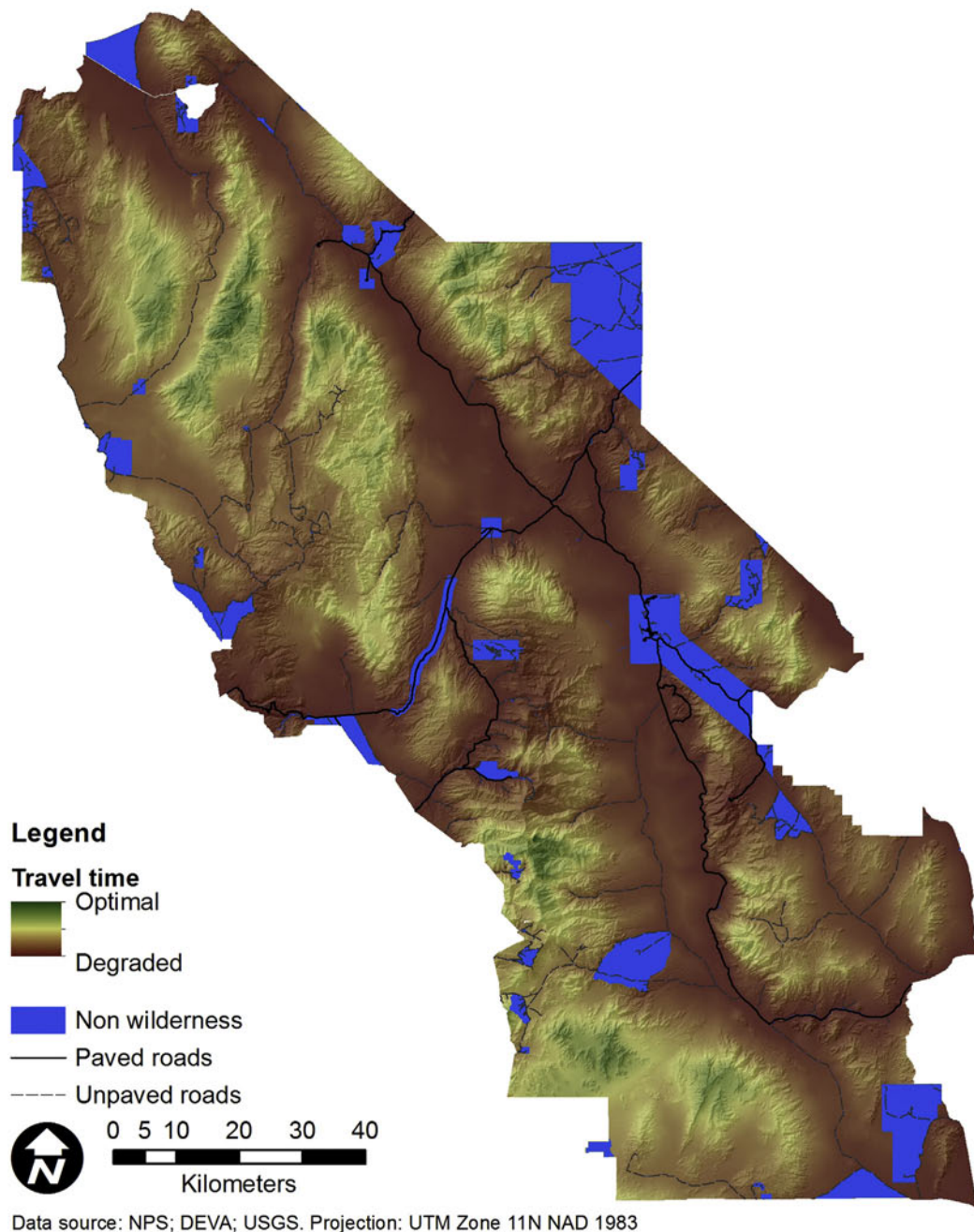| Indicator	Input	Weight	Rationale	Source	Scale	Accuracy
Remoteness from sights and sounds of people inside the wilderness	Travel time submodel	70	Remoteness is highlighted in the General Management plan as a park value to be preserved	USGS, Central Mojave Mapping Project, DEVA	30 m	High
	Viewshed submodel	30	Scenic quality is mentioned in General Management Plan as a park value to be preserved	DEVA and others	30 m	High
Remoteness from occupied and modified areas outside the wilderness	Over-flights	25	Issue of concern identified by the public during public scoping for the DEVA Wilderness Plan	DEVA	100 m	High – Moderate
	Soundscape	20		NPS Natural Sounds Program	100 m	Moderate
	Night sky – dark sky index	35	Important resource identified in the GMP as a park value to be preserved	NPS Night Sky Team	1 km	High
	Visibility (air quality)	20		NPS Air Resources Division	12 km	High
Facilities that decrease self-reliant recreation	Trails	20	Less influential on self-reliance	DEVA	100 m	Moderate
	Visitor facilities	80	More influential on self-reliance	DEVA	100 m	High
Management restrictions on visitor behaviour	Camping restrictions	20	Less impact on visitor use	DEVA	100 m	High
	Closed to visitor use	80	High impact on visitor use			

Legend

Travel time

Optimal

Degraded

Non wilderness

—— Paved roads

----- Unpaved roads

0 5 10   20   30   40
Kilometers

Data source: NPS; DEVA; USGS. Projection: UTM Zone 11N NAD 1983

Fig. 7. Travel time from paved road network.

indicate regions within the study area that are likely to be affected the most by uncertainty associated with defining model weights and therefore must be treated with greater caution. From Fig. 11, it can be seen that these are found principally in the north and west of the park, but more specifically in areas localised around particular data inputs.

3. Results

The four wilderness quality maps shown in Figs. 4–6 and 9 illustrate the overall pattern and variation in the natural, untrammelled, undeveloped, and solitude qualities, respectively, across the DEVA landscape. These exhibit a great degree of variability between the maps. Figs. 5 and 6 show how the untrammelled and

undeveloped qualities vary locally and exhibit only small, discrete changes around installations and specific land uses and inputs within the study area. In contrast, Figs. 4 and 9 show how the natural and solitude qualities exhibit much broader variability across the study area. The differences between the four quality maps are clearly a function of the input data layers and how the overall quality maps are defined through the weighting process. In Figs. 5 and 6 the data are highly skewed toward the higher end of the quality of wilderness character. This is to be expected in a landscape like DEVA where the far greater proportion of the landscape is untrammelled and undeveloped, and where impacts from human activity tend to be marked and very localised, for example, from borrow pits or cabins being recorded as binary present/absent data.
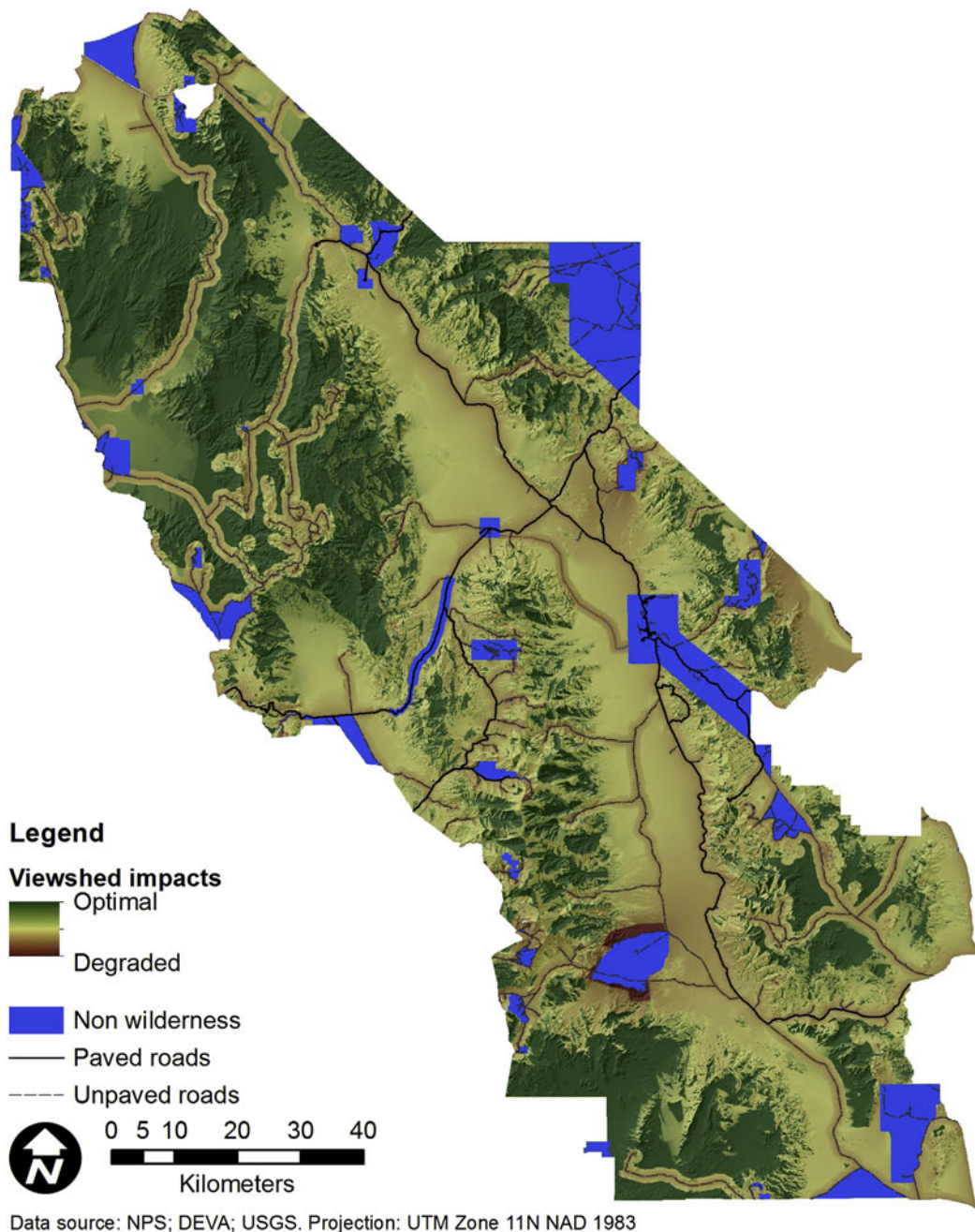
Fig. 8. Visual impacts in DEVA.

These differences propagate through the analysis and into the overall character map in Fig. 10. The bulk of the variability in wilderness character can be ascribed to the natural and solitude quality maps in Figs. 4 and 9. In Fig. 9, most of the variability is the result of the travel-time and viewshed sub-models within the solitude quality map. Terrain and distance therefore plays the greatest role in influencing wilderness character in DEVA either directly by influencing travel-times and visibility of human features, or indirectly by influencing the location of features in other input data layers. This is discussed further in the next section. As a result, the areas of the park with the optimal quality wilderness character tend to be the mountain ranges which are remote from vehicular access and shielded from human features by the topography. Example core areas include the Cottonwood Mountains in between Stovepipe Wells and Teakettle Junction, Tucki Mountain south of Stovepipe Wells, the Last Chance and Saline Ranges towards the north end of the park, the Grapevine Mountains east of Scotty's Castle, the Panamint Range in between Telescope and Sentinel Peaks, and the Funeral Mountains east of Furnace Creek (see Fig. 1). A histogram of mapped wilderness character values in DEVA reveals that the majority of the area falls into higher quality categories, with the top 10 per cent of highest quality areas to be found in the north and mountain areas of the park (see Fig. 12 and Fig. 10).

4. Discussion and conclusions

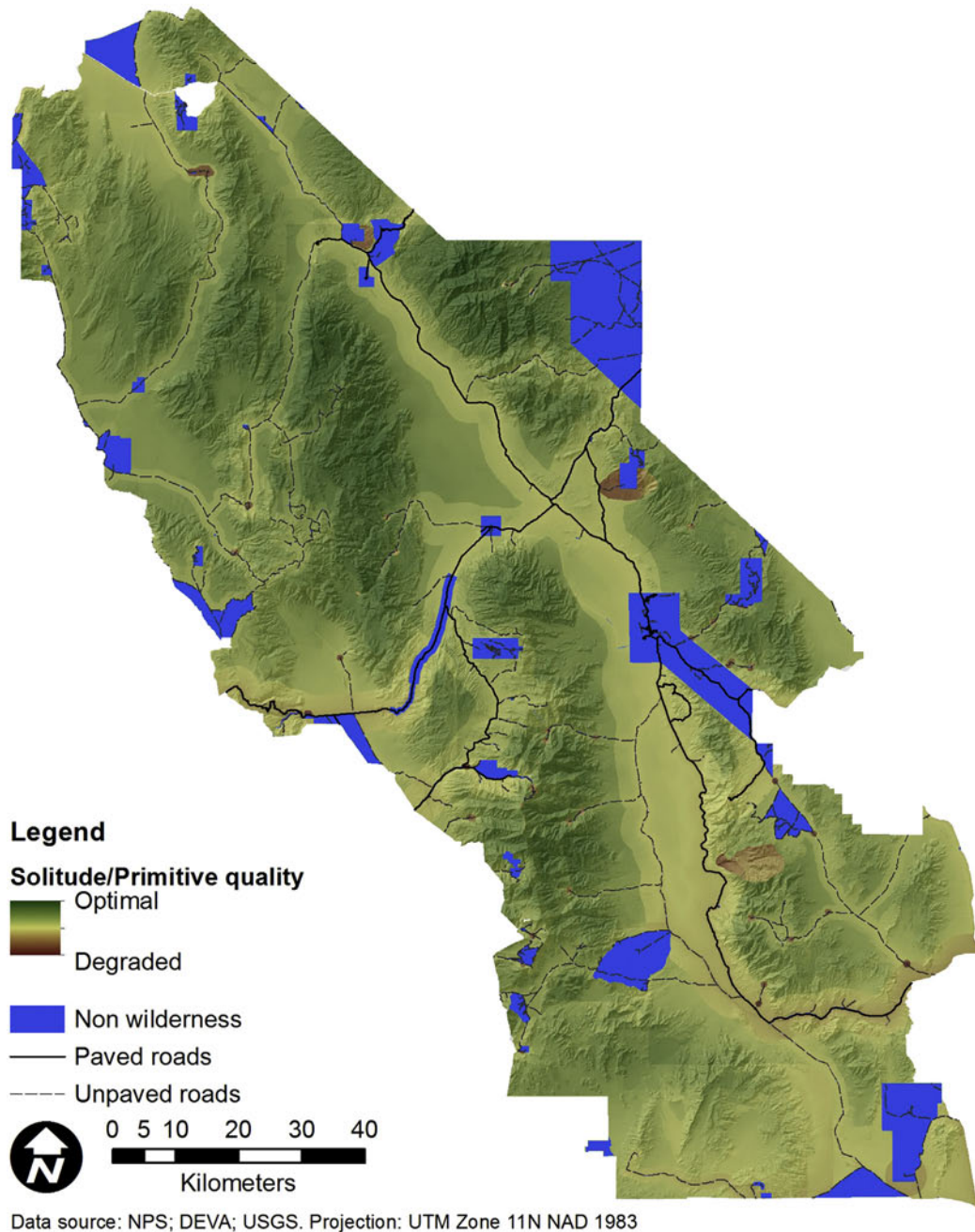The approach to mapping wilderness character in DEVA described here complements the existing non-spatial strategy for

Fig. 9. Solitude or primitive and unconfined quality of wilderness character in DEVA.

monitoring trends in wilderness character across the US National Wilderness Preservation System (Landres et al., 2008a). This GIS approach allows high resolution mapping of spatial trends within an existing wilderness to be used by wilderness managers to evaluate, on a pixel-by-pixel basis, the spatial impacts of various influences and drivers of wilderness character and the likely outcome of different planning alternatives such as those described below. The results shown in Figs. 4–10 and the uncertainty analyses shown in Fig. 11 demonstrate that the approach works and is robust to uncertainty in assigning weights to the data inputs. The application of such an explicit spatial framework for assessing impacts and monitoring trends in wilderness character represents an important step in the development of robust tools for wilderness planners and managers.

4.1. Advantages

There are a number of advantages in the approach developed here to map wilderness character. These include its flexibility, general robustness, and repeatability. The model is flexible because it can be applied to any wilderness of any size and of any type. The interagency framework of wilderness character (Landres et al., 2008a) is not specific to any one wilderness area and the GIS-based mapping approach developed and tested here for DEVA can be applied to any other wilderness in the US or elsewhere in the world. The ability to identify locally applicable data inputs and apply weights that reflect local conditions and priorities allows local wilderness managers to modify the approach to best suit their particular wilderness area taking into account local knowledge and
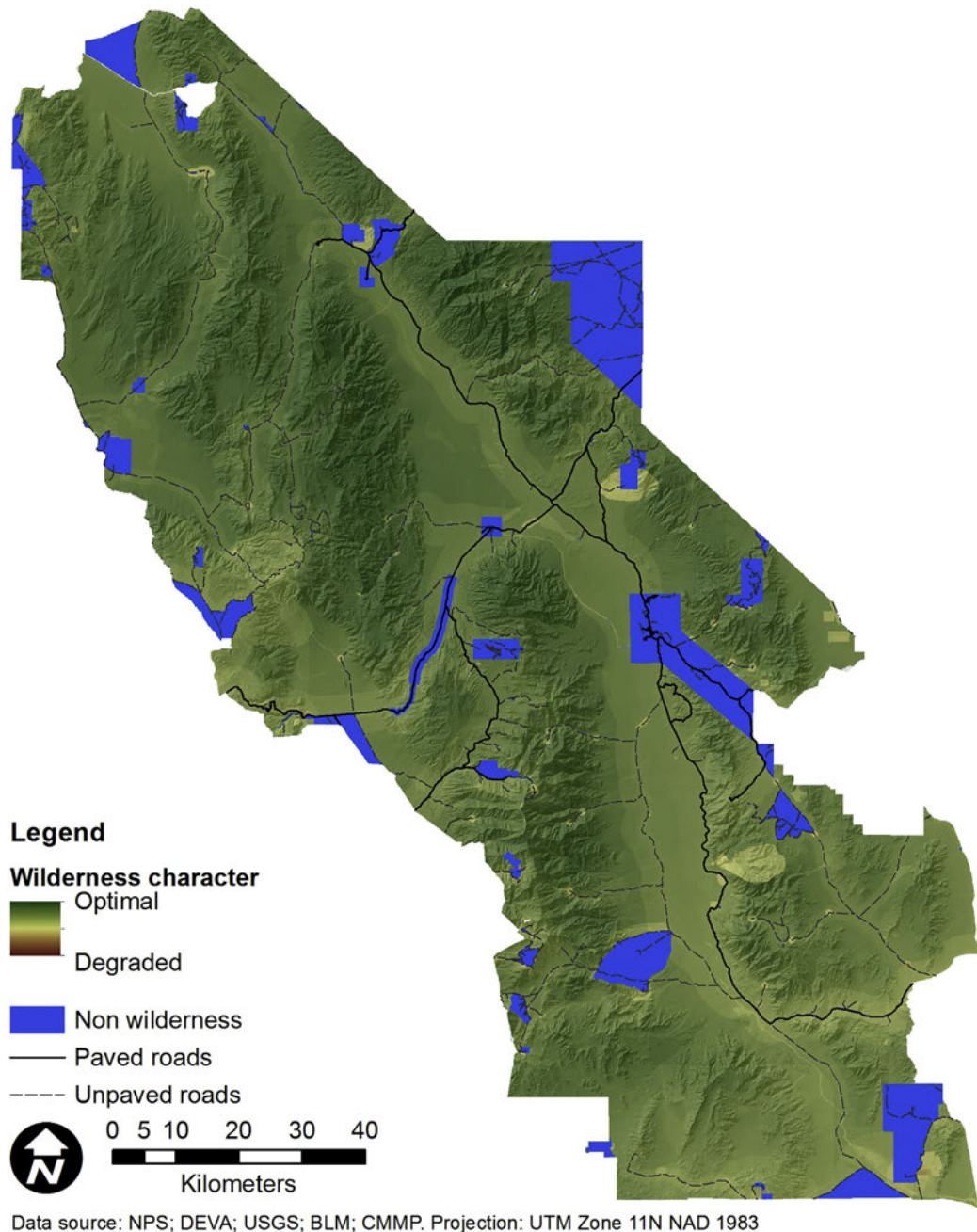
Fig. 10. Wilderness character in DEVA.

experience. For example, while the terrain-based inputs and sub-models have a large effect on the DEVA map outputs either through data input weights or the underlying character of the landscape itself, it is expected that in other wilderness areas different combinations of data inputs will be important. For example, the viewshed sub-model will be less important in heavily wooded landscapes. With some modification, the approach used here could be applied in other countries by adapting the hierarchy of data inputs, indicators and qualities shown in Fig. 3 to better suit other wilderness definitions and legislation.

A key advantage of this approach to mapping wilderness character is repeatability. Once developed to define baseline conditions, the map can easily be updated, either with new weights to reflect changing management priorities or new inputs as better data

becomes available or conditions change. For example, in the DEVA example, should the managers in the park consider upgrading the 32 miles of dirt road to the Racetrack Playa, the model shows that it would considerably reduce the access times and so have a marked impact on the remoteness of off-road areas in the Cottonwood and Last Chance Mountains as well as the Racetrack Playa itself (see Fig. 13) which in turn will have implications for the overall wilderness character of this remote corner of the park.

Another example concerns the existence of several "guzzlers" within the park. These artificial rainwater catchment tanks provide water to bighorn sheep and degrade two qualities of wilderness character. They degrade the undeveloped quality because they are a non-recreational structure and are input into the model as point data. They also degrade the natural quality because of their effect
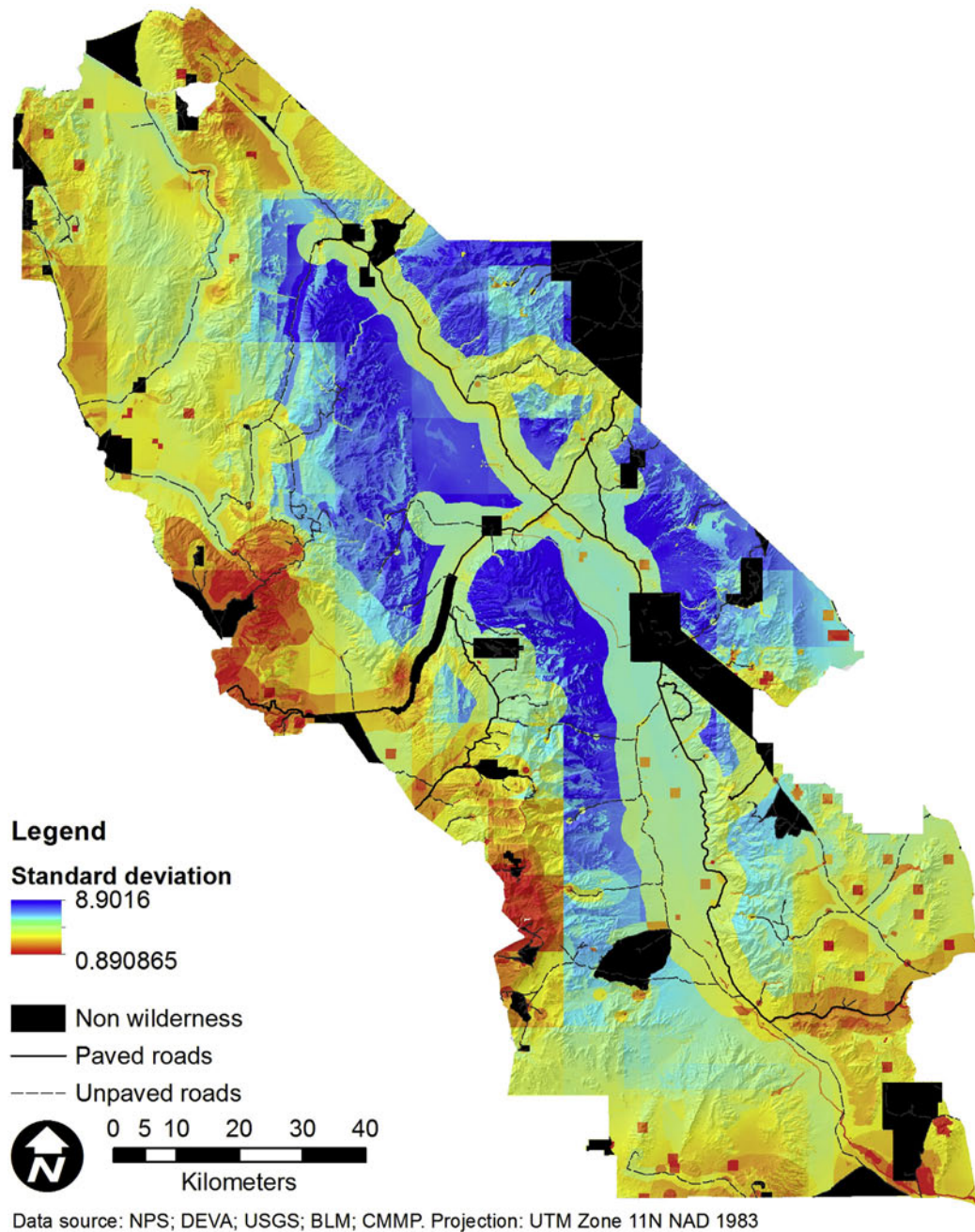
Fig. 11. Sensitivity to data input weight uncertainty.

on land cover through unnatural grazing, trampling, and animal droppings since animals are drawn to these artificial water sources. The guzzlers are input into the model for natural quality as areas buffered at 1–5 km distances to reflect the greater impact closer to the guzzler. One planning option is to remove these guzzlers and the model has shown that this management action could improve local conditions of natural and undeveloped qualities in the parts of the park affected.

These two brief examples illustrate the value of repeatability and "what if?" analyses in supporting strategic decisions within the park about activities such as road upgrades and management actions such as installation removal and landscape restoration. Repeatability also allows managers to track changes over time. For example, in DEVA the Hunter Mountain area has been

intermittently grazed for over 140 years. Should grazing rights be removed or stopped then the model could be used to monitor restoration of natural vegetation patterns in that area, but would likely require on-the-ground surveys to provide the data on rates of natural succession once grazing pressure was lifted.

4.2. Concerns

There are several concerns with the implications of the approach presented here that go beyond the typical concerns about data inputs and weights as described in the sensitivity analyses. One concern is that such mapping might facilitate creating so called "sacrifice zones" whereby managers may be tempted to focus their efforts on areas exhibiting the optimal wilderness character and
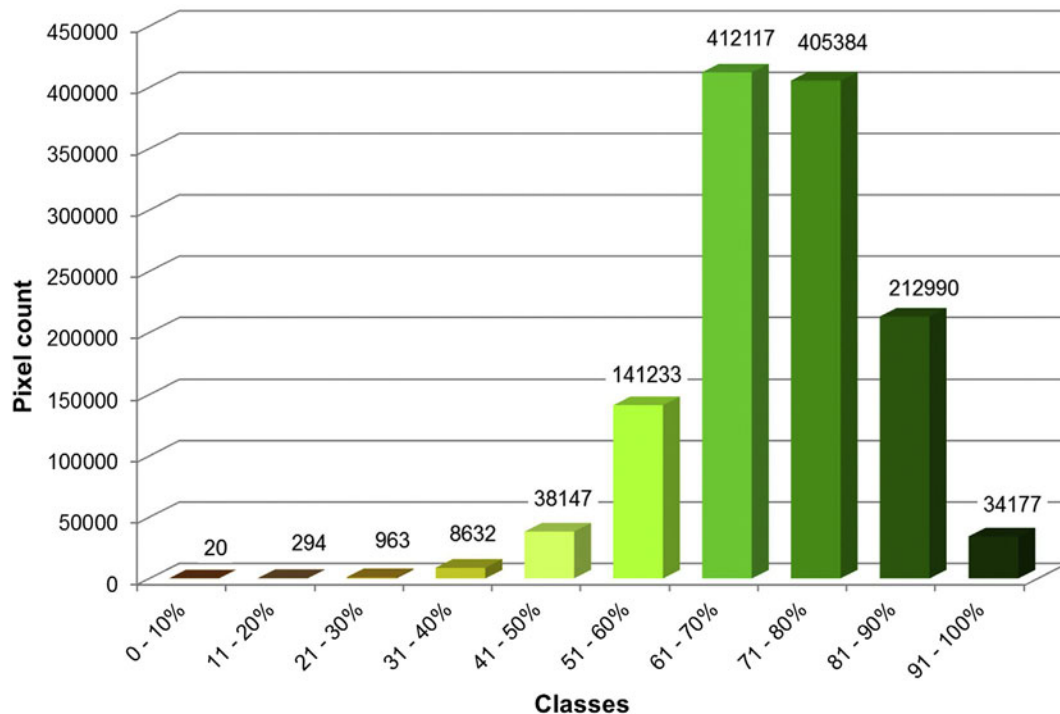
Fig. 12. Histogram of wilderness quality values in Fig. 10.

allow wilderness character to degrade in lower quality areas by continued and gradual change brought on by impacts in those areas. This would be in direct contravention of Congressional and agency mandates to preserve wilderness character across the entire wilderness. The intent of the wilderness character map developed here is to help wilderness managers maintain a broad and detailed spatial overview of the entire area. This spatial view would allow managers to maintain high quality areas and draw attention to the problems and impacts in degraded quality areas with the intent of improving these latter areas.

Another concern is that the ability to map and model wilderness character in this fashion will facilitate inappropriate inter-wilderness comparisons. While this would be numerically possible, and might seem attractive to do so, conceptually it would be meaningless since each wilderness area is unique and the wilderness character map is built from data inputs selected by each wilderness unit, which are scaled and weighted relative to one another. The mapping approach as described is therefore solely for use within the wilderness that it was developed for and not for inter-wilderness comparisons.

A final concern is one that is common to all GIS analyses, and focuses on the tendency of end-users to ascribe false levels of reliability and precision to model outputs and map products because they look accurate. These models are only intended as an estimate of selected aspects of wilderness character and their relative spatial dimensions of variability and pattern. They do not in any way portray the symbolic, intangible, spiritual and experiential values of wilderness character that are unique to the individual or the location and the experience of the moment (Watson 2004).

4.3. Model improvements

There are a number of ways the current approach to mapping wilderness character could be improved. These mainly concern data quality and sensitivity to data inputs and weights. As discussed, the approach presented here is dependent on the types of data required and how they are combined and weighted to spatially define wilderness character. Some, though not all, of the sensitivities of the approach to data quality could be addressed simply by using higher quality datasets as they become available. Several of the currently used datasets are of national or global origin and only currently available at very coarse resolutions. For example, night sky luminosity and air quality datasets are currently only available at 1 and 12 km resolution, respectively; the wilderness character map could be improved should new higher resolution data sources become available. Locally collected field data could further improve the quality of the datasets by allowing data points to be spatially referenced using GPS units.

The map developed for DEVA is sensitive to temporal variability at certain levels. For example, extreme summer temperatures will have a significant effect on wilderness character in some areas because off-road travel is very difficult, thereby increasing effective remoteness and markedly reducing visitor use. The travel time sub-model could be modified to take this into account and recalibrated to allow for the effects of having to carry more water, reduced walking speeds and needing to rest more during the hottest times of the day. Similarly, road closures due to snow and mud in the winter months could eliminate vehicular access in some areas of the park and so have a significant effect on remoteness and accessibility. Modifications to the overall travel time sub-model to include seasonality could therefore improve the temporal quality and consistency of the overall model.

Improving the way that the model handles "value added" or positive features would also improve the overall consistency of the model. While the measures used in the current approach involve modelling negative impacts on wilderness character, some features have a positive effect, such as preserving rare and endangered species, which, when encountered, would have a positive effect on visitor experience. However, we chose to not use "value added" measures because they would cancel out areas degraded by other measures when different layers are combined, and therefore the resulting maps would not show clearly those areas that were
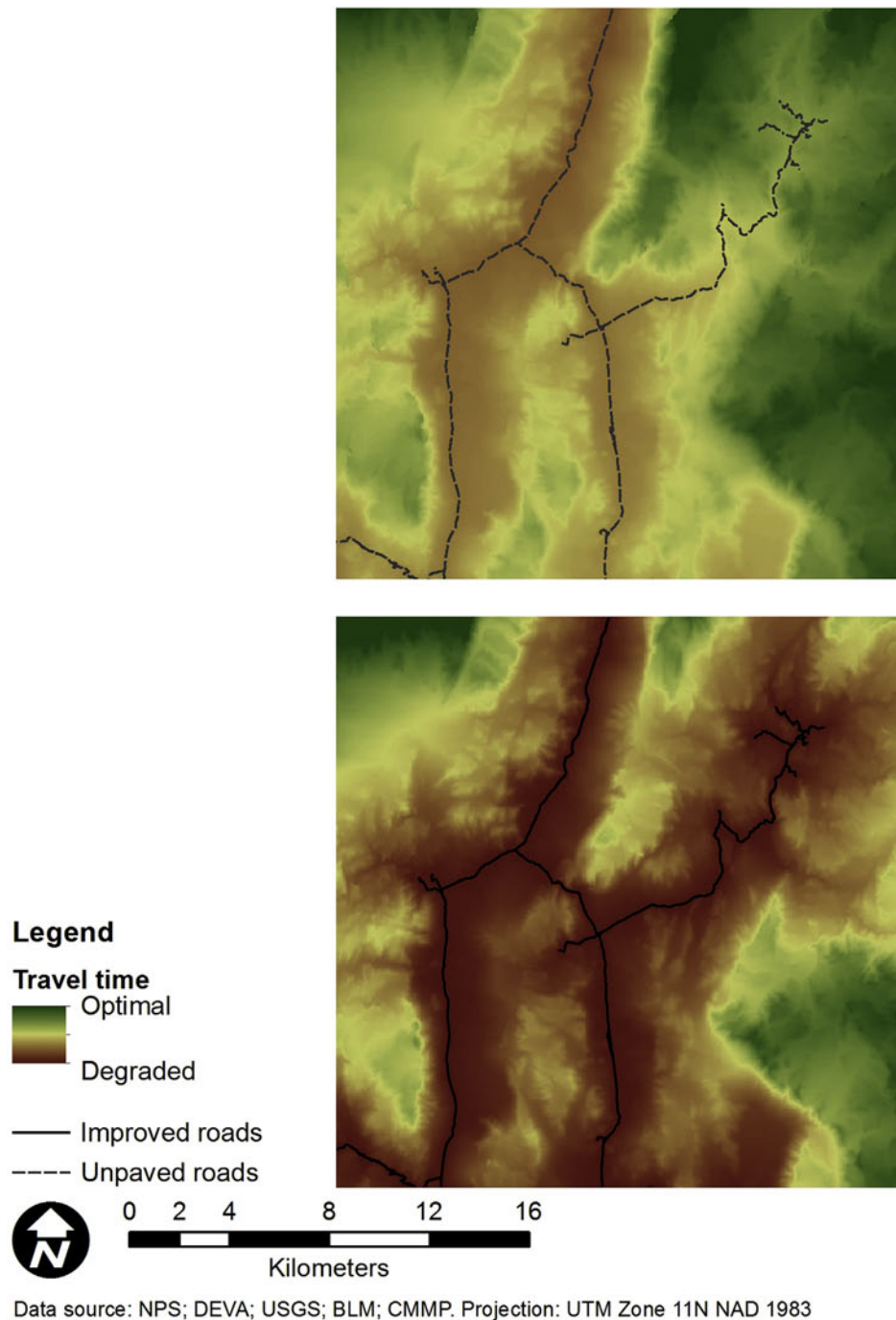
Fig. 13. "What if?" analysis of impacts of road upgrade on remoteness in Racetrack Playa area.

degraded. As an alternative, a separate "value added" or positive map could be produced showing just the attributes that add positive value to wilderness character.

Finally, the model is being used by the park staff to analyse the impacts on wilderness character of different alternatives being considered under the DEVA Wilderness and Backcountry Stewardship Plan. The approach described here to map wilderness character is currently being tested in several other wildernesses covering a range of sizes from small to large, a range of landscapes from desert to temperate rainforest to arctic tundra, and in an urban-proximate wilderness. Results from these additional test cases will help identify problems and improve the methods described here with the goal of demonstrating the applicability and usefulness of this approach across the National Wilderness Preservation System.

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