2 **Indicator-based assessment of wilderness quality in**
3 **mountain landscapes**

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Abstract

Wilderness is vitally important ecologically, economically, socially and culturally, yet it continues to decline globally. Despite high human modification and fragmentation in European landscapes, studies assessing wilderness in Europe suggest the presence of substantial areas of wilderness in mountainous areas. Following a European resolution, the importance of remaining wilderness areas has recently been recognised and efforts towards mapping and protecting remaining wildernesses have increased.

The central Alps lie within Switzerland and have been identified in multiple studies as a potential wilderness hotspot in Europe. In this study we develop robust, objective indicators to quantify wilderness and apply them to Switzerland. The indicators account for varying perceptions of wilderness and were evaluated by experts. Assessing international expert opinion to define indicator weightings has not been carried out in similar studies in the past, but serves as a transparent, objective and reproducible approach.

The indicators identified high quality wilderness areas, mostly at higher elevations, and demonstrate a suitable method for assessing remaining wilderness areas in landscapes subjected to large modifications by human activities. The spatial distribution of wilderness in the case study region Switzerland suggest that it may play an important role in wilderness conservation in Europe. Our study provides essential baseline information for wilderness monitoring, planning and protection, upon which future studies can build. Above this it provides robust, objective and adaptable indicators for wilderness quantification, which can be implemented in other countries and across various spatial scales. The method can be adapted for other countries - through the use of local expert opinions to weight indicators, and regions - with the inclusion of further datasets.

Keywords

GIS-based wilderness mapping, Multiple-Criteria-Evaluation, Switzerland, wilderness, wilderness conservation

1. Introduction

Wilderness areas provide critical refuges for rare plant and animal species (Sinclair, 2015), vital ecosystem services including carbon storage and sequestration (Luyssaert *et al.*, 2008), and act as buffers to regulate the local climate (Martin & Watson, 2016). Wilderness areas also offer a huge potential for education and research (Schwartz *et al.*, 2016), and are important for national and cultural heritage. As such wilderness is valuable economically, ecologically, socially and culturally. On a global level wilderness areas are however in considerable decline (Watson *et al.*, 2016, Sanderson *et al.*, 2002) and human pressures on the environment are increasing (Venter *et al.*, 2016).

European landscapes are largely transformed and fragmented (European Environment Agency/Swiss Federal Office for the Environment (EEA/FOEN), 2011), due to a long history of human settlement, agriculture, and as a result of industrialisation and urbanisation. Yet Europe still exhibits some large areas free from infrastructure, which are host to native species and ecosystems (Fisher *et al.*, 2010). With increasing demands on land to support an anticipated growing population (United Nations, 2015) these remaining wilderness areas are under threat. The importance of these remaining wilderness areas has been recognised, and is reflected in how wilderness has recently become an increasingly prevailing topic in politics and nature conservation legislation in Europe (Jones-Walters & Čivić, 2010). In 2009 the European parliament adopted a resolution calling for improved protection, funding and promotion of wilderness areas (European Parliament resolution on wilderness in Europe, 2009). This placed wilderness on the political agenda in Europe. The resolution also led to the development of guidelines for wilderness management within the Natura 2000 system (European Union, 2013). Since the resolution, strategies have been developed in several European countries to promote and initiate wilderness protection. WildEurope a partnership of 18 agencies, NGOs and other institutions was formed to coordinate protection and restoration strategies and was formally accepted as part of this resolution (Fisher *et al.*, 2010).

Figure 1. The wilderness continuum concept, adapted from Lesslie and Taylor (1985), shows wilderness at one end of a continuous scale ranging from high human modification to high naturalness. Wilderness is present at the most unmodified and most natural section of the scale.

Wilderness is generally perceived as the most untouched, pristine natural areas. In context of today's European landscapes, wilderness lies at one extreme of a continuous gradient of naturalness (ranging from pristine nature to highly modified urban areas) (see Fig. 1). Beyond this unanimous defining character the meaning of the term 'wilderness' is very subjective and opinions on wilderness vary greatly depending on people's past experiences, encounters and expectations. Consequently a wide variety of definitions have been developed in different cultures and landscapes.

This study uses the following definition of wilderness:

"A wilderness is an area governed by natural processes. It is composed of native habitats and species, and large enough for the effective ecological functioning of natural processes. It is unmodified or only slightly modified and without intrusive or extractive human activity, settlements, infrastructure or visual disturbance." (European Union, 2013)

Recent pan-European mapping of wilderness indicates that the Central Alps may contain some significant remaining wilderness areas (Kuiters *et al.*, 2013; EEA, 2010). Knowing the location of such areas is important for conservation (Mittermeier *et al.*, 1998), the development of protected area networks (Belote *et al.*, 2017; Locke & Dearden, 2005) as well as for the management of present and future recreational activities. Despite a recent boost in studies and inventories of wilderness in Europe at the national scale (Plutzer, 2013; Ólafsdóttir & Runnström, 2011; Müller *et al.*, 2015), and in smaller regions and protected areas (Carver *et al.*, 2002; Carver *et al.*, 2012; Orsi *et al.*, 2013) there is no comparable analysis or inventory of wilderness for Switzerland, an area that has repeatedly been mentioned to host remaining important wilderness areas. Moreover, there is a distinct need for robust and suitable indicators to evaluate and map wilderness, in order to identify remaining wilderness areas and to provide essential baseline information for wilderness monitoring, planning and protection.

The aims of this study are to:

1. Develop suitable and objective indicators, which account for varying wilderness perceptions, to quantify and map wilderness quality.
2. Identify areas of current high wilderness quality in the test region (Switzerland) using these indicators.
3. Demonstrate a robust method with suitable indicators, which may be applied in other geographical regions.

2. Materials and methods

2.1. Conceptual approach: the four wilderness indicators

Wilderness quality was quantified based on four main criteria, here termed wilderness indicators, similar to studies of Carver *et al.* (2012), Carver *et al.* (2013) and Müller *et al.* (2015). The four wilderness indicators refer to main properties wilderness is considered to have:

Naturalness – A wilderness is an area of pristine nature, expected to comprise of native flora and fauna. Naturalness addresses the relevant biological properties of an area.

Human impact – A wilderness should be as free as possible from traces of people, including infrastructure, settlements, light and noise pollution.

Remoteness – Wilderness is generally far from civilisation and not easily accessible. Through this quality wilderness provides refuges for species particularly sensitive to human disturbance, and also the opportunities for solitude and reflection that visitors may seek.

Ruggedness – Ruggedness is a measure of the terrain and is particularly relevant in mountainous landscapes. Ruggedness can be perceived as a measure of a visitors' perception of wilderness, however it also plays a biological role in terms of speciation as incredibly challenging terrain may present barriers to gene-flow for certain species, but also provide refuges in secluded habitat for others.

Wilderness quality was modelled using quantitative data for these four indicators (see Fig. 2). The wilderness indicators (and their input data layers) may vary in their individual impacts on wilderness. This variation was accounted for through the combination of certain input data layers and wilderness indicators via weighted linear summation. Weights were applied according to expert opinions on the importance of these elements (data layers and indicators) for wilderness. Implementing expert opinion was considered to result in a more objective and accurate assessment of wilderness quality, than arbitrary weight assignment or equal weightings. Assessing international expert opinion to define weightings has not been carried out in similar studies in the past, but serves as a transparent, objective and reproducible approach.

Figure 2. Overview of methods and dataflow. Input data to quantify the four wilderness indicators (naturalness, human impact, remoteness and ruggedness) were compiled for the whole of Switzerland at a resolution of 1 ha (100 x 100 m). Hexagons indicate procedures applied to input data and wilderness indicators. Each pixel (100 x 100 m) was assigned a wilderness quality value based on the assimilation of values for each indicator; these were scaled, weighted and combined to produce a wilderness quality value, resulting in a wilderness quality map. (Further information on input data available in Table A. 2. in Appendix)

The size of the areas of high quality wilderness identified was considered in the results. Wilderness areas should be large enough to support ecosystem functioning and natural processes. This study considers areas of ≥ 3000 ha, the minimum size for wilderness according to WildEurope (2013), and ≥ 1000 ha, the lowest size category for consideration on the European wilderness quality standard and audit system (European Wilderness Society, 2016) when comparing maps.

2.1.1. Expert survey

To weight the data elements and indicators in order to combine them to produce an objective map of wilderness quality, an expert survey was carried out. 25 experts, from five European countries, who work in wilderness related fields were sent a survey. Survey questions aimed to investigate the importance of individual input data elements and of the wilderness indicators in the professional opinion of experts.

2.1.2. Indicator combination

The wilderness indicators were tested for correlations, prior to combination, to ensure that no particular aspect was overrepresented in the model. Tests for correlation were carried out with Spearman's rank in R Version 3.3.0 (The R Foundation for Statistical Computing, 2016) using the "cor" function in the package "stats". Wilderness indicators were subsequently normalised to a scale of 1 - 5 using natural breaks. The indicators "naturalness" and "human impact" were normalised inversely, as high values for these indicators corresponded to low wilderness quality. Combination was then carried out using weighted linear summation, with the following formula:

$$W_i = \sum_{j=1}^n G_{ij} X_{ij}$$

Where W_i is the value for wilderness quality value for the i th iteration, j is the current wilderness indicator's number, G is indicator weight and X is the standardized value of each indicator (value on the normalised scale, see above), n is the number of indicators.

Spatial analysis was carried out in geographical information system ArcMap 10.4.1. Data were converted to raster format, with pixel size 100 x 100 m. Calculations were carried out in ArcMap 10.4.1 and in IDLE Python GUI version 2.7.8 (Python software foundation).

2.2. Test region

Switzerland is a central European country with an area of ca. 41, 285 km² (Swiss Federal Statistical Office, 1997). It is characterised by a highly variable climate and topography, featuring densely populated areas in the lowlands and remote areas in the mountains. It can be divided into 5 biogeographical regions; the Jura mountains, central plateau, northern Alps, central Alps and southern Alps (Gonseth *et al.*, 2001).

2.3. Quantifying the wilderness indicators in the test region

2.3.1. Naturalness

Naturalness is considered in terms of the degree of deviation in the composition of species and habitats from what would be expected to naturally occur in a particular area. In the absence of comprehensive data on vegetation, high resolution land cover data were reclassified to a hemeroby scale, similar to Plutzer, (2013) and Carver *et al.* (2013) and used to quantify naturalness. Values of the hemeroby scale ranged from 1 representing very close to natural conditions (ahemerobic) to 5, highly modified and completely unnatural conditions (metahemerobic).

Forests and grasslands were further subdivided into three elevation categories (colline-montane, subalpine and alpine) and assigned hemeroby values accordingly (see Table A. 1. in appendix), respecting their different management and use intensities at different elevations. Elevation levels were calculated based on the timberline definition using 9.5 °C July isotherms (Zimmerman & Kienast, 1995). The intensity of forest management was also considered in the quantification of naturalness. For the test region Switzerland forest inventory data were used to identify forest areas where the last management action took place over 50 and over 100 years ago respectively. Data layers were combined using maximum operator, the higher value for naturalness was retained where layers overlapped.

2.3.2. Human impact

Actions to modify and manage landscapes, along with constructions and infrastructure degrade wilderness quality. In this study human features were evaluated to most accurately represent their impact, e.g. noise emitted from roads and railways was incorporated into the model, rather than just assessing the visibility of such artefacts or using Euclidean buffers to simulate their impact.

Anthropogenic impacts were considered in several forms. Areas were categorised according to the degree to which they are free from infrastructure at a 500 x 500 m resolution (Kienast *et al.*, 2015). Infrastructure was assessed in three classes: completely free, where 0% of the 500 x 500 m area was covered with a structure, minimal infrastructure = 0-5% and considerable infrastructure >5%.

Roads and railway lines cover a considerable amount of the land area and are a source of noise. Several studies and reviews indicate that noise (pollution) has negative effects on both people (Basner *et al.*, 2014; Munzel *et al.*, 2014) and wildlife (Benitez-Lopez *et al.*, 2010; Barber *et al.*, 2010; Barber *et al.*, 2011). Based on guidelines for noise thresholds at night (World Health Organization,

2009) average daily noise over the threshold of 30 dB(A) was considered to have a negative impact on wilderness, noise data were thus categorised 0, 0-30 and >30 dB(A).

According to the wilderness definition used in this study, a wilderness is an area where people do not reside, but are visitors. To identify areas without human habitation, or with the least human habitation, population data were evaluated. Data were reclassified according to conservative parameters, 0 inhabitants, 1-10 and over 10 inhabitants. One effect of human settlements on the landscape is light pollution. Although only apparent at night, light pollution is known to negatively affect several wildlife species (Navara & Nelson, 2007). A recent review by Gaston *et al.*, (2013) highlighted the significant impact low levels of anthropogenic light pollution can have on wildlife, ecosystems and humans. Data on light pollution from the periods 1992-1994 and 2010-2012 were compared. Darkness was defined as complete darkness, i.e. radiance = 0, where radiance > 0 areas were considered "light". The entire test area was then classified according to these data and whether areas were dark in both periods, became light or were light in both time periods.

Other infrastructure was also taken into account. Guesthouses and huts were buffered by 200 m to more accurately represent their effect on immediately surrounding areas. Although hiking trails do not present barriers to the majority of wildlife, hiking itself is considered a disturbance in wilderness (Cole & Landres, 1996), and is known to result in changes to vegetation (Pickering & Hill, 2007). The effect of hiking trails and ski routes was assessed based on the length of trail or route in a 100 x 100 m area. Landscape fragmentation was additionally incorporated into the model. Areas were assigned values based on the size of the patch containing no fragmenting structures, including among other things; settlements, roads, motorways and railways as fragmenting structures.

2.3.3. Remoteness

Remoteness is essential for one function often assigned to wilderness; that such areas should protect and maintain species, particularly species highly sensitive to human presence and disturbance and those which can be harmful to humans (Aplet *et al.*, 2000). Remoteness, however, also describes the opportunity for solitude which some visitors may seek in wilderness (Boller *et al.*, 2010). Remoteness was calculated in two steps, considering accessibility by foot and road and accessibility using public transport.

The time required to reach each pixel of the map was calculated from pixels with a minimum of 15 residents. Barriers such as slopes over 45°, rivers, large water masses and glaciers were taken into account (as in Carver *et al.*, 2013) and walking speed was adapted according to land cover, based on assumptions from similar studies (Lieskovský *et al.*, 2014; Carver *et al.*, 2012). A walking speed of 4.2

km/h was taken for calculations on flat ground (Schweizer Wanderwege, 2015), changes in elevation were accounted for with additional walking time. Calculations were based on an extra 30 minutes walking time per consecutive slope increment, slope increments corresponded to a 300 m elevation change at velocity 4.2 km/h. A conservative travel speed of 30 km/h was applied to roads to represent travel in cars (here roads considered were all > 3 m wide) the same speed was applied for cable cars (see Table 1).

All train stations situated more than 200 m from the nearest road were assumed only accessible via public transport. These stations were all assigned a standard accessibility time of 30 minutes, from pixels on the map with more than 15 inhabitants, due to the outstanding public transport system in Switzerland. Stations situated within 200 m of a road were not considered, as travel with a private vehicle to such points is generally quicker. Both components of remoteness were combined and the shorter travel time was taken to generate conservative values for remoteness.

2.3.4. Ruggedness

The calculation for ruggedness (as in Müller *et al.*, 2015) followed Carver *et al.* (2012). Standard deviation of the curvature of terrain within a 250 m radius was calculated for the whole of Switzerland based on high resolution digital elevation model data. It is generally assumed that people perceive an area of ca. 250 m radius of their surroundings (Carver *et al.*, 2012).

Table 1. The expected speed of movement over different land cover types, with their associated costs for movement through a 100 m pixel. Calculations were based on a walking speed of 4.2 km/h on flat ground (Schweizer Wanderwege, 2015). Slopes were taken into account with an additional 30 minutes walking time per consecutive slope increment. Slope increments corresponded to 300 m change in elevation at velocity 4.2 km/h.

Landcover type	speed (km/h)	Movement costs for 100 m				
		0-4° gradient	4-8° gradient	8-12° gradient	12-16° gradient	>16° gradient
Paths/ trails	4	86	128	170	210	247
Background landscape	3.5	102	154	204	251	297
Forest	3	120	180	238	293	346
Dense, scrubby vegetation	2	181	269	356	440	519
Water		Barrier				
Roads	30	12	12	12	12	12
Cable cars	30	12	12	12	12	12

3. Results

3.1. Expert survey

22 experts responded to the survey, responses were evaluated collectively giving average (median) importance ratings for each of the four wilderness indicators and the data elements upon which their quantification was based. Weights for the four wilderness indicators and data elements for „human impact“ were calculated based on these importance ratings (see Tables 2 & 3). Weightings were calculated as follows:

$$G_i = IR / \frac{\sum_{IR=1}^n IR}{n}$$

Where G_i is the weighting, IR is the importance rating (median), and n is the number of wilderness indicators (Table 2) or the number of input data layers (Table 3) to be weighted. The median importance rating of all experts and the corresponding weightings are visible in Tables 2 & 3. In order to see how the weighting of the indicators and their input data layers can affect the wilderness quality map additional comparisons were carried out, using strongly contrasting weightings to those of the “collective expert opinion”.

Table 2. Weights of the four wilderness indicators, weightings based on responses to the survey question „In your professional opinion how important would you rate the following indicators for wilderness? (1 - not important at all, 10 - very important) “. Importance ratings are median values of expert responses (n=22).

Wilderness indicator	Collective expert opinion (n=22)	
	Importance rating (IR)	Weighting ¹
Naturalness	8	1.07
Human impact	9	1.20
Remoteness	8	1.07
Ruggedness	5	0.67

¹ Formula: $IR / \sum (IR) * \text{number of wilderness indicators}$

Table 3. Weights of the individual elements which contribute to the indicator „human impact“. Weightings based on the responses of experts regarding the importance of individual data elements of this indicator. Importance ratings are median values of expert responses (n=22).

Input data layer	Collective expert opinion (n=22)	
	Importance rating (IR)	Weighting ²
Noise from roads	9	1.29
Noise from trains	9	1.29
Light pollution	8	1.14
Huts	5	0.71
Guesthouses	7	1.00
Hiking routes	3.5	0.50
Skiing trails	3.5	0.50
Structures in the landscape	9	1.29
Fragmentation of the landscape /barriers in the landscape	9	1.29
High population in surrounding area	7	1.00

3.1. Wilderness maps for the test region Switzerland

Maps of the individual wilderness indicators (Fig. 3) show several similar areas to be valuable in terms of the aspects of wilderness they represent. Mountainous regions of the Alps were identified by all indicators as valuable. Despite some spatial overlap when visually assessing the wilderness indicators (Fig. 3) they were not considered collinear, $\rho < 0.7$ (Dormann *et al.*, 2013) (see Table 4).

Table 4. Matrix of Rho values from Spearman's rank correlation test, all values for $\rho < 0.7$ which is the threshold identified by Dormann *et al.* (2013) above which collinearity begins to distort model estimations.

Indicator	Naturalness	Human impact	Remoteness	Ruggedness
Naturalness	--	0.469	-0.651	-0.020
Human impact	0.469	--	-0.662	0.037
Remoteness	-0.651	-0.662	--	-0.140
Ruggedness	-0.020	0.037	-0.140	--

The wilderness quality map for Switzerland weighted according to all experts (Fig. 4) indicates areas of high wilderness quality at higher elevations in the Alps, with areas of very high wilderness quality over the Aletsch glacier, in small areas in south-eastern Switzerland on the boarder to Italy and in valleys in western Switzerland on the boarder to Italy. Some of the road network is recognisable in southern Switzerland, as areas in the red to red-orange range. In the central plateau it is not possible

² Formula: $IR / \sum (IR) * \text{number of input data layers}$

from the map to identify many individual cities, which demonstrates the impact of land cover and infrastructure on the model.

When quantified according to collective expert opinion (Fig. 4) 23,915 ha of Switzerland lie within the top 10% wilderness quality (wilderness quality value ≥ 19), comprising an area of ca. 0.6% of the Swiss territory. However no patches of this high wilderness quality form areas large enough to be recognised as wilderness according to the size definition of WildEurope (≥ 3000 ha) or the lowest size defined by European Wilderness Society (≥ 1000 ha). The patches of highest wilderness quality value are scattered and do not form continuous segments. Areas within the top 25% of wilderness quality (wilderness quality values 16-20) constitute ca. 12% of the land area, of which 384,502 ha (9% of the total land area) are comprised of areas over 3000 ha in size and 22 areas covering 35,619 ha represent wilderness areas over 1000 ha in size.

An additional comparison was carried out between wilderness maps derived from collective expert weightings of input parameters and maps based on strongly differing weightings to identify where differences may lie. Despite distinct differences, there was general agreement concerning the areas of highest wilderness quality. This indicates that the method, particularly the combination of indicators via weighted summation, is robust (as general patterns remain present despite differences in weightings).

Table 5. Overview of wilderness quality as weighted by collective expert opinion, here the total land area covered by the upper 10% and 25% wilderness qualities are shown: wilderness quality values ≥ 19 represent the upper 10% wilderness quality and ≥ 16 the upper 25% wilderness quality. The area covered by patches which meet the size definitions 1000 ha and 3000 ha are also shown.

Wilderness quality value	Collective expert opinion			
	Area covered (ha)	% of national territory	Area covered by patches ≥ 1000 ha	Area covered by patches ≥ 3000 ha
≥ 19	23914	0.6	0	0
≥ 16	531864	12.8	35619	384502

296 **Figure 3.** Maps of wilderness indicators, a) Naturalness – on a scale of 1-5, where 1 represents the most natural and 5 the most modified and unnatural areas, b) Human impact – on a scale of
297 1-5, where 5 represents areas with the highest human impact and 1 areas with very low human impact, c) Remoteness – displayed in terms of accessibility from the nearest considerably
298 populated area (< 15 residents), darker areas indicate lower accessibility and higher remoteness and d) Ruggedness – map depicts the ruggedness of the terrain in 5 levels, 5 represents high
299 ruggedness, 1 low ruggedness.

300 **Figure 4.** Wilderness quality in Switzerland based on the four indicators; „naturalness“, „human impact“, „remoteness“ and „ruggedness“, weighted according to expert opinion (n=22).
301 Wilderness quality is shown on a continuous scale, where dark blue areas represent areas with the highest wilderness quality, and red areas with the lowest wilderness quality.
302

4. Discussion

Wilderness is a highly valuable resource due to its multiple functions and services, yet it may be threatened by future human development. As such the assessment and quantification of wilderness quality is vital to enable its future protection.

The method of wilderness quantification presented in this study, although similar to that of Carver *et al.*, (2013) and Müller *et al.*, (2015) differs in the quantification and combination of indicators. The wilderness indicators implemented in this study are considered scientifically justifiable, reliably quantified and, as their quantification is based on existing datasets, their implementation is cost effective and applies accurately to large areas. Results of this study identified areas of high wilderness quality in Switzerland, most of which were present at higher elevations in mountainous areas. The spatial distribution of wilderness in this study concurs with results of studies in topographically similar landscapes (Carver *et al.*, 2012) and studies addressing larger spatial scales (European Environment Agency, 2010; Kuiters *et al.*, 2013). This indicates a high level of confidence in the maps produced and robustness in the data and methods implemented.

The wilderness map of the test region derived from collective expert weightings of the input parameters (Figure 4.) was additionally compared to wilderness maps created using strongly differing weightings to see where differences may lie. In comparing these maps it became clear that whilst distinct differences were visible there was agreement between the maps concerning the pattern of areas of highest wilderness value. This indicates that the method, particularly the combination of indicators via weighted summation, is robust (as general patterns remain present despite differences in weightings). The method is therefore considered suitable for adaptation; weighting of the indicators and input data elements could be adapted according to surveys of regional experts. In this way the method used in this study could be applied in other countries, where perceptions of the importance of wilderness indicators may vary, or where different elements may play stronger or weaker roles in the landscape.

We state that the methods could be applied in other geographical areas or ecoregions, and suggest here some adaptations to the methods to make them suitable for different topographical regions. Ruggedness (the degree of variation in elevation within a particular area) is the least universal indicator, as it requires rich topography. It is considered a proxy for the roughness and heterogeneity of habitats in mountainous areas. The higher their roughness and heterogeneity, the more likely the presence of original flora and fauna and thus wilderness, and the greater the human perception of wilderness. When analysing the wilderness quality of areas with less mountainous

terrain, this indicator could be removed from the model and the weights of the other indicators could be re-assessed accordingly. By removing the indicator ruggedness it would still be possible to quantify the main components of wilderness. Alternatively “ruggedness” could be substituted by an equivalent indicator which measures roughness and heterogeneity of habitats. For an ecoregion, such as arctic tundra this could be the spatial arrangement of solid ground and wetlands. For certain contexts, the indicator *remoteness* may be questioned as well. Remoteness measures the degree to which an area is accessible by humans and assumes that easily accessible areas are more likely to be disturbed by humans than remote ones. As this is certainly true on a global scale (e.g. Antarctica), it might not necessarily hold for close-by pristine areas such as waterfalls, caves or other landscape elements, which are close to civilisation but have not been transformed either due to their low economic or high cultural or aesthetic value.

This study provides a firm basis upon which to build and refine the picture of wilderness for a test study in mountainous terrain. It also allows the inclusion of newer datasets within indicators in the future as they become available. The method used to quantify wilderness could be further developed through the inclusion of additional more detailed data sets. As noise pollution from roads and railways was considered in this study, future studies could assess additional sources of disturbance such as noise from industrial activities, which has been shown to affect the breeding success of songbirds (Habib *et al.*, 2007). Occurrence data of mammal species were not implemented in the model as the available data are comprised mostly of chance observations or observation along trails and roads. Additionally there is room for debate as to which species are valid indicators of wilderness or wilderness quality (Ceașu *et al.*, 2015). This is a potential area for further investigation, but was not an aspect considered within the scope of this study.

Considering the results in context with other studies there is strong indication that mountainous regions are the areas which contain wilderness in heavily modified European landscapes. As a large part of the central Alps is situated in Switzerland and considerable amounts of this mountainous region have been identified to have high wilderness quality both in this study and also by Kuiters *et al.* (2013) and the European Environment Agency (2010), Switzerland may play an important role in central European wilderness conservation efforts in the future. Some areas of high wilderness quality identified lie on the country’s border, for example several valleys in south-western Switzerland (southern Valais), Fig. 4. When these results are considered alongside the unfragmented areas of the Alps, as highlighted in a study by Kaissl (2002), they could significantly contribute to internationally important areas worthy of protection.

Transboundary protected areas, protected areas which cross international boundaries (Vasiljević *et al.*, 2015), allow the protection of larger areas than solely concentrating on single countries. As such they could be implemented to provide high quality wilderness areas with suitable protection at the scale at which it is required. Conserving large unfragmented areas is particularly important for protecting whole ecosystems and their functions, therefore promoting ecosystem resilience to climate change (Martin & Watson, 2016). Moreover as wilderness areas are not confined to political boundaries, complementary mapping in neighbouring countries would be required to demarcate the high wilderness quality areas of conservation importance which cross international borders.

In order to assist practise (eg. Landscape planning and protection/conservation) the continuous scale of wilderness quality could be divided into categories of wilderness quality, however there is to date no scientific basis for setting thresholds for such categories. An additional map (See Appendix, Figure A. 1.) demonstrates a wilderness quality map with categories of wilderness quality rather than a continuous scale. Although this may be valuable as an overview to guide practice, the size of areas of high wilderness quality must be taken into account prior to any planning or protection development, as the size of connected areas of high wilderness quality is ecologically just as important as the quality itself. A connected network of different habitats can support long-term, viable meta-populations (Hanski, 2005), whereas fragmented areas mostly have small isolated populations. As such unfragmented wilderness areas are more valuable for conservation as the probability is higher that they support connected biotopes.

In order to assist practise (e.g. Landscape planning and protection/conservation) the continuous scale of wilderness quality could be divided into categories of wilderness quality. An additional map (See Appendix, Figure A. 2.) demonstrates a wilderness quality map with the highest wilderness qualities divided into categories rather than on a continuous scale. Although this may be valuable as an overview to guide practice in determining areas for conservation, the thresholds for category definitions are arbitrary and have no scientific bases. The size of connected areas of high wilderness quality are taken into account in this figure. This is crucial as a connected network of different habitats can support long-term, viable meta-populations (Hanski, 2005), whereas fragmented areas mostly have small isolated populations. As such unfragmented wilderness areas are more valuable for conservation as the probability is higher that they support connected biotopes. Consequently the size of connected areas of high wilderness quality is just as important as the quality of these areas and must be taken into account prior to any planning or protection development.

5. Conclusion

This study provides a search strategy to identify the geographical locations of wilderness using four indicators. Three of the four indicators can be considered universal, i.e. applicable to a range of different ecoregions. One indicator (ruggedness) is relevant in the context of mountainous terrain but could be removed or replaced should the search strategy presented in this study be applied to topographically uniform terrain. The application of the methods to the test area Switzerland yielded a spatially explicit overview of wilderness quality at the *national scale*, and solid baseline data upon which further studies can build. The method could *easily be applied in other countries*, as comparable data sets to those used in this study are available in most European countries (Kuiters *et al.*, 2013). Moreover the method is flexible and allows the opinions of local experts and or local people to be implemented in future assessments to define the weighting of data elements and wilderness indicators. The involvement of local people is invaluable for promoting the acceptance of regional developments and protected areas (Blondet *et al.*, 2017).

The method developed in this study is also suitable for application in regional studies where it could include more detailed data (data available at a higher resolution than national data) for example on forest dynamics (i.e. deadwood, stand age and structure). Further studies could investigate the current protection status and future threat status of high quality wilderness areas identified in this study, using land-use change scenarios (e.g. Price *et al.*, 2015) and information on planned developments.

As concerns the test region, Switzerland has a role to play in European wilderness conservation. Conservation of suitably large areas will most likely take the form of transboundary protected areas. The straightforward and cost-effective approach presented in this study could be implemented to facilitate transboundary wilderness quality assessments and strengthen transboundary cooperation and communication.

Authors' Contributions

SR, FK and JS conceived the ideas and designed methodology; SR and FK compiled the data; SR analysed the data; SR led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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