Article

Index Measuring Land Use Intensity—A Gradient-Based Approach

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Abstract: To monitor the changes in the landscape, and to relate these to ecological processes, we need robust and reproducible methods for quantifying the changes in landscape patterns. The main aim of this study is to present, exemplify and discuss a gradient-based index of land use intensity. This index can easily be calculated from spatial data that are available for most areas and may therefore have a wide applicability. Further, the index is adapted for use based on official data sets and can thus be used directly in decision-making at different levels. The index in its basic form consists of two parts where the first is based on the data of buildings and roads and the second of infrastructure land cover. We compared the index with two frequently used 'wilderness indices' in Norway called INON and the Human Footprint Index. Our index captures important elements of infrastructure in more detailed scales than the other indices. A particularly attractive feature of the index is that it is based on map databases that are updated regularly. The index has the potential to serve as an important tool in land use planning as well as a basis for monitoring, the assessment of ecological state and ecological integrity and for ecological accounting as well as strategic environmental assessments.

Keywords: infrastructure; land use; index; landscape; planning; monitoring

1. Introduction

Intensive human land use is widely acknowledged as the main driver of global biodiversity loss [1,2] . At the national level in Norway, land use change is listed as the major threat to red-listed species as well as nature types [3,4]. To monitor, interpret and understand the changes that occur in the landscape, and to relate these changes to ecological processes, we need robust and reproducible methods for quantifying the changes in landscape patterns, that can be applied repeatedly, e.g., at regular intervals [5]. Ongoing national monitoring programs in Norway include, e.g., changes in agricultural land [6], aggregated general land-cover changes [7], and the reduction in 'interference-free areas' [8]. Furthermore, a program for the area-representative nature monitoring (ANO) of indicators of ecological status based upon point sampling started in 2019 [9]. Even though robust tools and methods to quantitatively assess landscape change is pivotal for ecological accounting and management [10], a commonly accepted metric for quantification of the intensity of the human impact on landscapes is, however, still lacking. This is an obstacle to progress in the development of monitoring schemes for land use or land use change as drivers of ecological processes at the landscape level, in Norway and elsewhere.

Appropriately quantifying the human imprint on nature is a complex and challenging task that has been discussed in environmental sciences for almost 100 years (see e.g. [11]. Over the last decades, the number of available landscape metrics for the quantification of landscape patterns has increased strongly [12,13] and a multitude of frameworks now exist to guide the quantification of landscape changes. Landscape metrics can be

grouped in many ways. e.g., according to the treatment of land cover (or land use) as a categorical or a continuous variable [5]. In a categorical framework, land is assigned to distinct patches of qualitatively different land-cover types, e.g., forest, agriculture or urban land use, or by a simple dichotomy according to the presence or absence of one particular land cover category, e.g., 'forest/non-forest' or 'habitat/non-habitat'. Contrary to categorical mapping, continuum frameworks describe properties of the landscape by continuous variables, assuming more or less gradual variation. Examples of continuous variables that vary on landscape-relevant scales are the elevation, temperature, population density and variables derived from spectral data [14]. Both approaches address the spatial structure of the landscape, but they open the use of different analytic methods and hence, different inferences and insights [13] .

Categorical mapping of the human impact on nature can be exemplified by 'wilderness mapping' (see e.g. [15,16]. By this approach, 'wilderness' is identified by spatial analyses of the presence or absence of human-induced landscape elements, often combined with distance-based criteria such as the size and/or remoteness of focal areas. 'Wilderness mapping' is exemplified by the mapping and monitoring of interference-free areas in Norway ('Inngrepsfrie områder i Norge', INON), carried out by national governmental institutions since the mid-1990s [8,17], based on methodology adapted from [18]. An 'INON area' is defined as an area located more than a specified distance (1, 3 or 5 km) from a significant infrastructure element in the landscape. 'Wilderness mapping' is conceptually and computationally easy, resulting in graphically striking and easily interpretable outputs and has therefore become the preferred indicator of human impacts on Norwegian nature (see e.g. [8] .

Continuous mapping of human land use intensity can be exemplified by the Human Footprint Index [19], by which multiple proxies of human influence are combined into an index of the total, global extent of the human impact on nature. Conceptually, it resembles methods for total pollution-load assessments [20], which are important tools in the implementation of legislation. The Human Footprint Index, which takes into account built-up environments, crop and pasture land, human population density, nighttime light, railways, roads and navigable waterways, has been successfully applied for addressing structural changes in human land use (e.g., [21], and for relating such changes to ecological processes [22]. Nevertheless, due to coarse resolution (> 1 km²) and the large variation in data quality, methods intended for global-scale assessments tend to have a limited value for research, management and monitoring purposes at regional or local levels [23,24].

Simple dichotomies such as "nature vs. non-nature" or "wilderness vs. non-wilderness" based on subjectively selected cut-off distances from a selected set of objects will often fail to address the complexity of the human impact on the landscape. The intensity of the human utilization of landscapes varies along a continuum from natural areas with little human impact to semi-natural to heavily industrialized or urbanized areas [25,26]. When the continuous variation in human land use intensity is reduced to a few simple categories, as is the case in INON, variability within each category is overlooked and all other variability is discarded. Accordingly, it has become increasingly clear that metrics for quantifying 'naturalness' and/or the total human impact on natural areas need to account for a continuous variation in the intensity of the human impact and to include effects on our everyday landscapes, in addition to addressing remote and pristine wilderness areas [16,27,28]. Gradient-based indices of the human impact on landscapes, that may be operationalized for a variety of spatial scales, are urgently needed for research, management, and monitoring purposes, in Norway and elsewhere.

The main aim of this study is to present, exemplify and discuss a Land Use Intensity index' (LUI), that can be calculated from official spatial data that are available for most areas and may therefore have much wider applicability. The subsidiary aims are (i) to exemplify use of the LUI index for ecological analyses at the landscape level and for the monitoring of changes in human land use intensity over time and (ii), based on comparisons between the LUI index and other indices used nationally and internationally, to

discuss how the index can be developed into a useful tool for landscape characterization, mapping, planning, and for quantitative assessment of the human footprint on the landscape. There is a need in Norway to create an index of land encroachment and infrastructure that does not only have the distance to encroachment, such as Environmental regions without human encroachments (INON) [17], but which can show a stepless gradient in the infrastructure impact.

2. Materials and Methods

2.1. The LUI Theory

The Land Use Intensity (LUI) index is obtained as the sum of two or three component indices: (1) BI (the Building Index), quantifying the abundance of linear and discrete elements such as buildings and roads; (2) LCI (the Land-Cover Index), quantifying the cover of constructed, artificial and/or otherwise developed surfaces and, optionally, (3) ALI (the Additional Land use elements Index), that addresses the abundance, or magnitude, of other, less pervasive, human impacts such as regulated lakes, tractor trails, footpaths, pastures and fields.

The three component indices are obtained by calculating a focal statistic [29] for each cell in a grid (raster) with a predefined mesh width (grain), covering the targeted area. This method is also referred to as "spatial filtering", "convolution" [30], or the "moving window methodology" [14]. The cell for which the focal statistic is to be calculated, i.e., the focal, or central, cell, is circumscribed by a circle with a fixed radius. All grid cells within the perimeter of this neighborhood circle are used to calculate the focal statistic, which is typically the count of cells within the neighborhood in which a specific property, e.g., buildings, is present. In practice, calculations are made by moving the neighborhood window over the landscape, one cell at a time, calculating the focal statistic for the window and returning that value to the processing, central cell. The procedure is exemplified in Figure 1 by the calculation of the BI component of the LUI index for Norway [31] as the count of cells with the presence of buildings or roads in a raster neighborhood of the 81 grid cells, each 100 × 100 m, within a circular neighborhood with a radius of 500 m centered on the focal cell. Only cells with a major fraction of their area situated within the circumference of the circle are included in the neighborhood. In the example in Figure 1, the presence of buildings and roads was recorded in 17 grid cells, which gives a value of the key variable of 17 or, recorded as a frequency, 17/81 = 0.210. Cells for which the property cannot be meaningfully recorded, normally if covered by water or belonging to adjacent administrative areas, are compensated for by recalculating the fraction of presences out of relevant cells. Thus, if 23 of the 81 cells were irrelevant, the BI index, recorded as a frequency, would be adjusted to 17/ (81–23) = 0.293.
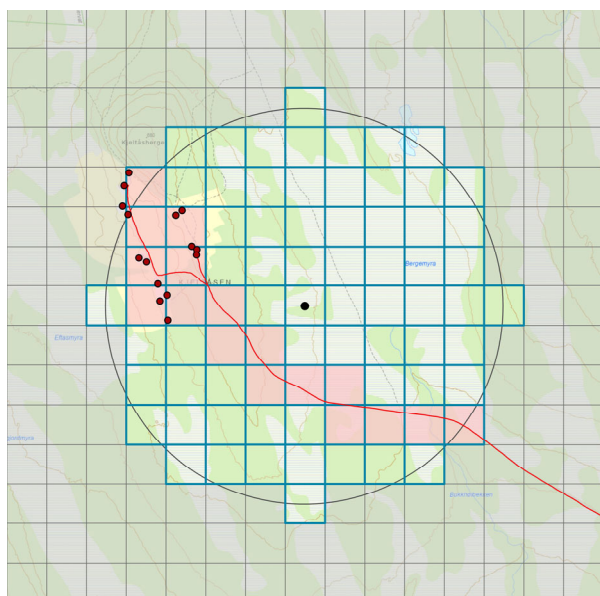
Figure 1. The calculation of the buildings and roads (BI) component of the LUI by focal statistics applied to a 100 m grid. The central 100 × 100 m grid cell for which the index is calculated is indicated by a black dot. The value of the BI index is obtained as the count of 100 × 100 m grid cells (pink squares) in the neighborhood circle with a radius of 500 m, in which buildings (red dots) and roads (red line) are present. In the neighborhood the circle is represented by 81 cells. The underlying map is from Kjeltåsen, Innlandet County, 11.137°E, 61.000°N (https://www.geonorge.no/ (accessed on 10 February 2023)).

The count of cells with the presence of the property in question (e.g., buildings and roads) could, in principle, be used directly as a component index. However, the environmental impact of different human-induced landscape elements varies among element types and also with element concentrations. This is exemplified by the many species which are sensitive even to small human disturbances [3,27]. A building, a road or another infrastructure element therefore represent a more 'severe' impact when added to previously 'undisturbed' land than when added to land that already has a high concentration of such elements. This should be reflected in the LUI index by a larger difference in the index value between 1 and 2 grid cells with the presence of buildings than between 61 and 62 cells with buildings. We achieved this by applying a base-2 logarithmic transformation to the BI, LCI and ALI counts, by which each doubling of the counted presence cells resulted in an increase in the index value by 1 unit. The logarithmic transformation was applied with a 'correction factor' (a scalar number added to the number of cells with buildings) to circumvent the problem with undefined values for 0 observed elements (the '$\log_2 0$' problem). The size of the 'correction factor' k affects the relative weight attributed to a unit difference in the lower versus the upper part of the scale. We applied a correction factor of $k = 4$, by which the index increases by one unit when the number of presence cells increases from 0 to 4, from 4 to 12, from 12 to 28 and from 28 to 60. The minimum value of $\log_2 (4 + x)$, obtained for $x = 0$, is 2. This value was subtracted from the transformed count to obtain the three component indices, which share the desired property of having a minimum of 0 when the type of land use in question is absent. Thus,

$$Component\ index = \ \log_2(4 + X) - 2 \qquad (1)$$

where X is either BI, LCI or ALI.

Arguments similar to those used above for emphasizing count differences differently for small and large values can be applied to the three component indices. We argue that the disturbance signal of discrete elements such as buildings and roads (captured by BI) are stronger than area-covering disturbances captured by LCI relative to the number of

pixels involved. We therefore weigh BI and LCI 2:1 in the *LUI* index, obtaining the following two-component version of the index:

$$LUI = 2 \cdot \log_2(4 + BI) + \log_2(4 + LCI) - 3 \cdot \log_2 4 \qquad (2)$$

which can be simplified as

$$LUI = 2 \cdot \log_2(4 + BI) + \log_2(4 + LCI) - 6 \qquad (3)$$

The *LUI* index varies from 0 to a theoretical maximum value of 13.23, which is obtained when all cells are occupied by buildings and roads [BI = 81; $2 \cdot \log_2(4 + ByI) = 8.82$] in a completely built-up area [LCI = 81; $\log_2(4 + KfI) = 4.41$].

Applying the *LUI* index to land management in Norwegian national parks [32], revealed a need for the incorporation of less pervasive impacts (cf. Table 1) in the *LUI* index. We accomplished that by adding the third component, ALI, to the *LUI* index. The elements contributing to the ALI are given half the weight of the LCI and one fourth the weight of the BI, based on the argument that the impacts of the ALI elements are less strong (i.e., paths) and relative to the number of cells they represent when the elements cover large areas (i.e., large regulated lakes). The extended *LUI* index, adjusted to a minimum of 0, is given by:

$$LUI_{ext} = 2 \cdot \log_2(4 + BI) + \log_2(4 + LCI) - 0.5 \cdot \log_2(4 + ALI) - 7 \qquad (4)$$

The theoretical maximum value of *LUIext* is 15.44. However, since the *ALI* and *BI/LCI* elements make up more or less mutually exclusive groups, the effect of adding the *ALI* component to the *LUI* index is rather to increase the resolution of the index in areas with a weak human footprint rather than adding it to high index values. In practice, then, the *LUIext* and *LUI* indices have the same maximum value.

Table 1. Landscape elements included in each component of the human land use (LUI) index. The data are included in the official topographic map of Norway and the data are downloadable in different GIS formats from https://www.geonorge.no/ (accessed on 10 February 2023) as part of the Norwegian official map strategy [33]. The data structure and quality are defined in the Norwegian SOSI standard [34]. The dataset "regulated lakes" is obtained from The Norwegian Water Resources and Energy Directorate: https://gis3.nve.no/metadata/tema/Magasin.html (accessed on 10 February 2022).

Component	Landscape-Elements Category	*LUI* Weight	*LUIext* Weight
Building component (Bl)	Buildings of any kind	2	4/7
	Linear elements from N50 'constructions' (power lines)		
	Linear elements from N50 'transportation' (main roads and railways)		
	Built-up technical facilities, ski-jump towers, communication towers, wind turbines, etc.		
Land cover, i.e., built-up areas (LCI)	Urban fabric (physical **urban** environment)	1	2/7
	Industry areas		
	Airports		
	Mine, dump, and construction sites		
	Graveyards		
	Sport and leisure facilities (including golf courses, ski-jump facilities, resorts, etc.)		
	Other built-up areas		

Other human impacts (ALI)	Regulated lakes		
	Agricultural fields	NA	1/7
	Tractor roads and footpaths		

A tutorial with a fully reproducible R-code and detailed documentation of the method is provided at github: https://github.com/trosim/land_use_intensity/blob/master/CLG_land_use_intensity_R_documentation.md (accessed on 10 February 2023). Development of the LUI index is based upon variables derived from existing topographical and thematical map databases [35]. The most important data source is the database of topographical maps to a scale of 1:50 000 (N50; Table 1). All variables cover the entire area of interest, i.e., the mainland of Norway. The data sources provide official, quality-controlled data that are updated on a regular basis, together representing all types of landscape elements listed in Table 1.

The original data were operationalized as variables by conversion from vector maps to raster maps with a resolution (grid-cell size) of 100 m. The presence or absence of landscape elements in each of the three groups (cf. Table 1) was recorded for each raster cell. The component indices BI, LCI and ALI were obtained for each 100 × 100 m grid cell by Equations (3) and (4), based on the method outlined in the theory section . An outline of the procedure is shown in Figure 2.
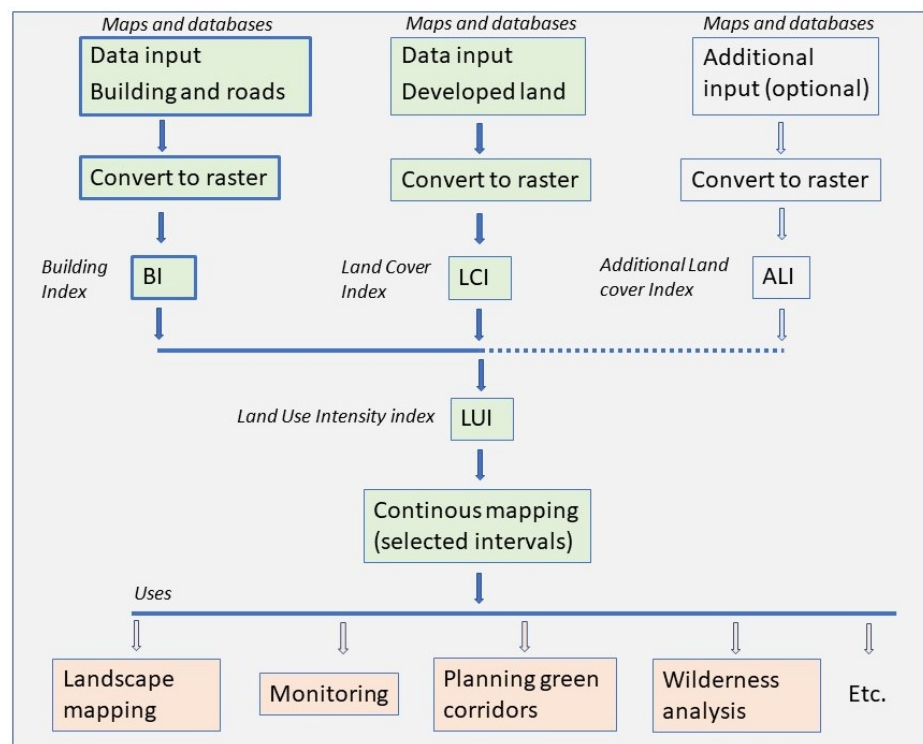
Figure 2. An overview of the procedure of calculating LUI with its components.

2.2. Overview of Examples and Calculations

We used the NiN landscape-type system for Norway [36,37] as a basis to describe the variation in human land use intensity across Norway (Section 3.1). This system divides Norwegian landscapes into three main-type groups (marine, coastal and inland landscapes), of which the latter two are further divided into six major types with 284 minor types.

The relationship between human land use in general and the presence of agricultural land (fields and pastures) was investigated (Section 3.2) by comparing the LUI indices, grid cell by grid cell, with an agricultural land use intensity index (AgI) calculated by the focal statistics method used to obtain the LCI index, i.e., by counting grid cells with agricultural land in the 81 100 × 100 m cells in the neighborhood circle of each focal cell. The effect of incorporating the ALI component in the LUI index was investigated in Section 3.3.

We compared the LUI with two frequently used 'wilderness indices'; INON (https://miljostatus.miljodirektoratet.no/tema/naturomrader-pa-land/inngrepsfri-natur/ (accessed on 10 February 2023)) and the Human Footprint Index (HFI; [19,21] in Section 3.4. INON was represented by a complete INON map for Norway, showing areas with more than 1, 3 and 5 km from a significant infrastructure element. We performed a graphical comparison between the LUI values, aggregated to 1 km^2 grid cells, and the INON map. We also calculated the mean LUI values for each of the INON 1-, 3- and 5-km zones. The LUI index values aggregated to 1 km^2 were compared with the HFI index calculated for a 1-km resolution.

The applicability of the Land Use Intensity index for studies of landscape change was explored in Section 3.5 by comparing the index values calculated from data collected in 2014 and 2019, respectively, for the urban area around the city of Trondheim. Finally, we explored the relationship between the LUI index and the distribution of red-listed plant species in Section 3.6. The material used for this comparison consisted of all occurrences of place-bound species, except birds and mammals, categorized as critically endangered (CR) on the Norwegian red-list for species [3]. Species occurrence data were obtained from [38].

3. Results

3.1. Patterns of Variation in Human Land Use Intensity across Norway

The map of the variation in the human Land Use Intensity index (LUI) across Norway (Figure 3) revealed the main cities (in red) and shows that the infrastructure is mainly concentrated to coastal plains and along the main valleys with large rivers and fjord lakes (in yellow). The fine-scaled variation in shades of green demonstrated the ability of the LUI index to differentiate between human land use intensities near the low-value end of the scale.

The distribution of the LUI index values within the major landscape types is shown in Table 2. The frequency of low LUI values (mean value within the landscape areas less than 0.5) varied from 57.4% of the landscape polygons in the inland hill and mountain landscapes to only 13.3 % in (coastal) fjord landscapes. The fraction of polygons with no registered infrastructure was 25.8% and 4.9% in the two major landscape types, respectively. Furthermore, a strong concentration of traces of human activity at the coast (coastal plains as well as fjords) was evident, reflecting the historical importance of the coast for human settlement and transportation in Norway. The high proportion of areas with a low LUI in coastal plain landscapes was due to the many landscape polygons along the coast consisting of small islands and skerries in which few of the pixels represent terrestrial areas. Land with few or small signs of human land use is mainly found in hill and mountain landscapes and inland plains, the latter containing wide plains both in the south and in the north.
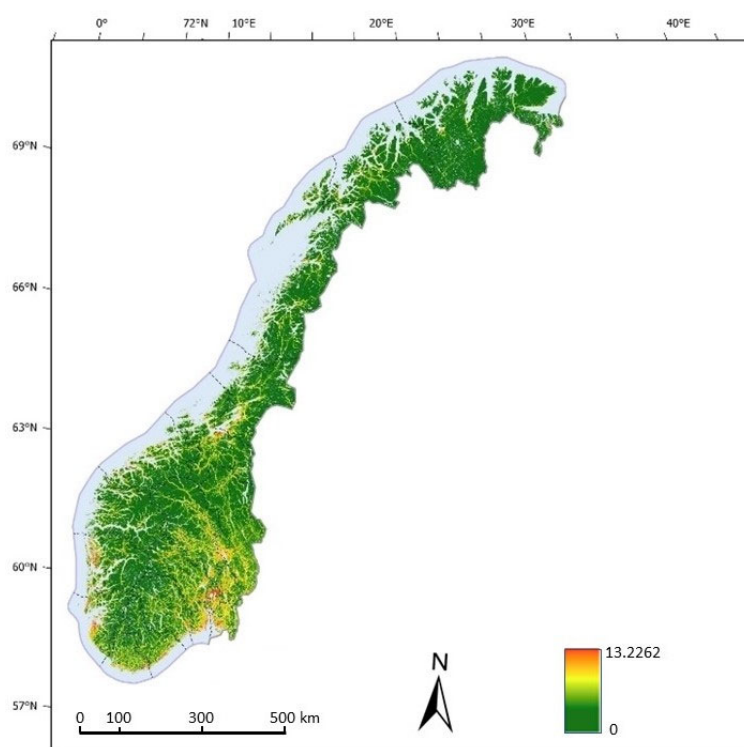
Figure 3. The human land use intensity across Norway, based on the calculation of the LUI index in a 100-m raster grid.

Table 2. The frequency distribution of human land use intensity, as expressed by the LUI index, for major landscape-type areas in Norway (as given by the NiN landscape-type map for Norway; [36].

Main Landscape Type	Number of Poly-gons	Frequency (%) in LUI Intervals					
		=0	<0.5	0.5–3	3–6	6–9	>9
Inland hills and mountains	21,781	25.8	57.4	30.4	9.2	2.6	0.4
Inland valleys	11,119	15.9	33.5	37.8	22.9	5.3	0.5
Inland plains	3,434	32.3	55.0	24.1	10.0	9.3	1.6
Coastal hills	77	31.2	48,1	18.2	16.9	11.7	5.2
Coastal fjords	3,748	4.9	13.3	27.0	38.7	16.8	4.2
Coastal plains	4,476	26.0	30.8	35.1	27.2	20.5	8.8

3.2. Relationships between LUI Agricultural Fields

A comparison between the LUI and a count of agricultural field pixels in the same neighborhood, i.e., agricultural index AgI, (Figure 4) showed that agricultural land use in Norway is associated with intermediate levels of roads, buildings and other elements related to infrastructure. The pattern shown in Figure 4 reflects that most of the country's agricultural land is connected to roads and situated near rural settlements. Furthermore, the low areal cover of agricultural land for high LUI index values demonstrates the effect of urbanization and infrastructure development: much of today's cities and industrialized areas are raised on former farmland.
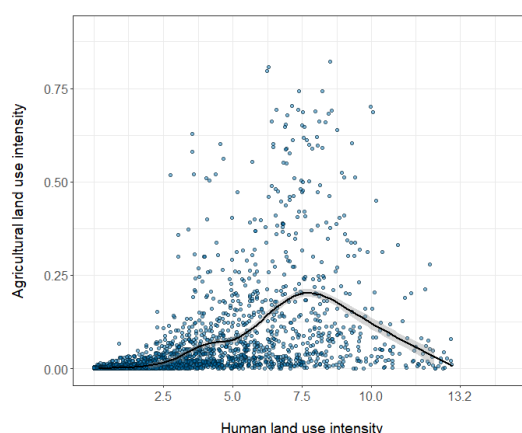
Figure 4. The relationship between the agricultural land use intensity index (AgI) and LUI. Each dot corresponds to one observation unit (spatial landscape unit), derived from a sample of 396 observation units throughout Norway. The solid line represents a LOESS smoother and the grey band around the line shows the uncertainty in the linear fit of the trend line with a 95% confidence level.

3.3. Exploring Properties of the Extended LUI Index

The extended land use index (LUI$_{ext}$) incorporated an element of agricultural land use (see Table 1). The effect of including the ALI component in the LUI index is clearly seen from Figure 5, in which maps of the LUI and LUI$_{ext}$ were compared for an inland area in SE Norway (around lake Mjøsa, the largest lake in Norway): the LUI$_{ext}$ index values were consistently raised to a higher level in the lowlands adjacent to lake Mjøsa where farming is still one of the most important occupations and a major fraction of the land is farmland. Furthermore, large lakes, all of which are regulated for hydropower electricity production, were given specific index values rather than a "no data" representation.
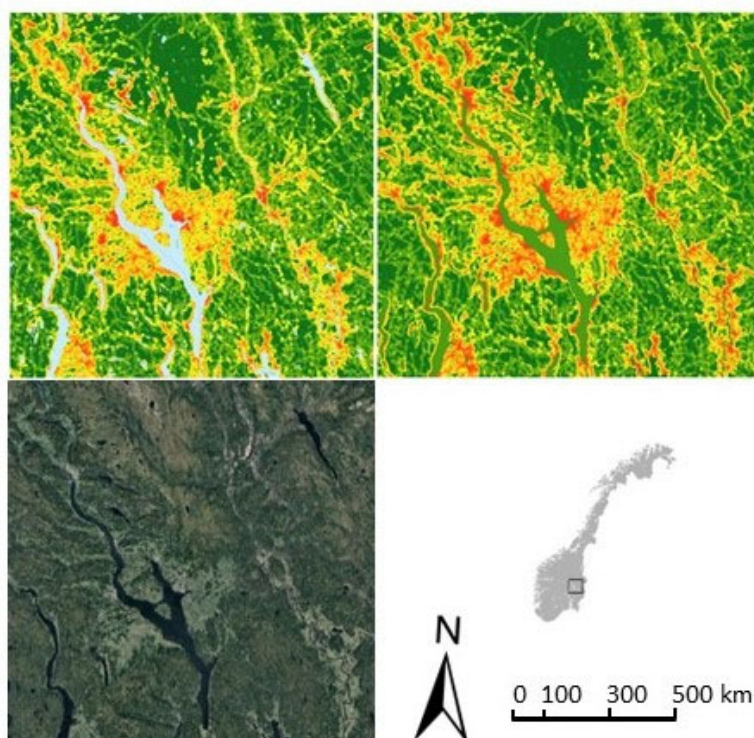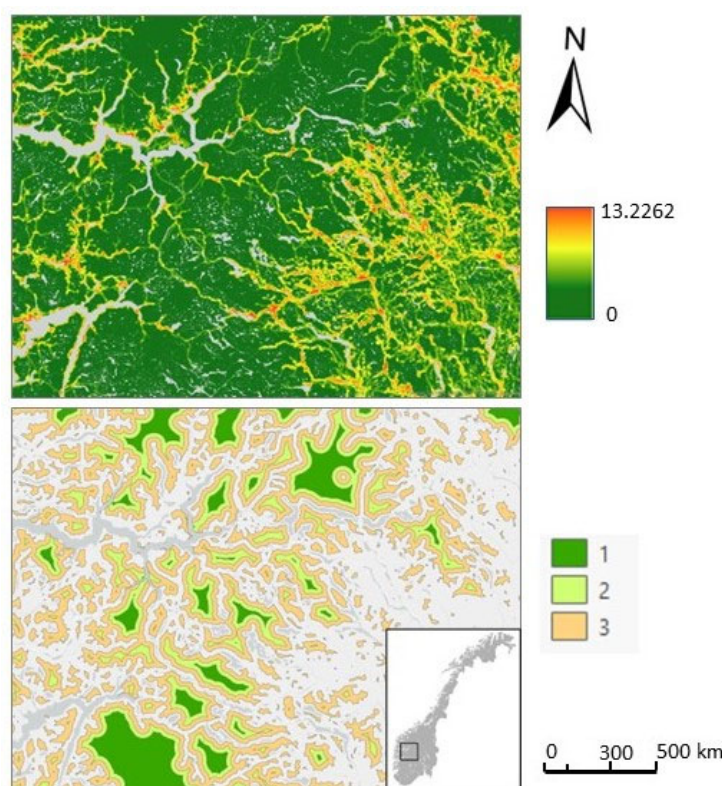

Figure 5. Maps of central SE Norway showing the LUI index in its original (left) and extended (right) version. Legend as in Figure 2. Below is satellite imagery over the area (Google Maps).

3.4. Comparison between the LUI Index and Two 'Wilderness Indices'

Of the more than 25,000 terrestrial (including coastal) landscape-type areas delineated for minor NiN landscape types on the landscape-type map for Norway, 44% had a mean LUI value below 0.5 (Table 2), indicating a very weak human footprint. A mean value of 0.5 is, for example, obtained by a landscape polygon of 10 km² in which one cluster of about 30 pixels contains buildings and/or roads or six clusters, each with 6 pixels, containing infrastructure.

A visual comparison between maps of the LUI index and INON areas (figure 6) show considerable similarities in broad patterns (as expected), but also suggests that the LUI index can reveal fine-scale patterns with a much finer resolution. Overlay measurements show a mean LUI index value of 0.04 in INON-zone 1, 0.06 in zone 2 and 0.10 in zone 3. A maximum value in INON zone 1 of 12.3 was, however, observed on a small island with traditional fishermen's cabins and boathouses not accounted for by INON. Here, the LUI value was boosted by the small area of land within the neighborhood circle, almost entirely occupied by buildings.


Figure 6. Maps of the western part of central Norway, showing the LUI index value (above) and INON zones 1, 2 and 3. Zone 1—a more than 5 km distance, zone 2—a 3–5 km distance and zone 3—a 1–3 km distance to the nearest significant infrastructural element (below). White areas are closer than 1 km to infrastructure elements.

The LUI and HFI indices were relatively weakly correlated with each other (Kendall's rank correlation coefficient: $\tau = 0.4471$, $p < 0.001$; Figure 7). The most likely reasons for this are the much coarser scale used for data input for the calculation of the Human Footprint Index and that this index makes use of proxies rather than detailed database information inputs (Figures 8 and 9).
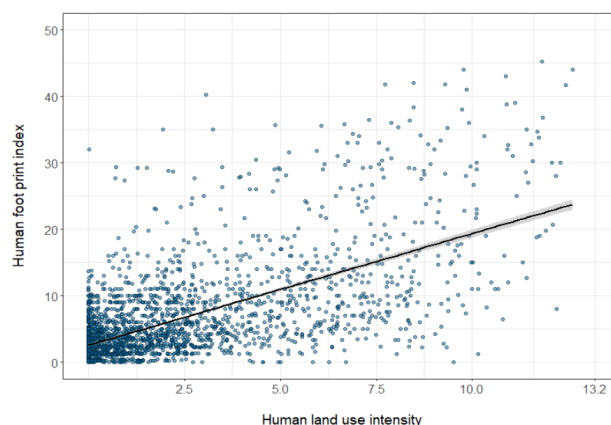
Figure 7. The relationship between The Human Footprint Index and the LUI for a sample of 3000 randomly selected points throughout Norway. The black line represents a regression line, while the shaded areas represent uncertainty in the linear fit of the trend line with a 95% confidence level.
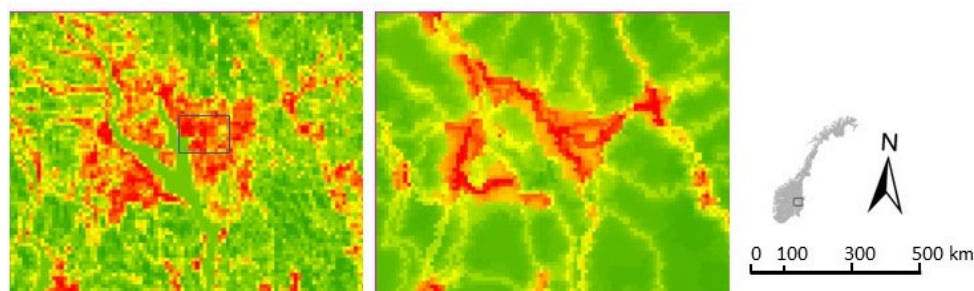
Figure 8. Maps showing the distribution of LUI (left), respaced to a 1 km² resolution, and the HFI to the right for the same area in central SE Norway as in Figure 5. Note the different generalization level of the HFI. The black rectangle shows the area addressed in Figure 9.
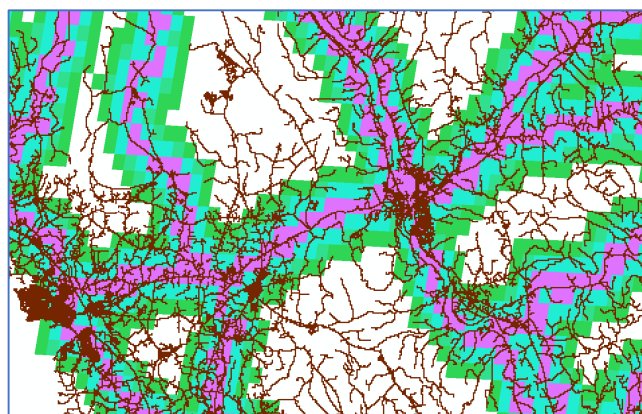

Figure 9. The input of index values of the HFI index, exemplified with the layer "roads" shown in intensity classes from purple (highest) to green (lowest) with a resolution of 1 km, overlayed by the road map input of the LUI with resolution 100 m. Note that the HFI index inputs are filtered and do not include small roads.

3.5. Applicability of the LUI Index in Studies of Landscape Change

Use of the LUI index in the quantitative analysis of landscape change is exemplified in Figure 10, showing that even small and gradual changes may be detected by the index. The median value of the index for Trondheim municipality, which comprises Norway's third largest city with about 200 000 inhabitants increased from 6.84 in 2014 to 6.90 in 2020. This increase was mainly due to the increase in the area with high values for the index (>

12). In this five-year period the areas with low values for the LUI index (<4) hardly changed, indicating that the LUI may also capture structural land use changes.
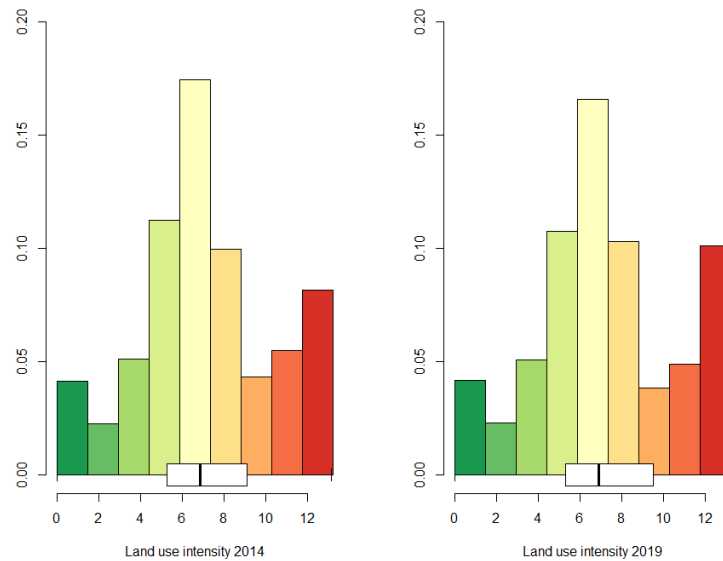
Figure 10. Changes in the LUI index values for 100 × 100 m pixels in the Trondheim municipality (321.8 km²) from 2014 (left) to 2019.

3.6. LUI and Red-Listed Species

Human activities impact biodiversity on many levels. As an example of this, we have illustrated the relation between the LUI index and occurrences of one category of red-listed species. Figure 11 shows the relationship between localities for critically endangered (CR) species and the LUI index, indicating a proportional overrepresentation (relative to the area occupied by each LUI interval) of CR species in cities and urbanized areas.
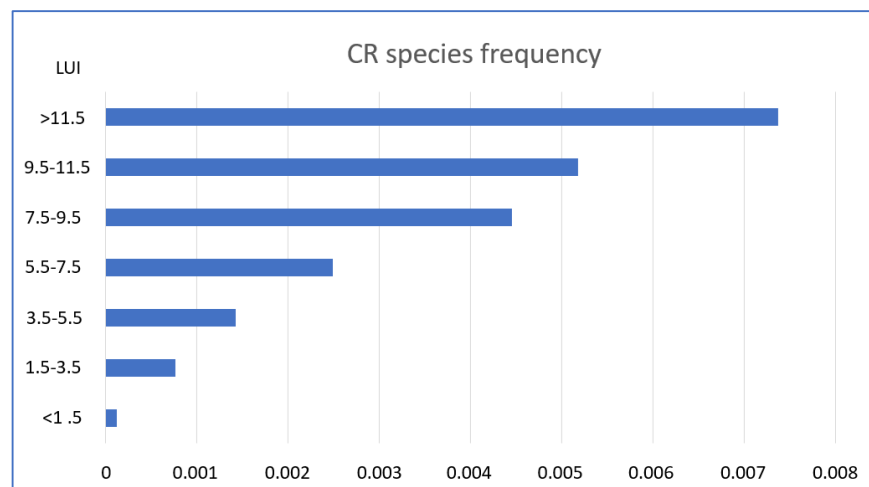
Figure 11. The distribution of known localities for critically endangered (CR) species in Norway for LUI index classes calculated as frequencies relative to the area.

4. Discussion

The calculation in Section 3.1 shows that the LUI provides information about the distribution of infrastructure in Norway with high precision. So far, the index has been actively used in the landscape-type characterization [31,36,37] where it is shown to represent a complex landscape gradient that explains the variation in landscape-element composition in all coastal and inland major landscape types. This indicates that most aspects of the human footprint at landscape-scales are captured by the index.

Section 3.2 raises the question if agricultural land use should be considered a landscape gradient on its own in studies of landscape-element diversity or be included in a general land use index. Kept as separate indices, the LUI and AgI can be combined freely with other gradients for a separate comparison with other landscape metrics and for the purpose of landscape typification. The relationship between the LUI and AgI in Norway is caused by the amount of arable land and its structure. Arable land makes up a small fraction only, some 3%, of the land area, and Norwegian fields are generally small in an international context [6]. Agricultural land mostly occurs close to farms and roads leading to farms, i.e., with intermediate infrastructure index values (LUI = 4–6).

Section 3.3 demonstrates that adding, with low weights, elements not included in the original LUI index, such as dammed lakes and arable land, into an extended index (LUI$_{ext}$), does not change the general geographical pattern of the index. Two noticeable effects may, however, may be noted from Figure 5: a small raise in the index values in areas with intensive agriculture and that large lakes switch from a lack of infrastructure to low impact due to water table regulations. Before this index or a modified version of it is taken into active use, its parameters should be tuned. Important questions are: how shall regulation height be incorporated? Shall all paths, even the smallest ones, be considered? How can the footprint of forestry be considered? For the present version of LUI$_{ext}$, we regarded all lakes that were recorded as regulated in the databases of The Norwegian Water Resources and Energy Directorate (NVE) as regulated, which in practical terms means a cut-off level for regulated lakes at a regulation height of 3 m or larger. Regulated rivers, river fortifications etc. were, however, not included, mainly because regional analysis [39] suggests that currently available data for all of Norway do not yet have the required quality. Defining thresholds based on the degree of regulation relative to water discharge and altered flow regimes, may in the longer term, improve the index. Similar considerations may apply to the lower threshold for path size, while the impact of forestry may more easily be incorporated based upon publicly available data.

Forestry and outfield grazing by domestic animals are very common activities in Norway, generally with diverse, intermediately strong environmental impacts [6] . Accordingly, both should be taken into account in an index that pretends to measure the total human footprint (e.g., [19,40]. This is particularly important if the index is used as empirical basis for assessments of the ecological character or value, e.g., by concepts such as 'ecological integrity' (cf. [41].

The comparison between the LUI and the official index of interference-free areas, i.e., the Norwegian wilderness map (INON; [8] in Section 3.4 shows considerable complementarity between the two indices. Important differences are, however, also visible. While INON provides a relatively coarse-grained picture based on a monothetic criterion—the distance from one single infrastructure element—LUI depicts a much more detailed pattern due to its polythetic nature where all infrastructure elements within the neighborhood circle are taken into account. Accordingly, the LUI index may be useful for the analysis of the intensity of human exploitation in all landscapes from wildernesses to large cities. The LUI also has a buffer element incorporated, but this is limited to the neighborhood circle, in our application with a radius of 500 m (Figure 1).

Section 3.4 also shows considerable similarities between the LUI and the Human Footprint Index (HFI) which is used worldwide [19,40]. In principle, the HFI incorporates several land use classes not accounted for in the LUI, some of which are, however, incorporated in the LUI$_{ext}$. The difference between the LUI and HFI indices is less than could

be expected, given that several land use classes (e.g., cropland, pastures and forestry) are not taken into account in the version of HFI used for our comparison. At the conceptual level, the main difference between the two indices is that HFI addresses a much coarser scale and is based on remote sensing data and other, more general data, while the LUI is based on detailed maps and database records. The data used as inputs to the LUI serve as a good proxy for intensive agricultural land use while the same is not necessarily true for forestry and grazing, although intensive forestry activities normally manifest themselves as a network of minor roads and skid trails, which are accounted for by the LUI. Global indices such as the HFI are normally not intended for local use and many of the differences between the LUI and HFI relate to the difference foci.

An attractive feature of the LUI is that it is calculated from quality-controlled data in official databases that are regularly updated. Accordingly, the LUI can be updated whenever necessary, e.g., on a regular basis, by automated procedures. The output can be presented both in a raster format and aggregated to landscape polygons or for landscape types as shown in Table 1. The LUI index is therefore well suited for general landscape monitoring as shown in Section 3.5. The LUI index may also provide a basic platform for strategic environmental assessments as it represents the total of the physical impacts to the landscape. The index may therefore serve as a proxy for the total impact load on the landscape and as a starting point for discussing the land's carrying capacity, alone or in combination with other information [42].

The intensity of the infrastructure, as expressed by the LUI index, has direct relevance for geodiversity, biodiversity and ecosystem services. In the context of geodiversity, the LUI may be used to indicate undisturbed or relatively undisturbed geomorphological processes. In the context of biodiversity and ecosystem services, areas such as farms, managed forests, rangelands, outfields and green spaces in urban areas are often of great importance [43]. This is underpinned by analyses of the Norwegian national red list for species, showing a clear concentration of threatened species to natural and semi-natural areas of South-East Norway [3]. This part of the country combines intensive human land use over centuries, as indicated in Section 3.6, with a favorable climate and exceptional geological diversity that includes sedimentary bedrock rich in minerals [44]. Maps that combine the LUI index with the concentration of threatened species may be useful for identification of biodiversity hotspots in need of conservation measures. Furthermore, this example shows the value of an infrastructure intensity index that not only addresses the wilderness but the entire scale of human footprints.

We have not included remote sensing as an opportunity to put additional data into the LUI index. Remote sensing advances in the continuous mapping of built-up areas, such as Normalized Difference Built-up Index (NDBI) [45] and ecological intactness such as the Intact Forest Landscapes [46,47], can give independent and gradient-like inputs. However, this will also add uncertainty to the index as all remote sensed products need quality checks, as well as interpretation or classification. A robust index based on official data will have qualities other than a remote sensed product and can be considered a lot more trustworthy as a source of information, for instance in an environmental management setting. In countries that lack reliable map databases, the use of remote sensing will be of vital importance to improve or validate data input.

5. Conclusions

The examples provided in this paper demonstrate the usefulness of the LUI as an index for the total physical human footprint, resulting from a combination of buildings, roads and built-up, artificial, constructed or otherwise developed land about which information is available from official map databases. The index has so far not been calibrated for relevance to specific aspects of ecology, but the LUI index captures important elements of the human footprint in a detailed scale, and can be used for a variety of uses such as wilderness assessments, green infrastructure and ecological integrity, etc. A particularly attractive feature of the infrastructure index is that it is based on map databases that are

updated regularly. Thus, the rapid development of global datasets based on crowd-sourced data e.g., OpenStreetMap (www.openstreetmap.org/ (accessed on 10 February 2023).) also opens the application of the index to areas that have previously lacked detailed geographical maps. In such areas, the index can be used in combination with remote sensing.

The LUI index has the potential to serve as an important tool in land use planning as well as a basis for monitoring, the assessment of ecological state and ecological integrity, and for ecological accounting.

The LUI index may also provide a basic platform for strategic environmental assessments that serve as a proxy for the total impact load on the landscape, alone or in combination with other information.

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