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## A framework for investigating the Land Degradation Neutrality – Disaster Risk Reduction nexus at the sub-national scales

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### Abstract

Specific guidelines are needed to overcome dichotomous classifications of lands into degraded or not for leveraging the Land Degradation Neutrality (LDN) concept. Overlooking degrading lands or those at risk of degradation can block LDN. Therefore, this paper proposes a detailed land classification method, and complements LDN with an indicator  $\alpha$  (wildfires, landslides and insights on aridity). Indicator  $\alpha$  taps the rarely studied LDN-natural hazards nexus. For separating degrading, degraded and non-degraded lands, twelve categories were defined, and indicators were then established. Subsequently, a land potential-hazard informed LDN intervention was planned. These methods target sub-national scales via the Lebanese/Mediterranean Aley district. Findings first revealed that Aley's land cover developed without considering land potential or hazard potentiality. Second, land status categories are distributed as 65% stable (of which 20.18 are lightly used), 8.14% non-degraded (adequately used, recovered and improving), 13.67% degraded, and 13.13% at risk of degradation. However, the district risks shifting towards less healthy land states due to unplanned development and natural hazards inconsideration. Accordingly, the LDN intervention targeted the stable/lightly used, at risk of degradation-/lightly used, overused and lightly used lands for optimization. This approach shifted 33.33% of Aley to adequately used lands, increasing the latter from 8.05% to 41.38%.

**Keywords:** Land degradation, Mediterranean, sub-national, natural hazards, mapping

### 1. Introduction

Ten years away from the United Nations' 2030 Sustainable Development Goals horizon, land degradation is still one of the most significant barriers facing the sustainable development of the world. From the globe's 195 countries, 169 are severely affected by land degradation (UNCCD, 2017a), making 75% of the Earth's lands degraded (Xie et al., 2020). In addition to the already existing losses, land degradation ravages agricultural lands each year, thus severely threatening food security (Zdruli et al., 2019).

Even after the acknowledgment of human dependence on lands, humans are still considered as the main drivers of land degradation. Fueled by the hunger for short-term economic revenues, humans have changed the land use/cover pattern of Earth in a rapid, and often unsustainable manner. As a result of demographic increases, land users of different socioeconomic statuses thrive to utilize their lands for generating economic revenues and for meeting their needs (Erdogan et al., 2019). However, the run for short-term economic gains, instead of promoting long-term sustainability (UNCCD, 2017b), made the lands needed for agriculture, urban development, and eco-services provision much greater than what is available (Erdogan et al., 2019).

In order to cope with the land degradation quandary and to concentrate efforts, the UNCCD proposed several concepts for combatting land degradation. One of the most widely accepted, efficient and up-to-date UNCCD contributions, is the Land Degradation Neutrality (LDN) concept (Orr et al., 2017). LDN aims to neutralize land degradation by counterbalancing land losses by land gains (Orr et al., 2017). It is based on three indicators to determine the state of lands, and a subsequent response strategy for attending to degradation (Cowie et al., 2018). The three LDN indicators are changes in land cover, soil organic C, and land productivity, while its hierarchical response strategy consists of avoiding, reducing, and reversing land degradation (Orr et al., 2017). The LDN indicators reveal areas of land losses, while the response strategy aims to provide land gains for creating a state of degradation neutrality (Gilbey, 2018).

To make use of LDN's power, the starting point should be a clear determination of which lands are degraded and which are not (Crossland et al., 2018). This separation is particularly important in countries where limited funds for restoring lands are available (Dallimer and Stringer, 2018). Nonetheless, drawing the line between degraded and non-degraded lands is one of the main barriers in land degradation studies, and often hinders effective interventions (Lewis and Kelly, 2014). This is because land degradation is a contested topic in its determinants, drivers, and causes (Al Sayah et al., 2019). Land degradation is often perceived based on the viewer's background and socioeconomic interests/benefits (Choudri et al., 2018). For farmers, land degradation is a process that influences the productive capacity of their lands or damages their yields (Choudri et al., 2018). Pedologists consider land degradation to be integrally tied to soil degradation (Dooley et al., 2015) by several processes, namely erosion (Kaffas and Hrisanthou, 2019). For engineers, soil structure interactions influence land stability, and hence its suitability for supporting buildings. Accordingly, what is defined as degraded in one's point of view, may not be applicable for others.

The different perceptions on land degradation not only create different definitions of the process (Gibbs and Salmon, 2015), but also influence the subsequent acceptance and willingness for the implementation of counter degradation measures. The above mentioned factors and their cross-cutting nature, make land degradation a complex discipline of research (Higginbottom and Symeonakis, 2014). This complexity makes the guidelines and criteria for classifying lands into degraded or not, contested and non-uniform, hence the difficulty of mapping land degradation (Safriel, 2017). However, mapping degradation is considered as the first cornerstone for achieving LDN (Liniger et al., 2019) and is needed to point the LDN response strategy at clear targets. According to Gibbs and Salmon (2015), the risk of wrongly estimating the availability of lands and their productive potential threatens the adequate implementation of anti-degradation measures. Chasek et al. (2019) further stressed that inaccurate information about the state of lands has the potential to disorient the LDN intervention, hence amplifying the risk of land degradation rather than mitigating it. Therefore, the establishment of accurate and simple tools for detecting land degradation is necessary for planning intervention policies. In addition to the challenges of land degradation mapping, the global LDN indicators aren't susceptible of clearly differentiating between degrading and degraded lands, and hence may not be enough for a holistic representation of land degradation (Akhtar-Schuster et al., 2017). For that reason, Wunder et al. (2018) stressed the need for tailoring a site-specific approach based on representative supplementary indicators.

In an attempt to respond to the above mentioned challenges, the objectives of this paper are to:

- 1) Propose a detailed land degradation classification scheme which extends beyond the dichotomous classification of degraded versus non degraded lands. Accordingly, the proposed method aims to highlight degradation hotspots for prioritized interventions and for classifying lands according to their vulnerability. That way, a tool for adequately orienting LDN, rehabilitating degraded lands, preserving healthy lands, and protecting those at risk is offered.
- 2) Integrate a supplementary indicator to the LDN framework based on its representivity of the Mediterranean region. The chosen indicators are wildfires and landslides, which are commonly occurring natural hazards in the study area, and in other Mediterranean settings (Abdallah et al., 2005). Additional insights on aridity are also provided given the amplitude of this threat. The integration of natural hazards was performed to account for the heterogeneity of land degradation and its drivers. Accordingly, natural hazards were introduced to widen the scope of land degradation mapping and also to tap the LDN-natural hazard relationship that hasn't been much discussed in literature.

For targeting the above-mentioned objectives, the Lebanese district of Aley was chosen as the study area. The reasons for this choice are: (1) the Mediterranean climate/characteristics of the district, (2) its rapid population increase rate and hence amplified pressures on land, (3) its national importance, and (4) the frequent occurrence of wildfires and landslides. Since these elements characterize most Mediterranean settings, Aley was chosen as a

representative of this context's sub-national scales. However, the outcomes of this study are also potentially applicable to other areas, although the particulars will differ. Therefore, this paper can be considered as an extension to land degradation literature and subsequent LDN efforts.

## 2. Materials and methods

### 2.1. Study area

Aley is one of the twenty four districts of Lebanon, and belongs to the Mount Lebanon governorate. The district covers an area of 263 km<sup>2</sup>, and accounts nearly for 2.5% of the country's surface. Extending from the coast to 2000 meters of altitude, and characterized by a Mediterranean climate, Aley presents a pedological setting mostly dominated by Leptosols (Darwish et al., 2006). Lands in the district are exploited as follows: 15% unproductive areas (rocky areas and abandoned lands), 15% agricultural areas, 20% grass and scrublands, 23% urban cover and 27% forests (Figure 1). Despite the relatively homogeneous distribution of land cover classes, increasing population rates (+6.61%) during the 2011-2017 period, have placed the lands of Aley under considerable pressure. In addition, the lack of urban planning and legislations led to unplanned urban expansion on agricultural and natural spaces, creating more pressure on the district's lands. Abdallah (2019) reported frequent occurrence of landslides and wildfires in the study area.

*Figure 1: Study area description*

### 2.2. Data and workflow

The general workflow of this research work is presented in Figure 2, while Table 1 presents the dataset used in this study.

*Table 1: The study utilized dataset*

Input type	Source/Description	Used in/for
Soil attributes (texture, depth, stoniness, pH, organic matter, drainage, erosion)	Darwish et al., (2006) / scale 1: 50 000	Land capability classification
Digital Elevation Model	National Council for Scientific Research Remote Sensing Center / resolution: 10 m	Land capability classification
LANDSAT imagery	From the USGS Earth explorer / Years: 1992, 2005 (LANDSAT 5), 2013 (LANDSAT 7) and 2018 (LANDSAT 8) For LANDSAT 7 images, gap filling was performed to correct scan line errors.	Extraction of NDVI time series Bands 3 and 4 are the red and Near Infra-Red (NIR) bands for LANDSAT 5 and 7 Bands 5 and 8 are the corresponding bands for LANDSAT 8.
KVR-1000, IKONOS, GEOEYE and WORLDVIEW imagery	National Council for Scientific Research Remote Sensing Center KVR-1000: 1992, 2 m IKONOS: 2005, 0.5 m GEOEYE: 2013, 0.5 m WORLDVIEW: 2018, 2 m	Establishment of land use/cover time series
Wildfires and landslides hazard potentiality maps	National Council for Scientific Research Remote Sensing Center / scale: 1: 50 000 m	Establishment of the integrated LDN indicator

*Figure 2: General workflow of the study*

### 2.3. Theoretical framework

The logic behind this approach was built on:

- 1- Setting up the LDN framework in analogy to the recommendations of Orr et al. (2017)**
  - a- The LDN vision:** Testing the concept's ability to restore degraded lands, and to investigate its efficiency for coping with natural hazards.
  - b- The baseline reference:** Set as the year 1992 given the availability of remote sensing data, and for covering a sufficient study period of 26 years (1992-2018).
  - c- Implementing the LDN mechanism:** Through a land-use plan based on a hazard informative/LDN response strategy orientation. This approach was adopted given the importance of land use planning for achieving LDN (Briassoulis, 2019), and for coping with natural hazards (Der Sarkissian et al., 2019).
- 2- Accurately representing land degradation for effectively orienting the LDN strategy.** According to Yengoh et al. (2016), four essential factors are needed to fulfill this purpose:
  - a- Type of degradation:** In this study, two types of degradation were studied; these are land use-cover change induced, and natural hazards induced land degradation.
  - b- Degree of degradation:** Determined by classifying lands into different states, based on the adequacy of their overlying cover with respect to their intrinsic capabilities.
  - c- Extent of degradation:** Revealed through graphical representations, since these are considered as the most comprehensible and representative tools for orienting land planning-restoration efforts.
  - d- Cause of degradation:** Addressed by attributing land degradation to several drivers, and through the integration of Mediterranean representative indicators (a tailored site specific approach)
- 3- Taking into consideration land potential and suitability:** given their importance for defining land degradation, and orienting intervention/restoration decisions (Cowie et al., 2018).

### 2.4. Establishment of the three global LDN indicators

#### 2.4.1. Land cover changes

Land cover maps were obtained by on-screen digitizing of the multispectral satellite imageries presented in Table 1. Complementary field validations were performed to verify findings. Accordingly, four different maps were established: land cover 1992, 2005, 2013 and 2018. These maps were classified according to the adapted CORINE classification as presented in Supplementary Information section A.

Since a baseline should be set for the application of the LDN mechanism, the year 1992 was set as the study's start line. The different land cover maps were then integrated into the "Intersect" tool of ArcGIS to determine changes of land cover classes for three time intervals: 1992-2005, 2005-2013, and 2013-2018. In order to track the transitions of the land cover classes between the baseline and the most recent land cover map, the Terrset Land Change Modeler (LCM) was used. The LCM model uses two maps with different acquisition dates to determine transitions in land cover categories through logistic regressions or multi-layer perceptron neural networks. LCM's "Contributions to net change" tool was used to determine the changes of each category at the expense of other classes for the 1992 and 2018 maps.

#### 2.4.2. Soil organic C changes

Soil organic C maps were obtained following the workflow presented in Al Sayah et al. (2019) using the equations below:

$$\text{Soil volume in one hectare (m}^3\text{)} = 10,000 \times \text{soil depth} \quad \text{Eq 1}$$

$$\text{Soil weight in one hectare (ton)} = \text{Soil volume} \times \text{Soil bulk density} \quad \text{Eq 2}$$

$$\text{Soil OC density (t/ha)} = \frac{\text{Soil weight} \times 100}{\text{soil OC content}} \quad \text{Eq 3}$$

$$\text{Soil OC stock (tons)} = \text{Soil OC density} \times \text{Soil area (per soil type)} \quad \text{Eq 4}$$

Soil bulk densities were obtained using the SPAW Soil Water Characteristics software, which computes bulk densities based on Saxton and Rawls' (2006) equations. Losses of SOC per change of land cover classes were estimated by overlaying the land cover transition map with the established SOC maps using the “Intersect” tool of ArcGIS.

#### 2.4.3. Land productivity changes

Land productivity was inferred using NDVI trends as these are one of the most used Net Primary Productivity (NPP) proxies (Yengoh et al., 2016). NDVI was extracted from the LANDSAT imagery presented in Table 1 using Rouse et al. (1974) equation:

$$NDVI = \frac{(NIR - Red)}{(NIR + Red)} \quad \text{Eq 5}$$

The images were downloaded for the months of October as representative of the winter period (prior to rainfall), and July as representative of summer since the highest vegetation proliferation per year occurs then. Land productivity was first inferred using graphical representations of the minimal, maximal and mean NDVI values for each year. Then a numerical comparison of mean NDVI values was carried out using the t-test to determine mean changes. The limitations of this approach are discussed in sections 3.1 and 3.5. The respective bands for each image (refer to Table 1) were input into the “Raster Calculator” of ArcGIS for NDVI’s computation using equation 5. Despite the criticism regarding the role of NDVI as a proxy, it was the only solution available for this study due to the absence of the necessary parameters needed for other methods.

The three land based indicators are not enough for a holistic representation of land degradation and should be complemented by additional ones, particularly at the sub-national scale (Akhtar-Schuster et al., 2017). As the global LDN indicators do not account for the occurrence of natural hazards, a supplementary indicator  $\alpha$  was added.

#### 2.5. Indicator $\alpha$ : The LDN-natural hazards relationship

Several hazards, namely of environmental and geophysical types (UNDRRR and ISC, 2020), e.g. soil erosion, landslides, fires and others, are well-known land degradation driving forces. Despite this fact, emerging concepts such as LDN do not directly integrate this dimension. Often, natural hazards are entwined with land degradation where both processes converge to cause a vicious cycle (Figure 3). This research paper aims to shift the vicious cycle into a virtuous one through a hazard-informed LDN intervention

*Figure 3: The land degradation-natural hazard general relationship*

As reported by Abdallah (2019), wildfires and landslides are commonly occurring natural hazards in the Aley district. During the 2019 wildfires outbreak, the Mount Lebanon Governorate, to which the Aley district belongs, witnessed one of the worst episodes ever recorded in the country. Moreover, Mount Lebanon is one of the most earth movement prone regions of the country. Accordingly, both hazards were integrated into this study for the following reasons:

- They are well documented land degradation drivers: while both wildfires and landslides are natural phenomena in Mediterranean settings, the first is a major agent of land degradation (Esteves et al., 2012), while the second is an important degradation driving force (Olsson et al., 2019). When part of the original dynamics of the system, wildfires are responsible for shaping ecological processes, maintaining the dynamic balance of biodiversity and influencing the setting’s land use/cover (Bajocco et al., 2010). However, when wildfires become recurrent - as a result of natural or unnatural reasons - their effects on soils and lands become destructive. According to Ice et al. (2004), wildfires alter the physical, chemical, mineralogical and biological attributes of soils, leading to water repellency (hydrophobicity), destruction of soil organic matter and soil structure. Due to these changes, water infiltration is significantly affected and soils become exposed to increased runoff and subsequent erosion (Ice et al. 2004). The latter causes significant loss of biodiversity and influences the land’s productivity, hence causing land degradation (Al Sayah et al., 2019). Landslides on the other hand cause sharp declines of land fertility/stability, affect soil organic matter content and disrupt the soil’s continuity (Chalise et al., 2019). These effects make landslides both a cause and manifestation of land degradation (Olsson et al., 2019) even when they occur naturally.

- Both are considered as some of the most important disturbances in the Mediterranean region (Abdallah, 2005).

- Their integration offers insights towards hazard informed land degradation mapping, and subsequent hazard informed land-use planning (Der Sarkissian et al., 2019).

The integration of natural hazards complements the LDN framework, while an LDN mechanism-based land use plan can act as a natural hazard coping tool by promoting resilience. To determine the extent of natural hazards induced land degradation, wildfire and landslide potentiality maps were used. The wildfire potentiality hazard map was extracted from the National Council for Scientific Research, Remote Sensing Center’s (CNRS-RSC) wildfire database. Landslides potentiality hazard maps were also obtained from the CNRS-RSC’s database which was built using the Value Analytical Bi-Univariate (VABU) method.

Another important land degradation driving environmental natural hazard is desertification. The latter is considered as one of the most serious global climatic manifestations. In order to integrate this angle, the Bagnouls-Gausson aridity index was studied [refer to Gausson, (1963) for more details] as part of desertification processes. For this purpose, the umbro thermal diagrams, known also as the Bagnouls-Gausson diagrams were used. Precipitation and temperature data were obtained from the Bayssour weather station located in the study area. At this point, it is important to explain that aridity and subsequent desertification assessments in Lebanon are severely handicapped by the country’s discontinuous and non-homogeneous weather record due to a 30-year war gap (Farjalla et al., 2014). As a result, climatic records of the country fall well under the continuous 30-year threshold set by the World’s Meteorological Organization. Even after the war period, much of the country’s weather station network is still disrupted and often networks do not exist. Even within single weather stations gaps and errors are observed. Only one weather station data was available with a record of 10 years (2001-2011). This certainly can be considered as a limitation of this study. While several datasets can be used for this purpose, the small spatial extent of the study area prevent their use for resolution purposes. Such a shortcoming should be considered in the case of assessments in similar regions and accounted for where possible (i.e. in contexts with better data or larger study areas).

#### 2.6. Land capability classification as an indicator of land cover suitability

Land Capability Classification (LCC), was performed following an adapted classification of the United States Department of Agriculture’s USDA (1961) version. The USDA (1961) classifies lands into eight categories coded by roman numerals (I to VIII). The first four classes present the agriculturally suitable lands, while the remainders present the non-cultivable areas. For this study, the USDA’s classification was adapted following the criteria set by Darwish et al. (2005) integrating soil depth, texture, stoniness, organic matter, drainage, slopes, pH and erosion risks as presented in Table 2.

Main factors and weight	Sub-factors and weight	Land Capability Class				
		I	II	III	IV	V
Soil type (0.3)	Texture (0.4)	Medium-fine	Sandy	Fine	Very fine	Very fine
	Soil depth, cm (0.4)	>100	50 – 100	25 – 50	25-10	< 10
	Stoniness % (0.2)	<5	5 – 20	20 -50	50 - 80	> 80
Level of nutrients (0.2)	pH (0.6)	5.5 – 6.5	6.5 – 7.0	7 – 7.5	7.5 – 8.5	> 8.5
	O.M. % (0.4)	> 3	3 - 2	2 – 1	< 1	< 1
Slope Gradient % (0.2)		< 5	5 – 8	8 –15	15 - 40	> 40
Erosion risk (0.2)		Very low	Low	Medium	High	Very high
Drainage conditions (0.1)		Perfect	Good	Restricted	Imperfect	Bad
Score		1.0-0.8	0.8-0.6	0.6-0.4	0.4-0.2	< 0.2

Table 2: The study adapted USDA (1961) land capability classification

The adapted classification scheme encompasses five classes based on five factors and sub-factors. Classes I to IV represent the USDA’s arable lands (best suited for cultivation in descending order of potential), class IV lands require extensive management to become suitable, while the additional class V groups the USDA’s classes V to VIII that are unsuitable for agriculture. Factors and sub-factors were assigned weights based on occurrence in previous studies and local study area knowledge.

The land cover 2018 map was intersected with the LCC map to determine the current cover’s suitability based on land potential. LCC is one of the most efficient tools for evaluating land suitability since it provides an understanding of the natural capacity/limit of lands, and relates it to the lands’ intrinsic abilities to support specific land covers or uses (Bandyopadhyay et al., 2009).

Suitable cover areas were defined according to:

- The occurrence of forests over all land capability classes. The presence of forests over any type of land is important for supporting biodiversity, enhancing land productivity, and replenishing SOC levels.
- The occurrence of grass, scrub/scrublands with bigger dispersed trees, unproductive, urban/urban activity categories over classes IV and V. The presence of these categories above weakly or non-productive lands is adequate with respect to the land’s capability. This occurrence also removes some stress on optimal land classes (I, II and III).
- The occurrence of agricultural categories over classes I, II and III. This distribution presents an adequate use with respect to the land’s capacity.

Unsuitable cover areas were defined according to:

- The occurrence of grass, scrub/scrublands with bigger dispersed trees, unproductive, urban/urban activity categories over land capability classes I, II, and III. This distribution was deemed unsuitable since it reflects land that are being lightly used.
- The occurrence of agricultural categories over classes IV and V. This distribution is considered as unsuitable since classes IV and V are not adequate for plantation activities.

## 2.7. Combining land cover suitability and land cover transitions to infer land degradation

Land cover suitability, based on land cover transitions (1992-2018) over lands of different capabilities was used for inferring the state of lands, and hence degradation. This was performed since land cover suitability reveals the cover’s sustainability and vulnerability to land degradation (Sonter et al., 2017). As accurate and reliable information on the state of lands are integral for an LDN approach and for allocating funds and restoration policies, an in-depth categorization of lands into the following 12 classes is presented: adequately used, recovered, improving, lightly used, overused, stable, at risk of degradation and degraded. Within the stable classes further sub-categories were also defined, these are stable/adequately used, stable/lightly used and stable/improving. Similarly, within the “at risk of degradation class”, a sub-category at risk of degradation/ lightly used was also added. The logic behind this classification was to provide an accurate distinction between degraded, non-degraded, degrading, or lands at risk of degradation for clearly defining land degradation and orienting the LDN intervention.

The lightly used, overused, at risk of degradation, and stable classes were defined since land degradation is almost indiscernible at its beginning, and only becomes noticeable when it has reached advanced stages. At this point, avoiding land degradation is no longer possible, and the need for restoration efforts becomes much greater than what was needed to avoid degradation in the first place. Accordingly, these classes were defined to provide an early detection of land degradation.

The classes adequately used, recovered and improving, correspond to the non-degraded classes; while the degraded class presents lands that are already degraded.

The criteria for classifying lands into their defined categories is presented based on their transitions from the 1992 to the 2018 cover on different land capability classes using the following form: *1992 cover* → *2018 cover (land capability class)* in the Supplementary Information section B. It is important to mention that class IV was considered as a hybrid class since it is the least optimal class for plantation. Therefore, the occurrence of agriculture, urban areas or natural spaces above this class is considered adequate.

## 2.8. Tailoring the LDN intervention through LDN based-hazard informative land use planning

The proposed LDN intervention was based on a land potential and hazard informative land use planning. Based on LDN’s response strategy (avoid, reduce and reverse), the proposed plan aimed to:

- Ensure the use of lands within their capabilities, rather than being used in manners that do not match their potential [i.e. light use or overuse]
- Minimize the vulnerability to the studied natural hazards by allocating lands to their optimal use. This was done by taking into consideration the occurrence of land cover classes in zones of different potentialities and planning their development accordingly.

The approach was focused on the stable/lightly used, at risk of degradation, at risk of degradation/lightly used, lightly used and overused classes since they represent lands that are not irreversibly degraded. Despite the inevitable need for their continuous use, these lands can be exploited without causing additional degradation. A general description of the plan consists of shifting optimal lands (classes I, II and III) to terraced agricultural covers in areas of low wildfire and high landslide risks, classes IV and V to agroforestry, and forestry where wildfire risks are low and landslides risks are high. In areas of low wildfires and landslides risk classes I, II and III were proposed for shifts towards agriculture, while several land use propositions were suggested for areas of high wildfires and landslides risks.

## 3. Results and discussions

### 3.1. The three global LDN indicators

**Land cover changes:** A total of 42 land cover classes were found in the study area. Changes were tracked during three intervals: 1992-2005, 2005-2013 and 2013-2018 (Figure 4).

*Figure 4: Graphical representation of land use and land cover changes in the Aley district 1992-2018*

As can be seen from Figure 4, considerable changes have occurred in the Aley district particularly within the urban categories during the 1992-2005 period. Accordingly, medium density urban fabrics increased by 8.3 km<sup>2</sup> during the 1992-2005 interval. Low density urban fabrics decreased by 3 km<sup>2</sup> during the 1992-2005 period. However, this decrease doesn't reflect a halt of urban expansion, but on the contrary, is due to the conversion of low density urban fabrics to medium density fabrics. Within the 2005-2013 interval, a 3.8 km<sup>2</sup> increase of low density urban fabrics was observed as a result of the continuous urban expansion in the district. Mineral extraction sites have also developed during the 2005-2013 interval, with an increase of 1.2 km<sup>2</sup>. Urban extensions followed the same trend with steady increases during the whole studied period. Naturally, this urban development occurred at the expense of other land covers. Some of the most considerable changes are observed within the dense mixed wooded lands and dense pine forests. Dense mixed wooded lands declined during the 2005-2013 and 2013-2018 periods by 1.9 km<sup>2</sup> and 2 km<sup>2</sup>, respectively, while dense pine forests decreased by 0.9 km<sup>2</sup>, 3.3 km<sup>2</sup> and 0.1 km<sup>2</sup> through the three studied time intervals.

For better insights, the land cover 2018 layer was compared with the baseline 1992 map using the LCM transition model's "contributions to net change". The chosen classes for transition studies were low, and medium density urban fabrics, dense urban fabrics, urban extension/construction sites, industrial/commercial areas, mineral extraction sites and burnt wooded lands. These classes were chosen since urban expansion and wildfires are the main drivers of land degradation in the study area, and for observing at the expense of what other classes they developed. Graphical results are presented the Supplementary Information section C.

In numerical terms, during 26 years 3% of the medium density urban fabrics' area developed into dense urban fabrics. Around 7 km<sup>2</sup> of the low density urban fabrics developed into medium density urban fabrics (44% of the contribution change is attributed to the densification of low density urban fabrics). Almost 66% of the dense urban fabrics' changes occurred through shifts from low and medium density urban fabrics to dense ones. Based on the above mentioned transitions, urban expansion in the study area can be attributed to the densification of urban fabrics. 18% of the medium density urban fabrics' development happened at the expense of scrublands, while 12% developed at the expense of dense pine forests, and 9% at the expense of clear mixed wooded lands. Nearly 7% of the dense urban fabrics' development is also due to scrubland regression. The development of urban extension/construction areas occurred at the expense of dense oak forests (26.5% of the change), dense pine forests (24.8%), dense mixed wooded lands (18%) and clear pine forests (11.8%). Most of the urban extension/construction areas developed into low and medium density urban fabrics, industrial/commercial areas, and diverse equipment. Mineral extraction sites have increased at the expense of bare rocks (46% contribution to change), and clear oak forests (17%). Most of the burnt wooded lands correspond to areas of clear and dense mixed wooded lands loss (an area of 44 hectares). The extent of burnt wooded lands reveals the study area's vulnerability to wildfires.

By computing the urban to rural areas ratio for each of the studied years, the ratio changed as follows: 0.21 in 1992, 0.27 in 2005, 0.39 in 2013 and 0.44 in 2018. The increase of the urban/rural ratio means that urban areas are continuously growing.

**SOC changes:** Following equations 1 to 4, the SOC map of the Aley district was established. According to Patrick et al. (2013), SOC values greater than 2% are considered as an indicator of healthy soils that are suitable for plant development. Most of the study area (58.47%) has SOC values greater than 2%. Nonetheless a significant fraction (41.53% of the district) corresponds to the less than 2% SOC stock areas. In order to reveal areas of SOC changes, an intersection of the SOC and the land cover transition map (1992-2018) was performed, and areas of carbon losses were revealed (Figure 5).

*Figure 5: Soil organic C stocks of the Aley district and losses per land use/cover change (1992-2018).*

As can be seen, most SOC loss areas correspond to areas of green cover loss. These are particularly amplified in the case of the olive trees and the dense mixed wooded lands.

**Land productivity changes:** Land productivity changes were inferred from NDVI trends for the studied period (Figure 6).

*Figure 6: a) NDVI trends in the Aley district during the winter period 1992-2018, b) NDVI trends in the Aley district during the summer period 1992-2018*

Figure 6a shows slight increases of minimal and maximal NDVI values during the winter period, in contrast to decreases of mean NDVI values. Overall, during the winter period a decrease of NDVI mean values signifies decreasing land productivity. However, during the summer period (Figure 6b), a contrasting trend is observed. Minimal NDVI values have decreased, while maximal NDVI and mean NDVI values slightly increased, thus implying increased land productivity through the studied period.

In quantitative terms the t-test was used for mean comparison. The mean and standard deviations of each NDVI map were extracted from each raster's property tab in ArcMap 10.3. The sample size was calculated based on the following logic: since LANDSAT images were used to extract NDVI maps, the cell size of each map is equal to the satellite's resolution, i.e. 30x30 m = 900 m<sup>2</sup>. This number was then converted to km<sup>2</sup> (0.0009 km<sup>2</sup>) to be divided by the district's area (i.e. 263 km<sup>2</sup>) for determining the total number of pixels in each NDVI raster. Results of the t-test show minor variations during the studied interval and particularly for the 1992-2018 period with a difference of 0.068 for winter and 0.114 for summer. Positive changes are observed during the 2013-2018 interval for both winter and summer (+0.424 and +0.314, respectively), thus indicating a minor increase of land productivity.

It is important to mention that results of land productivity changes oppose those of SOC and land cover changes. This may be due to the limitations of NDVI for land degradation assessments (Yengoh et al., 2016) and its sensitivity to underlying atmospheric processes (Xue and Su, 2017). The use of NDVI as land productivity proxy is very debatable; some studies favor its use while others do not recommend it. Nonetheless, the use of NDVI as a proxy of land productivity was the only means available for this study. Results of this indicator pose some short of limitation that needs to be considered.

### 3.2. Combining land cover and LCC maps: land cover suitability and land status classification

In order to reveal the type and extent of land cover change induced land degradation, the land cover 1992-2018 transition layer was intersected with the LCC map. The LCC map of the Aley district is presented in Figure 7.

*Figure 7: Land capability classification of the Aley district*

A large area of the Aley district is covered by arable lands (classes I to IV), meaning that the lands of the study area have considerable capabilities to support various activities. Nonetheless, the way these lands are exploited dictates whether they are adequately or non-adequately used. In order to determine the current cover's suitability, the land cover 2018 transition map was compared with the LCC map. Accordingly suitable areas were found to cover 51% of the study area while the remainder 49% corresponded to unsuitable areas. By studying the transition of land covers (1992-2018) above lands of different capabilities, and based on the definition of the adopted land state classification, figure 8 was obtained.

*Figure 8: Land degradation map of the Aley district*

The distribution of these classes reveals the heterogeneity of land states even within the same landscape. Based on the obtained results, a prioritized spot-on approach is made possible by focusing on the lands that should be targeted. The LDN mechanism approach targeted the stable/lightly used, at risk of degradation, at risk of degradation/lightly used, overused and lightly used categories as mentioned previously. By computing the sum of the chosen categories, a total of 87.51 km<sup>2</sup>, accounting for 33.3% of the study area was subjected to the LDN plan.

### 3.3. Indicator $\alpha$



Wildfire (Figure 9a) and landslide (Figure 9b) hazard potentiality maps were intersected with the 2018 land cover and LCC map.

*Figure 10: a) Wildfire hazard potentiality of the Aley district, b) Landslide hazard potentiality of the Aley district.*

### 3.3.1. Intersection of hazard potentiality layers with land cover 2018 maps

Fires are part of natural processes in Mediterranean ecosystems. Yet in the study area and in Lebanon as a whole, most of these fires are attributed to human related reasons: unintentional accidents, agricultural conversion, overgrazing, illegal timber/coal harvesting, land clearance for future building projects (Abdallah, 2019) and in many unfortunate cases are due to intentional arson. Whether of natural or man-induced causes, these fires severely affect both above ground biomass and the underlying lands/soils. According to Shakesby (2011), fires are capable of influencing soils by affecting their structure, properties, porosity and organic material. This however depends on the fire's severity, intensity and degree of burning (Bento-Gonçalves et al., 2012). Regardless of the fire's properties, soil erosion is one of the most serious problems that affects lands following a fire outbreak, it is also one the most studied post-fire effects (Depountis et al., 2020). The same Authors found a 36.2% increase in soil erosion rates after a fire event in Greece, and reported that accelerated post-fire soil erosion is common throughout various Mediterranean countries, namely Southern Europe. Given the fact that soil erosion is the most amplified biophysical form of land degradation (Dooley et al., 2015), wildfires can be considered as a land degradation driving force.

By intersecting the wildfire potentiality map with the 2018 land cover map, most of the urban categories (sprawls and fabrics) were found to be most affected by wildfires. The same is applicable for forests where most classes of different densities are affected, likewise for scrublands and grasslands. In term of agricultural areas field crops, fruit trees, vineyards and protected areas were found to be the most impacted classes. Abandoned agricultural lands also heavily affected. This underlines the fact that agrarian abandonment is an important cause of in fire spreads. For urban areas the findings are alarming since the land cover change indicator revealed that urban expansion is continuous within the study area. This means that urban expansion might progress further into different levels of wildfires risks, putting more people at risks at the wildland-urban interface (increased exposure), while increasing the hazard's potentiality.

The same land cover classes described above (in addition to bare rocks) were found to occur in different zones of landslide hazard potentiality. The occurrence of natural, unproductive and agricultural classes within landslide zones of different levels is a soil loss aggravating factor which in turn leads to land degradation. For agricultural classes particularly, this forms a direct threat to food security. Overall, the occurrence of urban and agricultural zones in the proximity, or within different potentialities of wildfire and landslides hazards, clearly underlines the absence of land use planning visions and regulations.

### 3.3.2. Intersection of hazard potentiality layers with the land capability map

Both wildfires and landslides hazard potentiality layers were intersected with the LCC maps to determine which land categories are subjected to the studied hazards (Tables 3 and 4).

*Table 3: Distribution of wildfire potentiality levels on the different land capability classes of the Aley district, classes I, II and III are referred to as prime lands.*

Wildfire potent.	Area on class I (km <sup>2</sup> ); % from class I	Area on class II (km <sup>2</sup> ); % from class II	Area on class III (km <sup>2</sup> ); % from class III	Area on class IV (km <sup>2</sup> ); % from class IV	Area on class V (km <sup>2</sup> ); % class V	Total area on all classes (km <sup>2</sup> )	% on prime lands
Very Low	3.73; 0.30%	2.9; 0.08%	3.8; 0.29%	3.7; 0.30%	6.7; 1.05%	21.02	50.0
Low	408.6; 32.35%	473.4; 12.24%	160.9; 12.40%	431.4; 34.14%	73.1; 11.46%	1547.5	67.4
Moderate	494.6; 39.17%	2613.4; 67.56%	577.4; 44.49%	607.2; 48.06%	182.9; 28.66%	4475.7	<b>82.3</b>
High	231.3; 18.31%	614.4; 15.88%	280.6; 21.62%	73; 5.78%	106.4; 16.69%	1305.9	<b>86.2</b>
Very High	124.6; 9.87%	163.9; 4.24%	275.2; 21.20%	148.1; 11.72%	269; 42.15%	980.9	<b>57.4</b>
Total	1263	3868.2	1298	1263.6	638.2	8331.7	

*Table 4: Distribution of landslides potentiality levels per land capability classes of the Aley district, classes I, II and III are referred to as prime lands.*

Landslide potent.	Area on class I (km <sup>2</sup> ); % from class I	Area on class II (km <sup>2</sup> ); % from class II	Area on class III (km <sup>2</sup> ); % from class III	Area on class IV (km <sup>2</sup> ); % from class IV	Area on class V (km <sup>2</sup> ); % from class V	Total area on all classes (km <sup>2</sup> )	% on prime lands
Very Low	0; 0%	0.01; 0%	0.03; 0%	0.01; 0%	0.09; 0%	0.1	28.57
Low	24.7; 0.14%	35.3; 0.07%	59; 0.23%	17.3; 0.01%	64.7; 0.40%	201.2	59.22
Moderate	157.1; 0.89%	598.2; 1.15%	187.8; 0.74%	76.1; 0.04%	884.8; 5.49%	1904.1	<b>49.53</b>
High	6449.3; 36.67%	24386; 46.95%	20940; 82.09%	7950; 3.76%	14110.9; 87.60%	73836.3	<b>70.12</b>
Very High	10955; 62.29%	26916; 51.83%	4323.2; 16.95%	203333; 96.19%	1048.4; 6.51%	246575	<b>17.11</b>
Total	17586.2	51935.6	25510.1	211376.4	16109	322517	

From tables 3 and 4, one can notice that both hazards severely affect prime lands since moderate, high and very high hazard potentialities are most commonly found on them. Accordingly, natural hazards in Aley can be considered as direct threats to the productive capacity of the district's lands. Further, the frequent occurrence of these hazards makes land degradation no longer a slow process, but rapidly amplifies its rates.

### 3.3.3. Insights on aridity

Throughout the studied period, the BGI diagrams (Supplementary Information section D) showed aridity during the typical Lebanese/Mediterranean dry season (post-March). However, within this interval, the extent and duration of arid periods have fluctuated. From 2001 to 2003, the length of the arid period varied between three to four months. In 2004, the arid period began almost in mid to last April and ended in mid-November. This implies an arid period with almost double the length than those of the previous years (nearly seven months). The years extending between 2005 and 2009 were characterized by arid periods somewhat similar to those of the years 2001-2003, with either earlier or later start/end dates. In 2010, arid periods became once again longer and persisted for seven months (March–September) with an additional extension towards November, thus stretching the arid period to around eight months. In the year 2011, the trend was somewhat similar to previous years. In addition to the changes of arid period lengths, the start date of these events was found to be highly fluctuating with years starting as early as March and April. While changes of arid periods do not reflect drought trends (Salvati et al., 2013), they indicate to a certain extent environmental dryness and long-term water stress (Mishra and Singh, 2010). Accordingly, the progression of aridity will shift the area towards desertification and amplify land degradation. While this hazard is a slow-onset event, its impacts are not to be undermined as these are directly related to climate change.

### 3.4. The LDN intervention: A combined approach

The aim of the proposed LDN plan was to restore the targeted lands mentioned in section 3.2, and to turn Figure 3's cycle from vicious to virtuous. The LDN intervention was based on: (i) the concept's Avoid, Reduce and Reverse response strategy; (ii) the allocation of suitable covers with respect to the land's capability while taking into consideration the effect of the hazards' potentiality levels; and (iii) the trade-off between wildfire and landslide hazards. Accordingly, the proposed plan per LDN response, land state class and hazard potentiality level is as follows (refer to Supplementary Information section E for detailed tables):

**a) LDN response - Avoid:**

- Lands at risk of degradation on classes I, II and III, and located on all levels of wildfire and landslide potentialities (very low to very high).

These correspond to natural areas that became urban extension/sprawl zones above prime lands. Urban sprawls are considered as ignition promoting factors (Price and Bradstock, 2014). In Aley, most of the urban sprawls are located in high wildfire potentiality zones. In order to avoid further degradation and to reduce the exposure of humans and assets at the wildland-urban interface to fires and landslides, the lateral expansion of buildings should be halted. Instead, buildings should develop vertically (more stories) for housing more people, while reducing their expansion over potent lands. The remaining uncovered land areas should be planted for three reasons: (1) for taking advantage of the substrate's potential, (2) for promoting agricultural use in the wildland-urban interface to form protective agricultural belts, and (3) for stabilizing lands through plant root and cover effects. In order to prevent fire spread, these vegetated lands should be regularly thinned out, maintained, irrigated and surrounded by hill lakes or ponds. In areas of high and very high landslides potentiality zones, it is recommended that agriculture practices involve terracing, ditching and building palisades to mitigate the risk of landslides while cutting the continuity of any potential fire belt. The retention ponds or hill lakes can serve as a mitigation/preparedness tool for both landslide and wildfire hazards since they can divert excess runoff, traped material and serve for fire extinction.

- Stable/lightly used lands on classes I, II and III, and located on all levels of wildfire and landslide potentialities (very low to very high).

These areas correspond to grasslands, rock outcrops and scrublands that persisted from 1992 to 2018. Given their presence on prime lands, these areas should be converted to agricultural uses. That way, the use of these lands will provide short term economic revenues while promoting long term sustainability. In zones of high and very high wildfires potentialities, planted species crop growth curves should be studied for harvest before the dry season. Planted agricultural spaces should also be surrounded by hillakes. The latters could be used for irrigation as well as wildfire preparedness measures. In zones of high and very high landslides potentialities planted agricultural spaces should be arranged into terraces. That way, soil/land loss is reduced while land use with respect to the land's potential is optimized.

**b) LDN response - Reduce:**

- Overused lands on classes IV and V, located on the very low to moderate wildfire potentialities, and all levels of landslide potentiality.

These areas correspond to agricultural classes above non-cultivable soils. To make use of the lands' potential, these classes should be converted to forests, since they are located in low to moderate wildfire risk zones. That way, SOC stocks are replenished, biodiversity is supported and all landslide potentiality levels are buffered. Agro-forestry is also proposed on class IV settings for fully exploiting the potential of these lands. In areas of high and very high wildfire potentialities, native/less fire-prone tree species should be chosen. These forests should then be regularly managed, their understories should be regularly cleaned, while their biomass and soil moisture contents should be closely monitored. Moisture monitoring is important for preventing fire outbreaks by reducing the exposure of dry substrates and covers.

**c) LDN response - Reverse:**

- Lands at risk of degradation/lightly used on classes I, II and III and located on all levels of wildfire and landslide potentialities.

This category consists of abandoned agricultural lands. According to Gibbs and Salmon (2015), these lands are signs of land degradation, a form of land potential loss, and are capable of fueling forest fires. For this reason, these should be converted to active agricultural use.

i. In areas of very low to moderate wildfire and landslide potentialities:

Since most of the district's agriculture corresponds to irrigated crops or plantations, these abandoned lands become much less fire-prone due to regular watering. That way, wildfire risks are reduced while lands become optimally exploited. In areas where the risk of landslides is relatively low, mechanical or structural measures are not necessary.

ii. In areas of high to very high wildfire and landslide potentialities:

Crop growth seasonal calendars should be set to harvest the planted species before the dry season (early harvest species) while agricultural activity should be done in terraced settings. Retention ponds are also recommended for addressing both hazards.

- Lightly used lands on classes IV and V and located on all levels of wildfire and landslide potentialities.

These zones consist of forests, agricultural areas and scrublands, which transformed into grass, scrubs, and rock outcrops, respectively on class IV. For class V lands, these consist of forests that transformed into grass or scrublands.

i. In areas of wildfire potentialities:

In very low to moderate potentiality areas, these zones are proposed to be shifted to grasslands and/or forests. That way SOC stocks are replenished and biodiversity is enhanced away from wildfire risks. On the other hand, in high to high to very high pontetiality levels, grasslands are proposed instead of forests. Organized periodic grazing is recommended so biomass is reduced, hence minimizing the presence of flammable material and subsequently wildfire risks.

iii. On all landslide potentiality levels:

These zones are proposed to be shifted into grasslands and/or forests. That way SOC stocks are replenished and biodiversity is enhanced. Further, the presence of natural cover in the different landslide potentiality zones is bound to reduce risks by enhancing the structural stability of soils. Ecotourism and recreational activities are recommended in low to moderate landslide classes.

**d) LDN response - Avoid /Reverse:**

- Lightly used lands on classes I, II and III, and located on all levels of wildfire and landslide potentialities.

These areas correspond to lands that are used in manners that do not match their capability, i.e. less than their capabilities (refer to Supplementary Information section B for further details).

In areas of very low to moderate wildfire and landslide potentialities, agricultural use should be promoted. That way, land potential is taken into consideration in zones where risks are relatively low. In areas of high to very high potentialities of both hazards, agricultural practices should focus on irrigated and terraced plantations while taking into consideration early harvest periods. Water drainage schemes should also be envisaged to avoid water entrained/induced earth movement.

- Overused lands on classes IV and V, and located on the high and very high wildfire potentialities

These areas correspond to agricultural classes above non-cultivable soils. Since these zones are in high and very high wildfire risks, afforestation is not recommended. These areas should be focused towards recreational activities, ecotourism or mineral extraction sites.

By optimizing the cover of the targeted lands, i.e. 33.3% of the study area (refer to Figure 8), the percentage of adequately used lands shifted from 8.05% to almost 41.4%. As the proposed intervention simultaneously takes into consideration the land's suitability and hazard potentiality levels, the new cover can be considered as more or less optimal. The presented approach reveals the efficiency of LDN as both a land degradation and natural hazard mitigating tool. On this basis, LDN can be considered as a powerful tool for safeguarding land resources in Mediterranean and different contexts.



### 3.5. Strengths and weaknesses of the study

#### *i. Limitations of the approach*

While the presented approach can be considered as a contribution to land degradation mapping and to the LDN-DRR nexus, several elements must be highlighted:

Concerning the global LDN indicators, land productivity changes were assessed using NDVI trends. While this method is criticized in literature, it was the only means available for the study. Had the study area been larger platforms or datasets such as Trends.Earth would have been used. Nonetheless the spatial extent of the study area doesn't allow the use of global datasets. Accordingly, the study's trends of land productivity are not to be considered as representative.

Concerning the methodology, the inclusion of socioeconomic indicators of land degradation wasn't accounted for in this study. Nonetheless these indicators are necessary for holistic representations of land degradation. In contexts where such data is available, their inclusion is highly recommended. This is important as land degradation asymmetrically influences people according to their socioeconomic levels and hence vulnerability.

While this study proposed many land cover shifts, it did not consider public acceptance, legislative frameworks or the feasibility of these transitions. Stakeholder participation is also an additional factor to account for. The integration of stakeholder analysis, despite its complexity, is needed. The same applies for local indigenous knowledge and best practices.

Also, the proposed changes will require a considerable amount of time to become "functional". This is further complicated by land tenureship issues and governance that characterize the situation in Lebanon.

The climate change angle is also an important dimension to consider. Nonetheless, the absence of robust climatic data, not only in the study area, but in Lebanon as a whole made the investigation of climate-induced land degradation beyond the scope of this study. The same can be said for the BGI diagrams that only reveal a portion (2001-2011) that is well under the threshold needed to depict accurate trends.

#### *ii. Beyond the study area: A replicable methodology*

Despite the above-mentioned shortcomings, the presented methodology can extend beyond the study area's limits due to:

- The novelty of the proposed land health status classification that helps overcoming the dichotomous and often unrepresentative classifications of lands into degraded or not. The proposed method allows to clearly draw the line and separates between non-degraded, degrading, at risk of degradation and degraded lands. The 12 proposed classes can provide insights for priority areas and can contribute to the accurate orientation of intervention decisions. These can be considered as a contribution to land degradation mapping hence addressing the complex "LD" part of LDN.
- Its interdisciplinary nature: The study can be considered as an effort for strengthening interdisciplinary research and solidifying the synergies between several international agendas namely the UNCCD's, the SDGs and the Sendai Framework.
- The presented methods are justifiable, Mediterranean tailored, and can be easily replicated using readily accessible and available data. Moreover, they can be complemented by additional factors such as data on biological or chemical land degradation.
- The nature of the environmental challenges considered in this study (i.e. land degradation, wildfires and landslides) currently reflect "hot topics" in Mediterranean settings. Despite their occurrence, these challenges are often studied using silo approaches. By tapping the LDN-DRR relationship, this study offers a starting point for investigating this link further, and for determining its connection with other environmental processes.

### 4. Conclusion

Given the complexity of land degradation and the different perspectives on the process, judgment calls are often made for prioritizing intervention areas. Nonetheless, these decisions should be justified in order to avoid any unwanted losses or efforts in vain. Under this context, this study proposed a framework for studying land degradation by combining land cover mapping and land capability classification. The latter was integrated since it relates several land related properties, topography, and soil erosion to reveal the natural limits and capacities of lands. By intersecting the land capability maps with the actual land cover map, the adequacy of the current cover was assessed. This evaluation is the first step of any LDN intervention. Then, by intersecting the land capability layer with the land cover transition map (transitions between the baseline year and the current cover), different classes of land health status were obtained. Accordingly, 12 different classes were defined, and their distribution was found to be as follows: 8.05% adequately used, 0.08% recovered, 0.01% improving, 9.11% lightly used, 2.04% overused, 65.06% stable (26.36% stable/adequately used, 20.18% stable/lightly used, and 0.37% stable/improving), 1.5% at risk of degradation (0.48% at risk of degradation/lightly used) and 13.67% degraded. This in-depth categorization provides a comprehensive mapping approach for pointing the LDN intervention at clear targets. While most of the study area corresponds to the stable class, a significant proportion of the other categories risks falling into the less healthy classes given the study area's land cover dynamics and absence of regulations. The progression of arid periods as revealed by the BGI diagram, although studied on a short period due to weather data station limitations, also indicates alarming trends and can be considered as a potential progression towards desertification. Accordingly an area of 87.51 km<sup>2</sup> (33.3% of the study area) consisting of the stable/lightly used, at risk of degradation, at risk of degradation/lightly used, overused and lightly used categories was targeted for the intervention.

The integration of wildfire and landslide hazards into the LDN framework widened the scope of land degradation mapping, and added a new dimension for LDN's operationalization. By combining all of the above listed elements, an LDN intervention strategy based on land potential knowledge and a hazard informative angle was proposed. Land use planning in the target area following LDN's response strategy, and taking into consideration the different levels of hazard potentialities and land capability classes was used for this purpose. This step served as a linker between sustainability, land resilience, vulnerability to natural hazards and LDN. Accordingly, the optimization of the targeted lands' cover shifted the distribution of adequately used lands from 8.05% to almost 41.4% of the study area. On this basis, LDN can be considered as a valuable tool for simultaneously safeguarding land resources and mitigating wildfires and landslides.

The presented approach can be further developed by integrating other factors such as climatic and socio-economic parameters as well as ecological processes. However, the methods offered in this study are replicable, justifiable methods and require relatively simple data. The proposed classification scheme and the integration of natural hazards can be applied and further developed in other Mediterranean settings for promoting the sustainable development of the Mediterranean region.

### Conflict of interest

The authors declare no conflict of interests.

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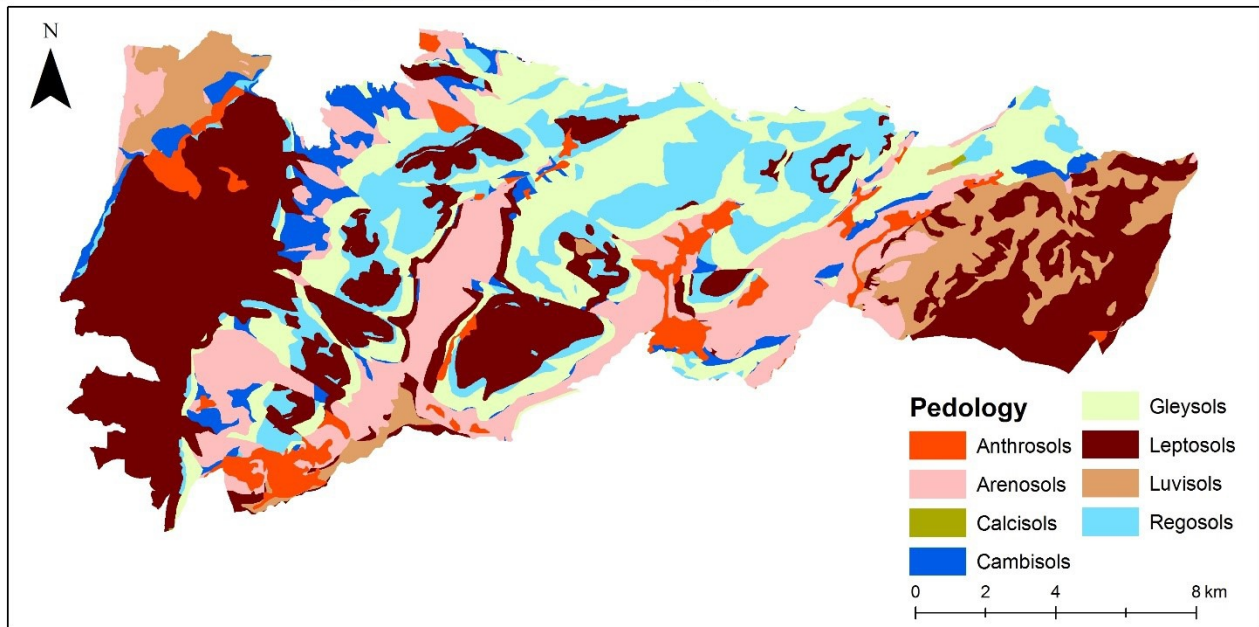
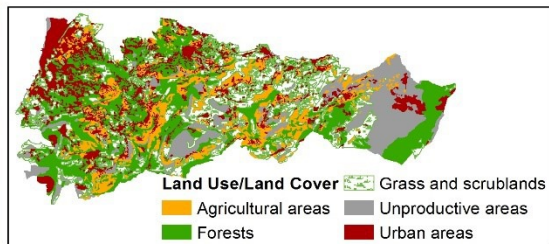
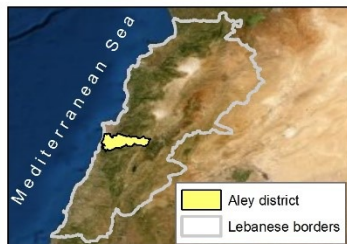
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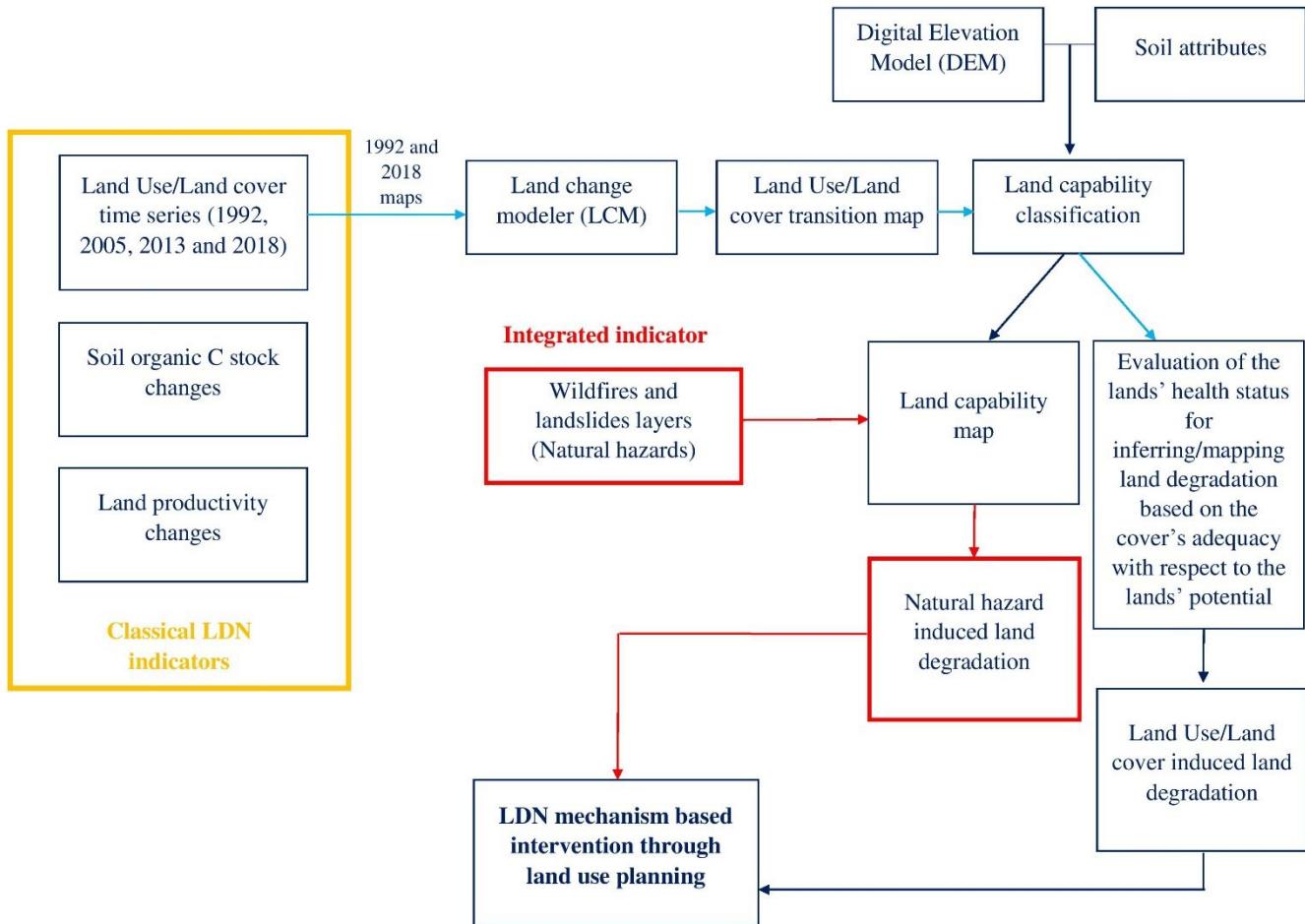
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**Sustainable Development  
and Resilience**

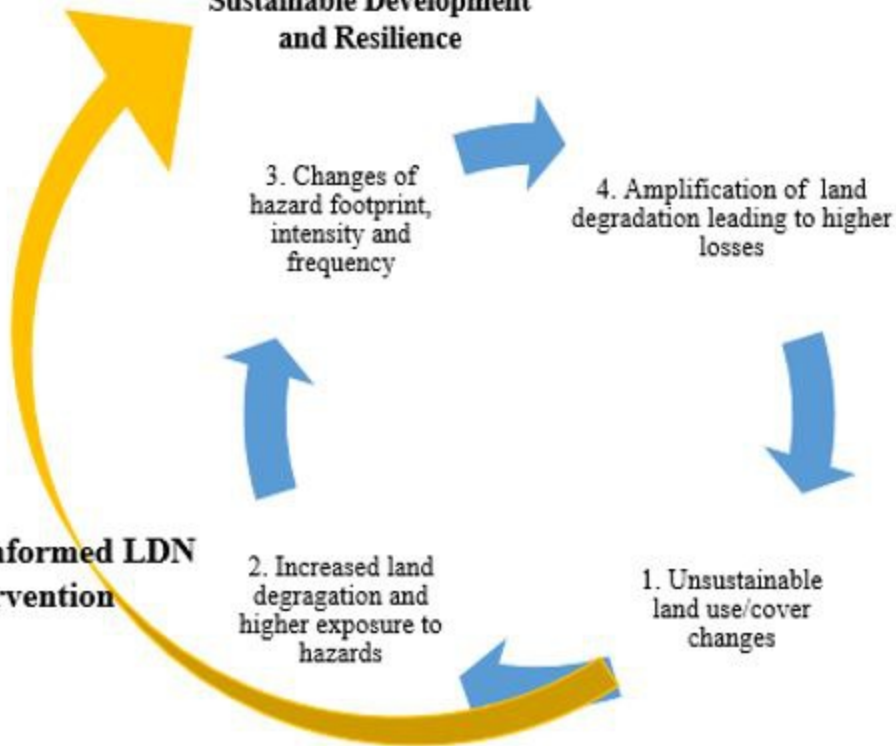
3. Changes of  
hazard footprint,  
intensity and  
frequency

4. Amplification of land  
degradation leading to higher  
losses

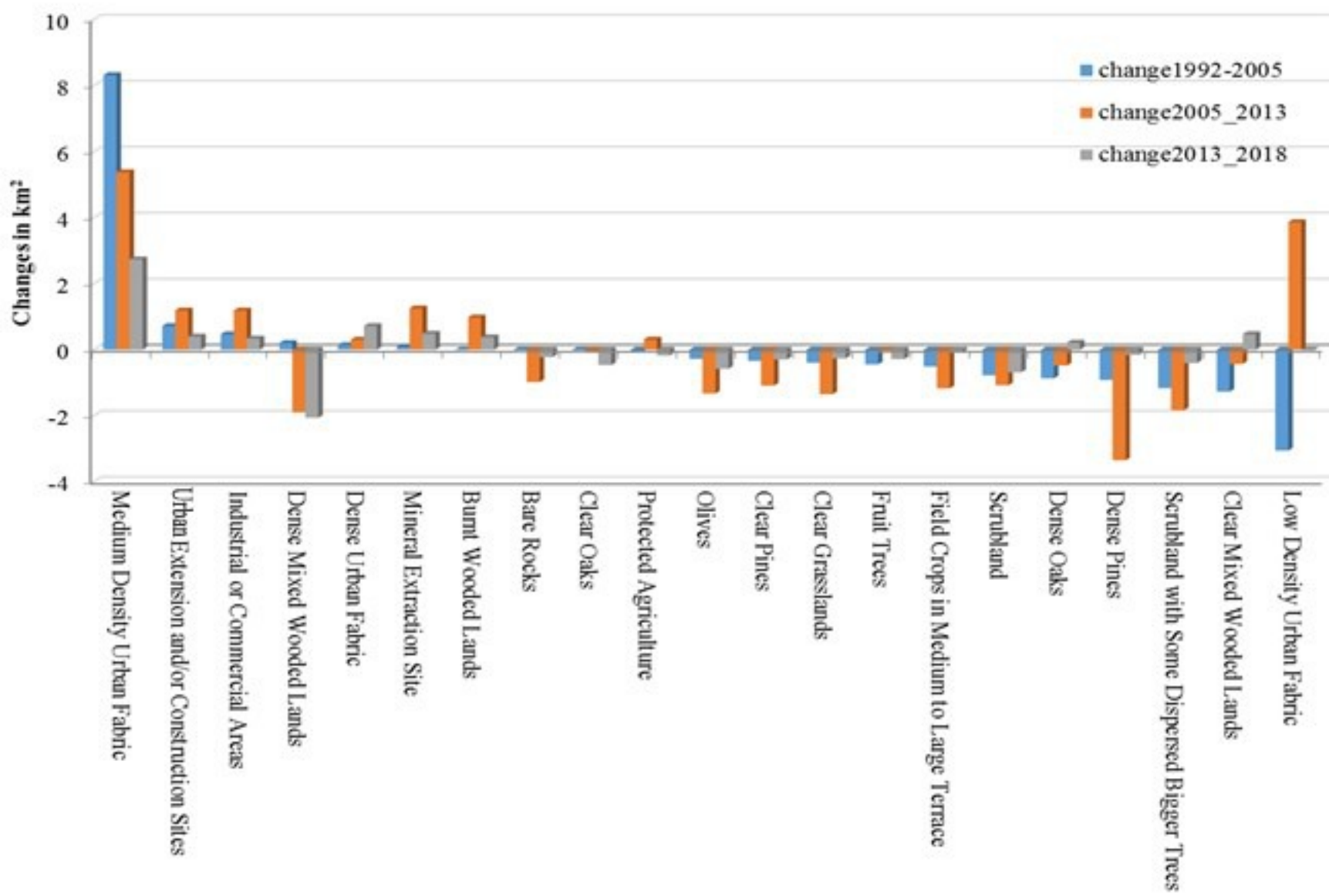
**Hazard-informed LDN  
intervention**

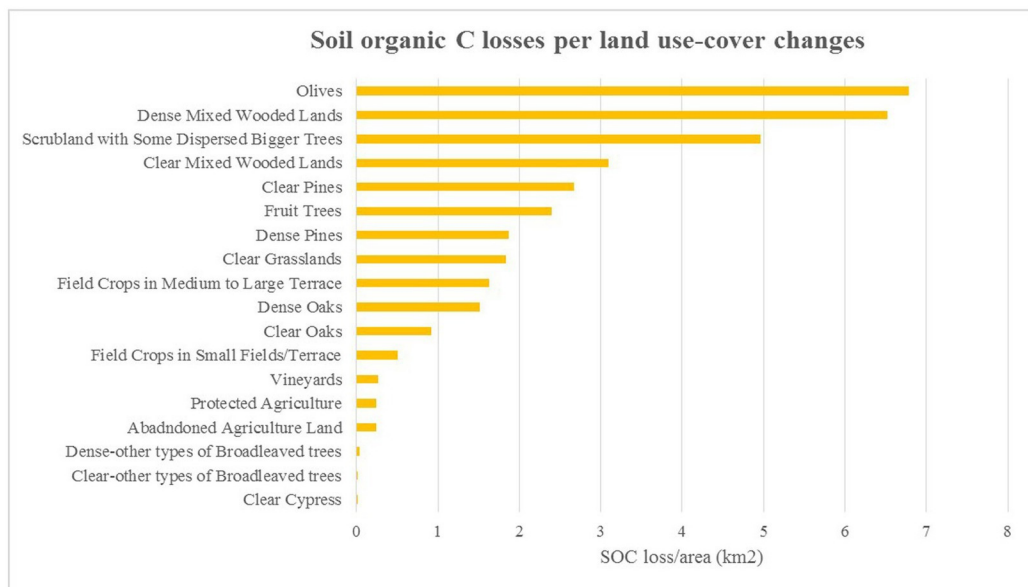
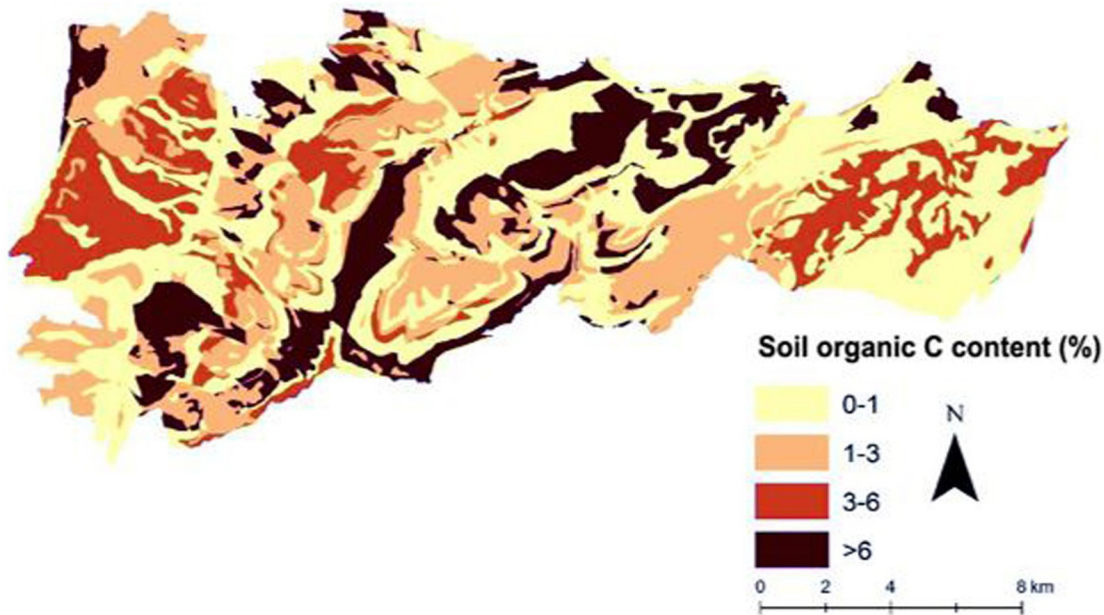
2. Increased land  
degradation and  
higher exposure to  
hazards

1. Unsustainable  
land use/cover  
changes



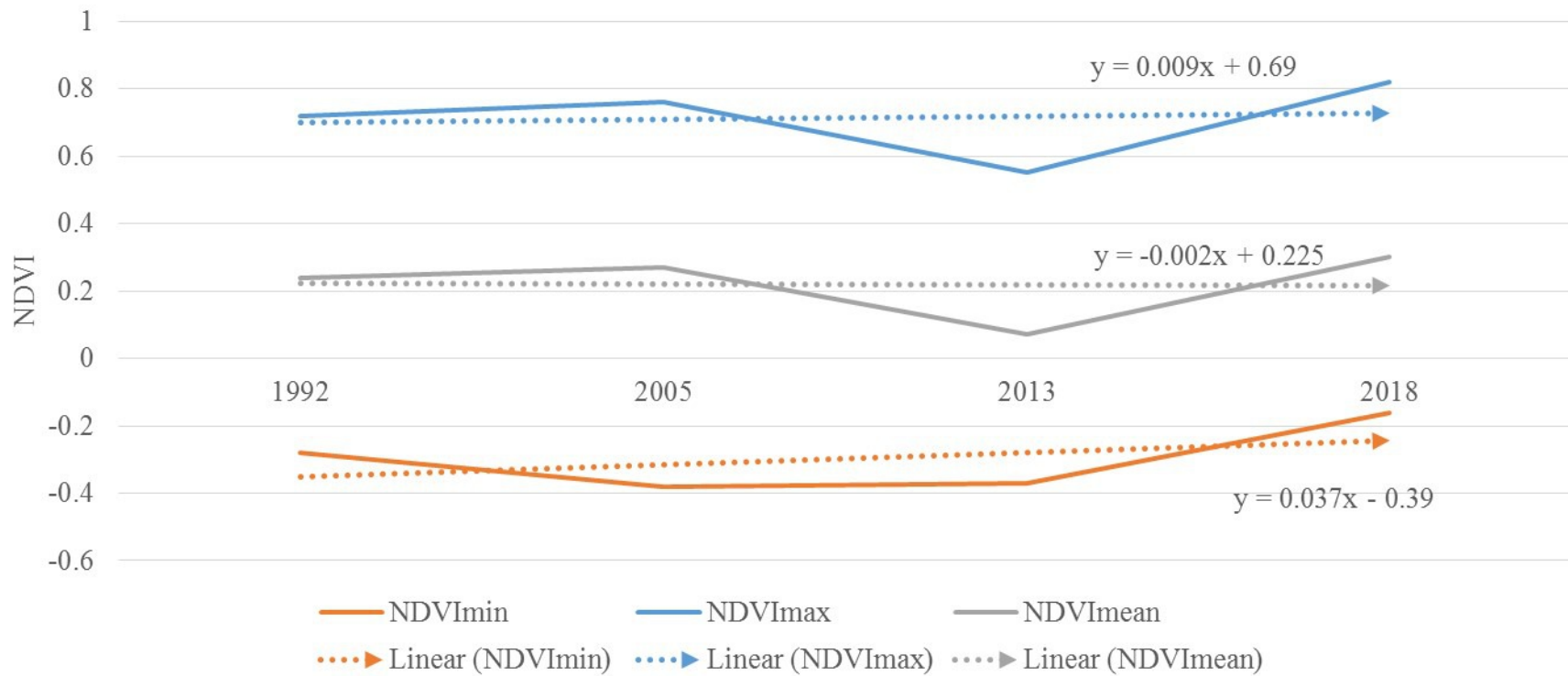
# Land use and land cover changes in the Aley district 1992-2018





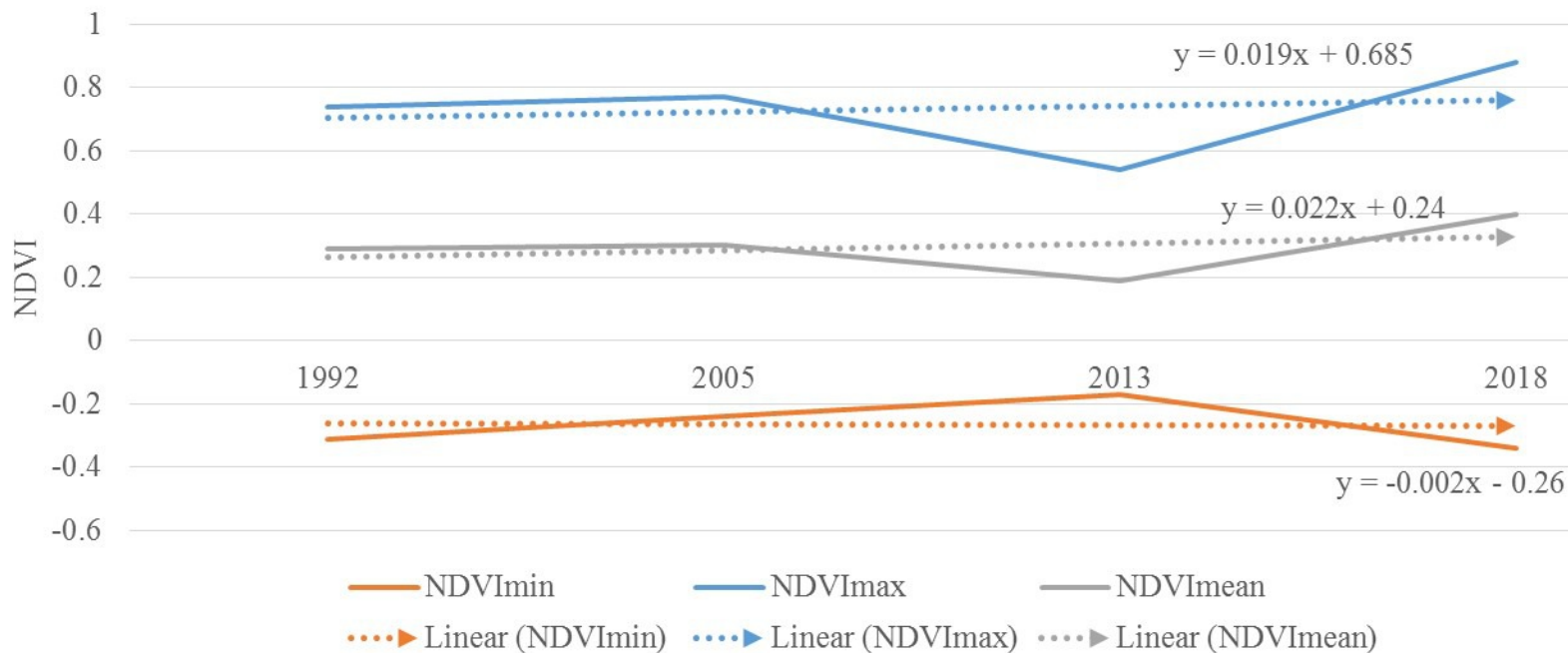
a)

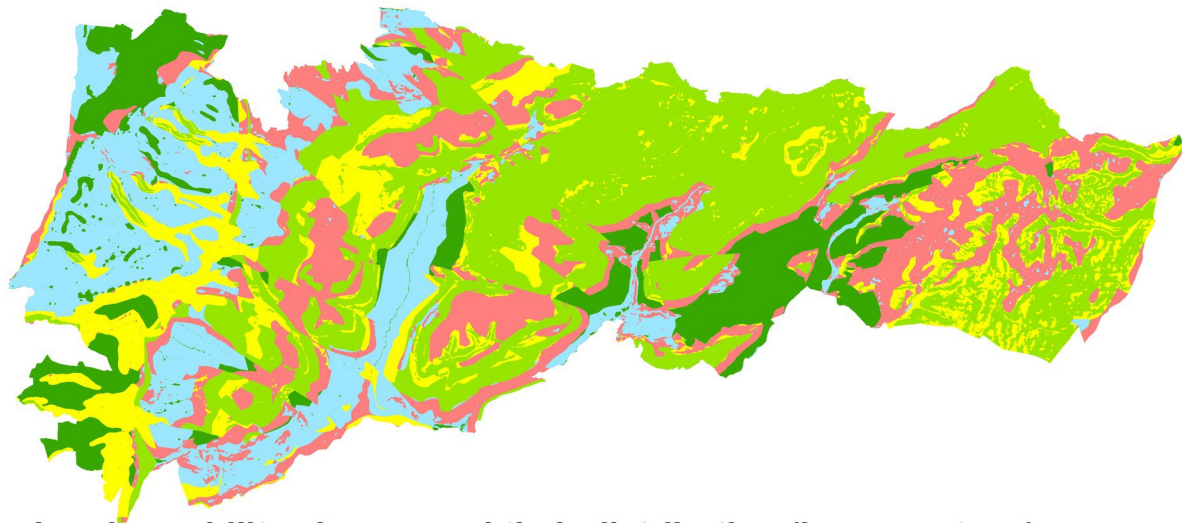
## NDVI winter



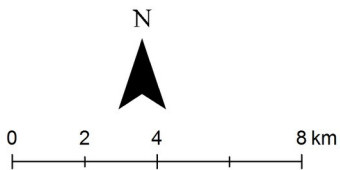
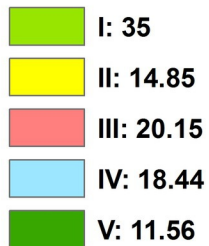
b)

## NDVI summer

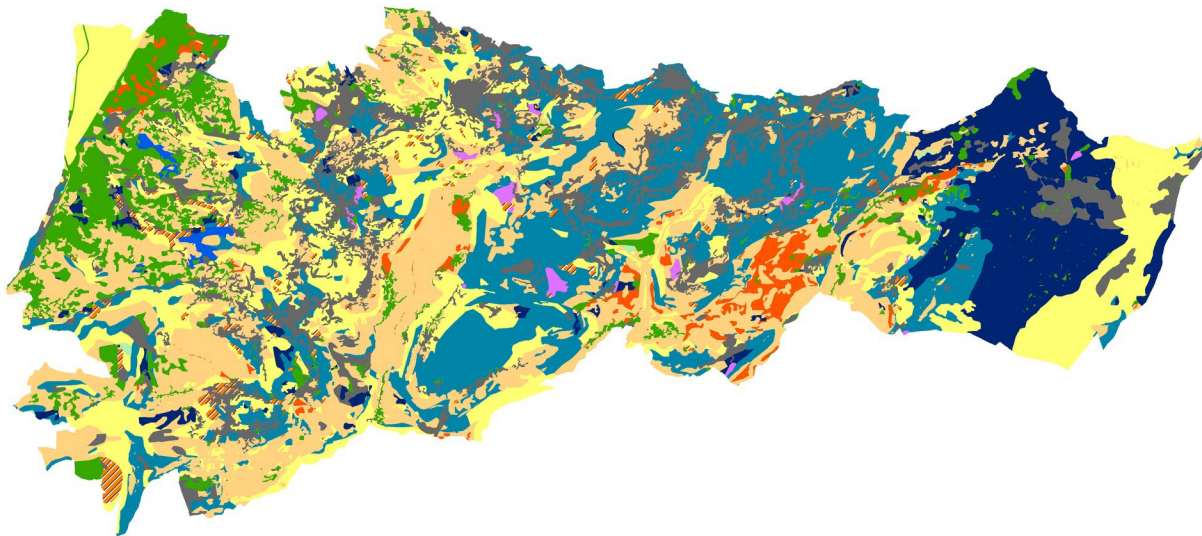




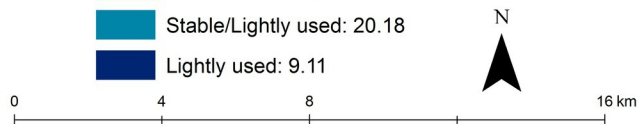
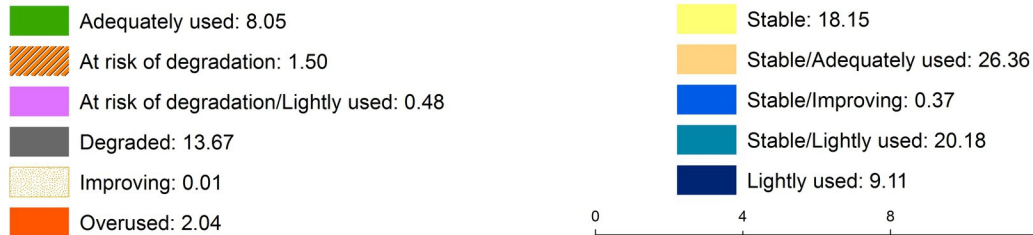
**Land capability classes and their distribution (in percentage)**



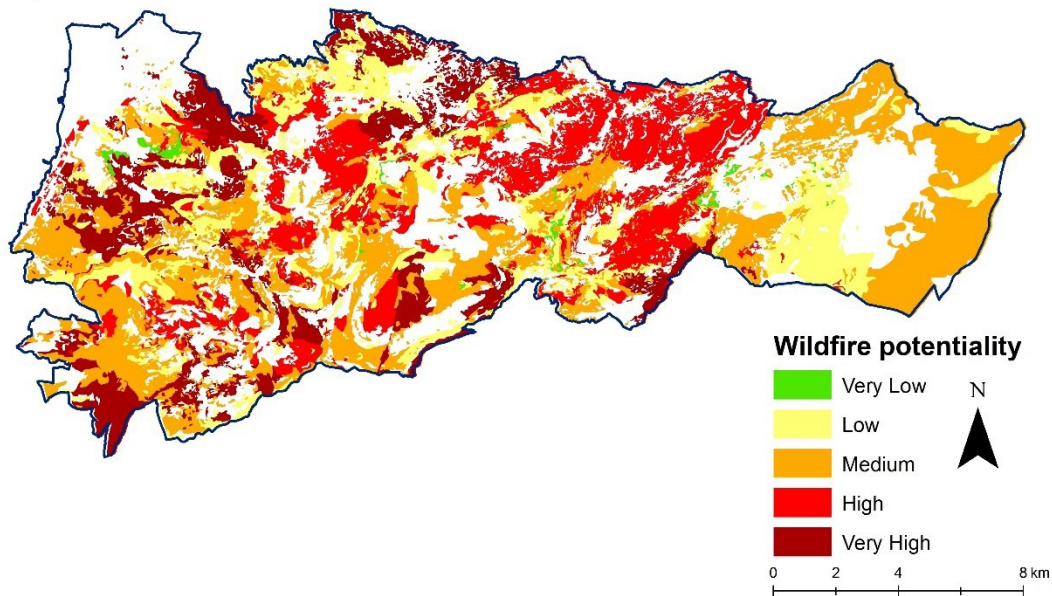




### State of lands in Aley (distribution in percentage)



a)



b)

