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How will land degradation neutrality change future land system patterns? A scenario simulation study

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ABSTRACT

Land degradation is a major global issue and achieving a land degradation-neutral world is one of the Sustainable Development Goals. However, striving for land degradation neutrality (LDN) is challenged by increasing claims on land resources and could result in major land use conflicts. The aim of this study is to demonstrate how LDN can be implemented in land system modelling and how achieving LDN alongside sufficient supplies of food, timber and shelter could affect future land system patterns, using the Republic of Turkey as a case study. We developed a LDN scenario with full implementation of the guidelines and a business-as-usual scenario without pursuing LDN, and compared the resulting differences in land system changes. Additionally, the influence of different elements of the LDN framework on the land use projections was tested. Our results show that although it is possible to achieve LDN in the context of increasing demands for resources and housing, it might require a considerable re-organization of the land systems. Intensification of annual cropland systems was the main driver of new land degradation, which was in the LDN scenario primarily counterbalanced by large areas of afforestation, while other land improvement options only played a minor role. To achieve a no-net-loss, about 20% of Turkey's territory was afforested in our scenario, mainly claiming extensively used annual cropland (~70%) and grassland (~30%). All individual LDN principles had a substantial impact on the final land system patterns meaning that the final outcome is not the result of just one of the principles, it is affected by all. Our findings suggest that pursuing LDN under growing demands for land-based products could stimulate a land sparing approach which might have trade-offs with other sustainability dimensions. This highlights the need for local support and new solutions for rural areas, thereby avoiding poverty, migration and illegal use of restoration areas.

1. Introduction

Land degradation is a severe global problem affecting food security, economic development, livelihoods and well-being of 1.5 billion people (Stavi and Lal, 2015; van der Esch et al., 2017). Degraded lands lose their capability of providing essential ecosystem services, including resources, habitat, healthy soils, clean water and air (Montanarella et al., 2018). The processes behind degraded land are diverse and complex, but all are directly or indirectly driven by human pressures on land (Conacher, 2009). For example, deforestation can lead to soil erosion, causing sediment and nutrient discharge, subsequently deteriorating water and soil quality (Pacheco et al., 2018). Other common causes of land degradation include overgrazing, which results in vegetation loss and soil compaction, cropland intensification and overcropping, which leads to soil erosion and salinization, and urban expansion, which causes soil sealing and permanent soil loss (Cowie et al., 2018; Gisladottir and Stocking, 2005).

Land degradation is not a new phenomenon. Evidence of historical degradation has been found in hotspots of ancient civilizations and migration, such as regions of former Maya settlements (Beach et al., 2006), ancient Greece (Runnels, 1995) or Anatolia (Bal et al., 2003). In the Mediterranean, human induced land degradation reaches as far back as the Neolithic (Kapur et al., 2006). In the last decades, however, socio-economic changes have caused abrupt and widespread land use and land cover changes leading to unprecedented rates of land degradation in the Mediterranean and worldwide (Hill et al., 2008). Today, the global expanse of degraded land is estimated between 1–6 billion hectares (Gibbs and Salmon, 2015), including 73% of the world's dryland rangelands and 47% of marginal rainfed croplands (Gisladottir and Stocking, 2005). With the forecast of increasing population and

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lifestyle changes, human pressure on land will increase in the future. Climate change impacts, such as droughts and floods, will further exacerbate the extent of land degradation, if we do not take urgent actions (Conacher, 2009; Stavi and Lal, 2015).

The severity of impacts of land degradation and the urgency to act is well recognized in the international community. The member states of the 2012 United Nations Sustainable Development Conference (Rio20+) agreed to combat desertification and to strive for a degradation-neutral world by 2030 (Akhtar-Schuster et al., 2017). Achieving zero-net land degradation and later-called land degradation neutrality (LDN) has since been integrated in the Sustainable Development Goals (SDGs) as part of target 15.3 (United Nations (UN), 2018). LDN is achieved when the quality and amount of land that sufficiently supports ecosystem services is maintained or improved (United Nations Convention to Combat Desertification (UNCCD), 2015). The main components of LDN are not only sustainable land management, but also a neutrality mechanism that is comparable to no-net-loss policies, which have been adopted in some places for example for biodiversity (Ermgassen et al., 2019; Safriel, 2017). Such a neutrality mechanism aims to not constrain all development, and recognizes that some degradation is inevitable, but requires an equal area to be restored. An important condition is the adaptation of a mitigation hierarchy by only restoring when loss is unavoidable.

Striving for LDN should support other SDGs and global commitments (Akhtar-Schuster et al., 2017; Cowie et al., 2018; Orr et al., 2017). However, trade-offs with the ‘Life on Land’ goal, which the LDN target is a part of, have been found for 12 of the 16 other SDGs, including the ‘No Poverty’, ‘Zero Hunger’ and ‘Reduced Inequalities’ goals (Pradhan et al., 2017). To enable policies to support local communities and ecosystems in achieving as many SDGs as possible, it is important to understand the future spatial implications of achieving LDN, thereby balancing trade-offs with other SDGs or commitments, protecting local land-tenure and identifying potential competing land claims. Previous research on LDN focused mostly on the challenges for implementation and social implications of LDN, for example by investigating socio-economic drivers of success (Salvati and Carlucci, 2014), local perceptions of restoration measures and beneficiaries (Crossland et al., 2018), the progress of LDN target setting and implementation (Allen et al., 2020; Aynekulu et al., 2017) or resilience assessment as a preliminary step towards LDN (Cowie et al., 2019). LDN implementation is also supported by platforms such as Trends.Earth that enable an assessment of current and historic degradation trends, and identification of the location of degraded areas (Conservation International, 2018). While LDN has been adopted at local level, it remains mostly unknown how future land use and management patterns would change under implementation of LDN at national level. Land use and land management (hereafter referred to as land systems) responds to competing demands on land resources, and implementation of LDN, as a ‘no-net-loss’ policy, will interact with the other pressures on land systems. Therefore, achieving LDN in the context of multiple competing claims on land resources is exemplary for the challenge of achieving multiple SDGs.

The objective of this study is to demonstrate how a land use modelling approach can be used to determine how land use will change, if the LDN target would be achieved alongside future human demands for food, wood and shelter. We thereby use the Republic of Turkey as a case study. Land system modelling can support national decision-makers to understand competing land claims and potential future trajectories of land use, identifying the impact of different policies and actions. Besides investigating the land system consequences of achieving LDN, this study furthermore explores the impacts of different key LDN principles, as set in the LDN framework (Orr et al., 2017) through several sensitivity analyses.

1.1. Case study description

There is much evidence on land degradation in the Mediterranean region. Typical degradation patterns and major land use and land cover changes are here the results of a complex interplay of biophysical conditions, a long history of human use and socioeconomic changes in the recent decades (Bajocco et al., 2012). Two opposite processes can be observed that influence land degradation patterns: on the one hand agricultural areas are abandoned as a result of degradation, often followed by extensive grazing or more frequent wildfires (Bajocco et al., 2012; Ries, 2010). At the same time, in other regions land use is intensified, and degradation is caused by, for example, overgrazing, deteriorating the quality of the Mediterranean forests and other woodlands (Jucker Riva et al., 2017). Land degradation and desertification have become an issue of regional security, as they pose environmental stresses on all the countries in the Mediterranean basin (Kepner et al., 2006).

As a Mediterranean country, the Republic of Turkey was one of the first countries to commit to LDN and join the 2014 pilot project by the UNCCD to set voluntary targets to achieve LDN and translate these into national policies (The Global Mechanism of the UNCCD, 2016). Shrinking forest areas, as well as declining productivity in forests, grassland and cropland were identified as the main negative trends of land quality (Ministry of Forest and Water Affairs, Republic of Turkey (MFWA), 2016). Voluntary LDN targets, therefore, included afforestation, decreasing forest areas affected by fire, rehabilitating degraded forests, grasslands and croplands and increasing areas of irrigation (Ministry of Forest and Water Affairs, Republic of Turkey (MFWA), 2016). We use Turkey as a case study as it exemplified a large country, home to more than 80 million people and among the top producers of agricultural commodities in the region, that experiences large land degradation challenges while being projected to face large increases in demand for land-based products. While over the last 30 years, total production amounts steadily increased, land productivity decreased over the same timeframe (Food and Agriculture Organization of the United Nations (FAO), 2018; European Environment Agency (EEA), 2017; Gökbulak et al., 2018). Most farms are small, family owned and characterized by low input and basic technologies (Kaygusuz, 2010). Turkey is highly vulnerable to desertification and land degradation, due to its climate, soils and topography and a long history of pressure on lands due to human settlements and agriculture (Ministry of Forest and Water Affairs, Republic of Turkey (MFWA), 2016). These pressures will intensify in the future. The country has a rapid population growth of about 2% per year (Gökbulak et al., 2018). Climate change is projected to heavily affect the country with higher temperatures and changing precipitation patterns, amplifying the risk for desertification in the South and East and of flood damage and water erosion in the North and West (Ministry of Forest and Water Affairs, Republic of Turkey (MFWA), 2016; Tatar, 2016).

2. Methods

2.1. Land system approach

As LDN relates both to land cover and land management, we followed a land system approach, where information on land cover is combined with land management, both in terms of cropland intensity and livestock density (van Asselen and Verburg, 2012). While often most attention is given to land cover, accounting for all these components is necessary to understand the impacts of human management on land resources and assess degradation or restoration patterns (Turner et al., 2013). The land system approach chosen here does not use human indicators, like population density and market access, to determine land use intensity, which enables the use of such factors as drivers of future land system allocation (van Soesbergen, 2016). A version of the CLUMondo model was used to allocate future land system changes (van Asselen and Verburg, 2013), with the model being adapted for this study to include algorithms that enable simulation of the LDN mechanism.

CLUMondo builds on spatial data of initial land system patterns. We extended the land system classification prepared for the Mediterranean by Malek and Verburg (2017) to the expanse of Turkey and fitted it to the purpose of this study. Classes that are less representative for Turkey or not determinative for our purpose, were excluded or aggregated (Table S1). Planted forest and forest used for wood production were assigned within the forest cover of the extended Mediterranean land systems. The assignment was based on likelihood maps (Schulze et al., 2019), national data (Food and Agriculture Organization of the United Nations (FAO), 2016; Ministry of Forestry and Water Affairs and Republic of Turkey (MFWA), 2010) and location of protected areas (more details in supplement – Section 1.1 and 1.2). Spatial data on aridity (Zomer et al., 2007, 2008) were used to exclude rainfed intensive agriculture from arid areas, where intensive agriculture is only possible within irrigated land systems. Our final land system map (Fig. 1) contained 14 different classes. Just as the original land system map (Malek and Verburg, 2017), it has a $2 \times 2km^2$ resolution and represents the land system patterns in 2010. This served as starting point to model land system change until 2050.

There are some simplifications in our land system classification that may in reality be different. Turkey is the top producer of hazelnut and especially in the Black Sea region it is one of the most important commodities. However, the area of permanent crop in this region classified in the original land system map was negligible. This can be due to the resolution or misclassification, as hazelnut plantations are often rather small and components of agroforestry systems.

2.2. Demand and supply

Land system change trajectories modelled with CLUMondo are driven by future demands, which are represented in this study as annual demands for food, timber and housing until 2050. Food demand was divided into annual and permanent crops and ruminant livestock, i.e. cattle, sheep and goat, and was based on the following assumptions and data. Future demand scenarios followed the 'Middle of the road' storyline of the shared socioeconomic pathways (i.e. SSP2), which largely assumes a continuation of current development with small shifts towards more sustainable resource use and moderate population growth (Fricko et al., 2017; O'Neill et al., 2017; Riahi et al., 2017). Data for the food demand scenarios were provided by the SSP database hosted by the IIASA Energy Program (available at https://tntcat.iiasa.ac.at/SspDb). The underlying scientific data is published in Fricko et al. (2017). To be consistent, the demands for the initial year (2010) were derived from the same repository.

Supplies of crops and livestock per land system were determined following the methodology from Malek and Verburg (2018) which is explained in more detail in the supplement (Section 1.3 in the Supplementary Material). In brief, data on the amount of food production in 2010 were divided by the respective area, which was based on spatial data on the distribution of livestock (Robinson et al., 2014), annual cropland (Fritz et al., 2015) and permanent cropland (Copernicus, 2019). Crop production within systems of different intensities (i.e. extensive, intensive, irrigated) was distinguished based on shares, adopted from International Food Policy Research Institute (IFPRI) and International Institute For Applied Systems Analysis (IIASA) (2015). Similar to other regional scale land system modelling studies (see for example Wolff et al., 2020; Zhu et al., 2020), we used for each land system mean values for the supply of commodities. As we do not deal with spatial variation this can lead to counterintuitive values, e.g. irrigated systems having lower yields than rainfed due to their location in less favourable areas. Disentangling this interplay is complex and not possible with existing data on such scales.

Average livestock density was adjusted for some land systems to exclude indoor livestock farming (Table S3). We did not include chickens in our livestock demands, even though pasture raised chicken are an important source of income and subsistence for Turkey's population (Sekeroglu and Aksimsek, 2009). As chickens are primarily raised in intensive indoor factory-farms, often in close vicinity to urban areas and with high concentrations in small locations (Robinson et al., 2014),

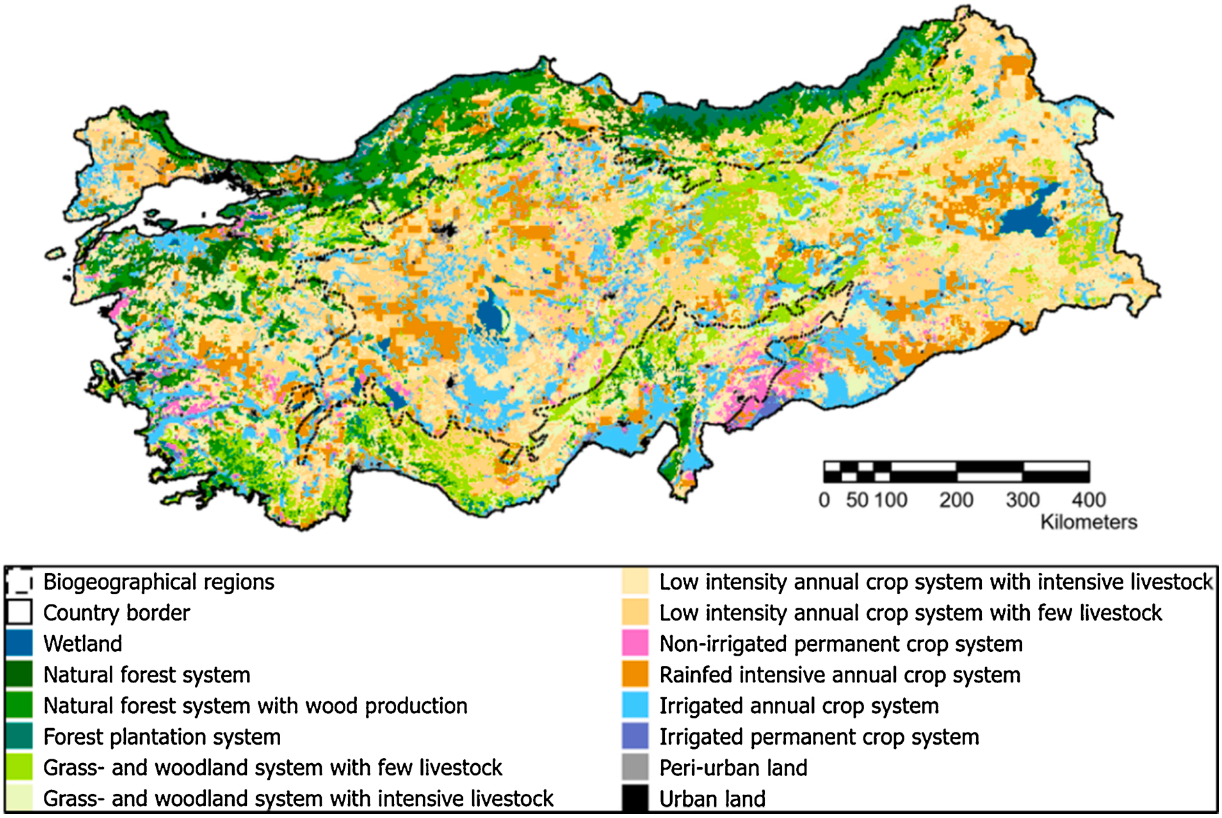


Fig. 1. Land systems patterns of Turkey in the initial year (2010), derived from modified Mediterranean land systems classified by Malek and Verburg (2017).

we expect the area of pasture chicken to not be driving land use change substantially, also in consideration of the resolution of this study. Similarly, we did not consider honey production, which could, however, have an impact on protection of forests and woodlands or pesticide use in agricultural fields.

Timber demand represents the amount of wood that is produced within the country (i.e. including exports, but not imports) used for building material or wood fuel. Initial timber demand was derived from timber production projections from the IMAGE model (Doelman et al., 2018; van Vuuren et al., 2017). While the IMAGE model projected timber production to decrease in the future, we kept the amount constant. The decrease in the IMAGE model follows the current trend of decreasing fuelwood production due to increasing migration of rural population (Atmiş and Günşen, 2018; van Vuuren et al., 2017). However, while the production of fuelwood has been decreasing over the last years, production of industrial roundwood increased approximately at the same rate (Atmiş and Günşen, 2018). As the country with the highest national forest cover in Central and Western Asia (Food and Agriculture Organization of the United Nations (FAO), 2016), we assume Turkey will maintain its role as major timber exporter in a region, where timber is scarce. Timber production was subdivided into wood from natural forests and wood from planted forests (d'Annunzio et al., 2015). To calculate the average timber supply per forest type, the amount of timber produced in either planted or natural forests were divided by the area of the respective forest system. The demand for shelter was expressed as built-up areas and the supply was derived from spatial data on artificial surfaces (Chen et al., 2015).

2.3. Land system modelling

The CLUMondo model allocates future land system change across the region to match the demands for goods and services at national level with the supply of goods and services by land systems. The allocation is based on the suitability of the locations for each system and conversion rules that restrict either certain conversions or locations. Land suitability describes the preference for each land system at a particular location. These spatial layers were created for each land system separately (Fig. S3), using binary logistic regression based on the current land system pattern and a wide range of location factors. Regression models were estimated based on a balanced random sample of occurrence and absence in the land system map of the initial year. The size of the random sample depended on the extent of the land system, with a higher proportion sampled for land systems with smaller expanses (Table S4). In total, 21 location factors were used as explanatory variables covering biophysical (for example, soil and climate) and socio-economic (for example population density and market accessibility) conditions (Table S2) similar to the selection of factors use by Malek et al. (2018) for the Mediterranean.

We defined several conversion rules (Table S5). Conversion from urban areas, wetlands and any conversion within protected areas was prohibited, as well as conversion to rainfed agriculture in arid areas (i.e. aridity index < 0.2) and in previously irrigated land systems. Furthermore, it was assumed that planted forests and permanent crop systems would not convert to natural forests within the time-scale of analysis. Higher conversion resistance was assigned to intensive systems in order to respect the mitigation hierarchy of the LDN framework (i.e. avoiding land degradation, when feasible, see Table S6). Finally, irrigated areas received a competitive advantage over rainfed agriculture in semi-arid areas, by increasing the suitability for irrigated cropland by an arbitrary 5% and decreasing the suitability for rainfed intensive crops by 5% in these areas relative to the suitability estimated by the regression approach. This was implemented to respond to adaptive behaviour towards climate change, where historic land use no longer represents current choices (Zagaria et al., 2021). The suitability maps were updated yearly for projected change in aridity by calculating the aridity index for 2050 (Trabucco and Zomer, 2018) and assuming linear change each year. We did not account for all restrictions of land use, for example we did not include water availability, which has been found to limit irrigation potential in Mediterranean countries (Fader et al., 2016). We also did not include economic restrictions, which could largely constrain rather costly land system conversions, such as afforestation and cropland intensification.

2.4. Accounting for land degradation neutrality

To guide countries in understanding, implementing and monitoring their land degradation trajectories, the concepts and goals of LDN were conceptualized in a framework, which serves as scientific basis (Chasek et al., 2019; Cowie et al., 2018; Orr et al., 2017). LDN follows a mitigation hierarchy (Cowie et al., 2018) in which degradation should always be avoided when feasible. If degradation is unavoidable, the no-net-loss requirement stipulates that the extent of areas experiencing negative changes in land-based natural capital has to be counterbalanced with areas of the same size where degradation is reversed, the land improved and there is a gain in land-based natural capital. Land-based natural capital refers to geomorphological, biotic and hydrological features that influence the provisioning of ecosystem services (Orr et al., 2017). Land improvement, i.e. restoration thereby needs to occur in the same landscape, ecosystem and benefit the community that is affected by degradation, following the so called like-for-like principle (Orr et al., 2017; Stavi and Lal, 2015). To measure degradation the change in three indicators is considered: (1) land cover, (2) land productivity and (3) soil organic carbon, whereby the direction, rather than the magnitude of change is considered (Orr et al., 2017). Furthermore, an one-out-all-out principle applies, meaning the significant decrease of one indicator is enough to consider the land conversion as degradation, even if other indicators increase (Orr et al., 2017).

The capability of the CLUMondo model to match demand and supply for a range of goods and services was used to ensure that the no-net-loss condition of LDN was achieved. We determined the change in land-based natural capital for each land system conversion based on the recommended metrics for the indicators: (1) soil organic carbon (SOC) content for carbon stocks, (2) net primary productivity (NPP) for land productivity and (3) land cover changes for land cover (Orr et al., 2017). To implement the binary, area-based approach (considering the direction, rather than the magnitude of change), average values of SOC and NPP for each land system and separately for biogeographical regions were calculated using spatially explicit data (Food and Agriculture Organisation of the United Nations (FAO) et al., 2019; Running et al., 2011 derived by AppEEARS Team, 2018). To avoid outliers originating from location inaccuracy, the average was derived from a truncated (trimmed) dataset, discarding an arbitrarily set 10% from each end of the data range, to avoid very small changes having large impacts on the results (Table S7, S8). During the simulation, average values of the initial and final land system were compared, determining if a land conversion results in loss or gain in land-based natural capital. The LDN framework states to consider 'significant' positive or negative changes. To avoid that conversions between similar systems would be counted as loss or gain, we applied a 10% threshold, which follows the Trends.Earth methodology for analysing change in SOC (Conservation International, 2018). Hence, if the value for the converted land system was at least 10% higher than the initial one, we considered the conversion as improvement, or gain in land-based natural capital. If the value was at least 10% lower, we considered the conversion as degradation, or loss in land-based natural capital (Fig. S4). As land cover is a categorical, rather than a numerical indicator, the change was assigned using a hierarchy, which followed the approach of Sims et al. (2019) as well as the default transition matrix from the Trends.Earth tool (Conservation International, 2018). The direction of change in land cover was assigned by ranking forests first, followed by grassland, cropland and lastly urban land (Fig. S4). We only considered land system change, including land cover, land system configuration and land management change, as a driver for land degradation or improvement and did not account for smaller nuances of management changes within the same land system. Additionally, by using average values per land system for NPP and SOC, we did not account for spatial variation within biogeographical regions or degradation caused by droughts or other environmental factors.

Second, the so-called ‘one-out, all-out’, principle was applied, stipulating that the decrease of at least one indicator results in degradation, even if other indicators increase. Gain in land-based natural capital was assumed to be achieved, if at least one of the indicators increased and the others remained stable (Orr et al., 2017). In the model algorithm, a demand for land improvement and hence natural capital gain was specified as soon as the balance between natural capital gains and losses was lost. Similarly to a demand for food production and timber, this demand exerted an impact on land system changes, favouring those that contributed to natural capital gains. So, in the model, demands for food, timber, housing and land improvement (i.e. gain) were competing, mimicking the decision making processes based on local suitabilities for land systems, current land system conditions, higher level market pressures, for example the efficient production of commodities by favouring some land systems over others, and policy targets, such as pursuing LDN.

Finally, to fulfil the ‘like for like’ principle, areas of loss in land-based natural capital have to be counterbalanced with areas of land improvement and natural capital gain in the same land type or ecosystem (Orr et al., 2017; Stavi and Lal, 2015). Land types are based on land potential to sustainably generate ecosystem services, which is in turn based on climate, topography and static soil properties (Orr et al., 2017). The framework suggests stratifying land by means of agro-ecological zones and land cover. However, suitable data on land potential or agricultural zones is not available for Turkey. Using land cover to delineate land types would prohibit land cover changes including expansion of cropland or urban area, as well as afforestation. Furthermore, if stratification was based on land cover, it would have no effect as an LDN indicator. Therefore, we used Turkey’s biogeographical regions instead: (1) the Black Sea region, (2) Anatolia and (3) the Mediterranean (European Environment Agency (EEA), 2016, see Fig. S1). Each of these regions has distinct climatic, topographic and socioeconomic features, which are further described in the supplement (Section 1.5 in the Supplementary Material). Counterbalancing within the same region was used as an implementation of the like-for-like principle, which is a rather rough estimation, but most suitable for the resolution of this study in a country with many small-farm agricultural systems and mosaic systems.

2.5. Scenarios and sensitivity analysis of the LDN principles

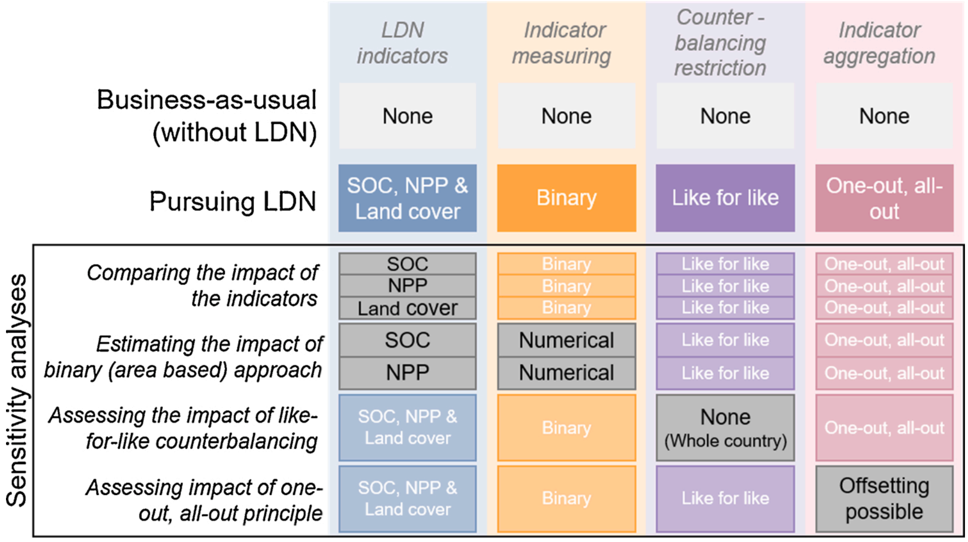
We compared a business-as-usual scenario without LDN implementation with a LDN scenario in which no-net-loss was achieved. In the business-as-usual scenario, LDN is not accounted for and future projections follow solely the demands for food, timber and housing. The LDN scenario accounts for LDN with all principles, as described above.

In addition, we conducted sensitivity analyses on how the different LDN principles influence future land system patterns (Fig. 2 provides an overview of the different scenarios and sensitivity analyses). This included the influence of the choice of LDN indicators, by including only one LDN indicator at a time. The impact of the binary, area-based approach was investigated by testing two separate model runs with numerical values for either SOC or NPP. The ranking of land cover could not be converted to numerical values and hence the indicator was not included in the numerical assessment. The effect of the ‘like-for-like’ principle was explored by pursuing no-net-loss at a national level. Finally, it was tested how the ‘one-out, all-out’ principle influences the result, by allowing that the increase in one indicator could offset the decrease of another.

2.6. Analysis of land degradation causes and mechanisms for land improvement

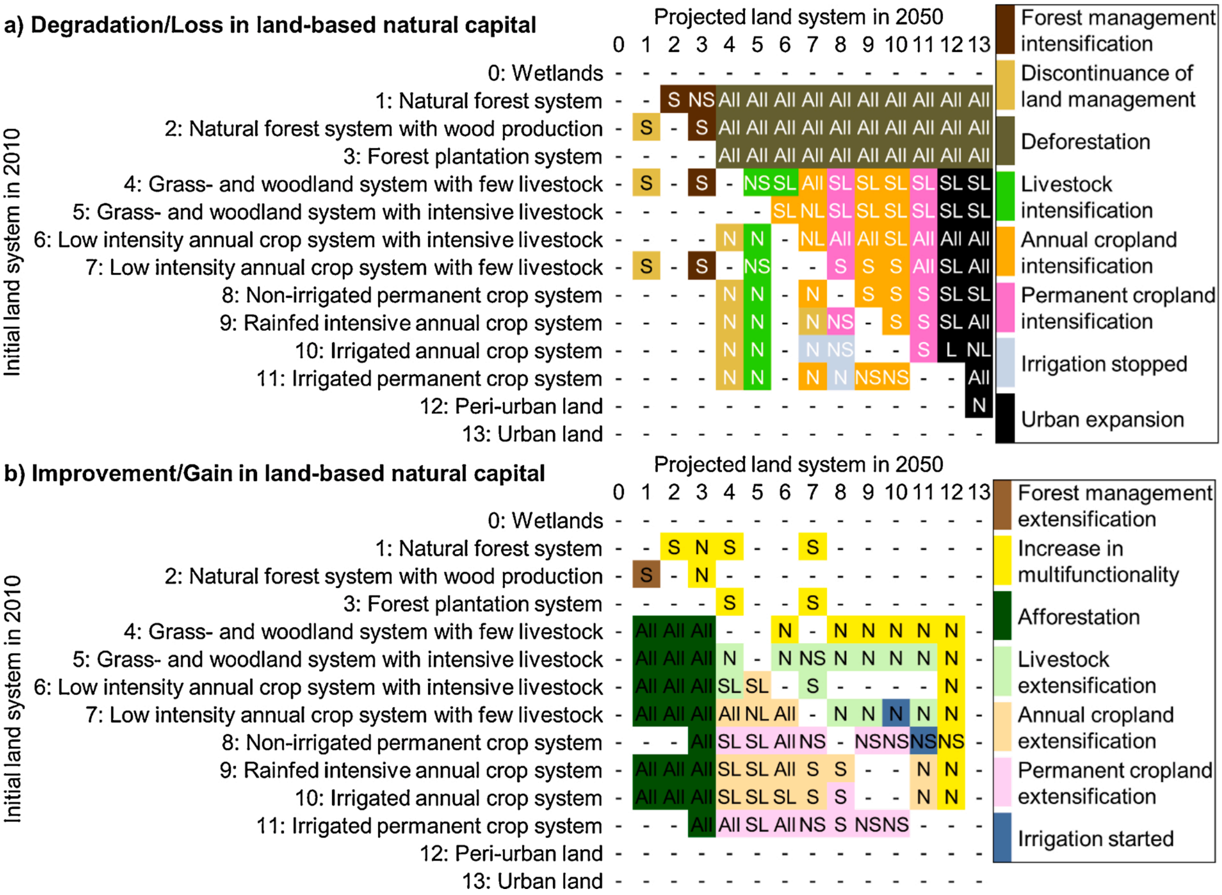
We compared the land system map of 2010 with future land systems in 2050 to identify projected land system conversions for each of our scenarios and sensitivity analyses. We then assigned loss or gain in land-based natural capital to these conversions using the land conversion matrix for the LDN scenario. Land system conversions were categorized according to the causes leading to either land degradation or improvement, hence loss or gain in land-based natural capital (Fig. 3). We thereby do not consider the type of degradation, such as soil erosion, landslides or salinization, but rather the general impact of land conversions on the LDN indicators, which is a limitation of this study. Eight different causes for degradation were categorized: (1) deforestation, intensification of respectively (2) annual crops, (3) permanent crops, (4) livestock or (5) forest management, (6) discontinuation of land management, (7) discontinuation of irrigation and (8) urban expansion.

Deforestation included all land conversions from forested to non-forested systems, including urban or cropland expansion (Fig. 3a).



		LDN indicators	Indicator measuring	Counter - balancing restriction	Indicator aggregation
	Business-as-usual (without LDN)	None	None	None	None
	Pursuing LDN	SOC, NPP & Land cover	Binary	Like for like	One-out, all-out
Sensitivity analyses	*Comparing the impact of the indicators*	SOC NPP Land cover	Binary Binary Binary	Like for like Like for like Like for like	One-out, all-out One-out, all-out One-out, all-out
	Estimating the impact of binary (area based) approach	SOC NPP	Numerical Numerical	Like for like Like for like	One-out, all-out One-out, all-out
	Assessing the impact of like-for-like counterbalancing	SOC, NPP & Land cover	Binary	None (Whole country)	One-out, all-out
	Assessing impact of one-out, all-out principle	SOC, NPP & Land cover	Binary	Like for like	Offsetting possible

Fig. 2. Overview of scenarios and sensitivity analyses investigated in this study. Boxes in color represent the principles following the LDN framework (Orr et al., 2017), gray boxes indicate modifications of the LDN principles to test their impact.



a) Degradation/Loss in land-based natural capital

Projected land system in 2050 (columns); Initial land system in 2010 (rows)

Initial land system in 2010	0	1	2	3	4	5	6	7	8	9	10	11	12	13
0: Wetlands	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1: Natural forest system	-	-	S	NS	All	All	All	All	All	All	All	All	All	All
2: Natural forest system with wood production	-	S	-	S	All	All	All	All	All	All	All	All	All	All
3: Forest plantation system	-	-	-	-	All	All	All	All	All	All	All	All	All	All
4: Grass- and woodland system with few livestock	-	S	-	S	-	NS	SL	All	SL	SL	SL	SL	SL	SL
5: Grass- and woodland system with intensive livestock	-	-	-	-	-	-	SL	NL	SL	SL	SL	SL	SL	SL
6: Low intensity annual crop system with intensive livestock	-	-	-	-	N	N	-	NL	All	All	SL	All	All	All
7: Low intensity annual crop system with few livestock	-	S	-	S	-	NS	-	-	S	S	S	All	SL	All
8: Non-irrigated permanent crop system	-	-	-	-	N	N	-	N	-	S	S	S	SL	SL
9: Rainfed intensive annual crop system	-	-	-	-	N	N	-	N	NS	-	S	S	SL	All
10: Irrigated annual crop system	-	-	-	-	N	N	-	N	NS	-	-	S	L	NL
11: Irrigated permanent crop system	-	-	-	-	N	N	-	N	N	NS	NS	-	-	All
12: Peri-urban land	-	-	-	-	-	-	-	-	-	-	-	-	-	N
13: Urban land	-	-	-	-	-	-	-	-	-	-	-	-	-	-

b) Improvement/Gain in land-based natural capital

Projected land system in 2050 (columns); Initial land system in 2010 (rows)

Initial land system in 2010	0	1	2	3	4	5	6	7	8	9	10	11	12	13
0: Wetlands	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1: Natural forest system	-	-	S	N	S	-	-	S	-	-	-	-	-	-
2: Natural forest system with wood production	-	S	-	N	-	-	-	-	-	-	-	-	-	-
3: Forest plantation system	-	-	-	-	S	-	-	S	-	-	-	-	-	-
4: Grass- and woodland system with few livestock	-	All	All	All	-	-	N	-	N	N	N	N	N	-
5: Grass- and woodland system with intensive livestock	-	All	All	All	N	-	N	NS	N	N	N	N	N	-
6: Low intensity annual crop system with intensive livestock	-	All	All	All	SL	SL	-	S	-	-	-	-	N	-
7: Low intensity annual crop system with few livestock	-	All	All	All	All	NL	All	-	N	N	N	N	N	-
8: Non-irrigated permanent crop system	-	-	-	All	SL	SL	All	NS	-	NS	NS	NS	NS	-
9: Rainfed intensive annual crop system	-	All	All	All	SL	SL	All	S	S	-	-	N	N	-
10: Irrigated annual crop system	-	All	All	All	SL	SL	SL	S	S	-	-	N	N	-
11: Irrigated permanent crop system	-	-	-	All	All	SL	All	NS	S	NS	NS	-	-	-
12: Peri-urban land	-	-	-	-	-	-	-	-	-	-	-	-	-	-
13: Urban land	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Fig. 3. Matrices of land conversion categorization for degradation (a) and land improvement (b), including the LDN indicator metric(s) that show a significant change (N = net primary productivity, S = soil organic carbon, L = land cover change, All = all metrics). The impact on the metrics thereby relates to any region, meaning that a metric does not necessarily change in all regions. Only land conversions that occur in at least one of the biogeographical regions are included. The full land conversion matrices for all indicators and regions can be found in Figure S4.

Forest cover loss is often a result of agriculture or urban area expansion, driven by increasing population and demands. It causes land degradation through soil erosion by wind or water as a result of exposed soil and surface runoffs alteration. Intensification of livestock, annual or permanent crop production is also often a result of increasing demands or can be caused by reorganization of land systems, e.g. due to increasing aridity. In our classification, these land degradation causes included conversions from extensive to intensive systems and the expansion into other land systems (except forest systems and urban land, which are classified as deforestation or urbanization). While fertilizer application might temporarily increase land productivity and NPP of annual and permanent cropland, agricultural intensification usually decreases SOC stocks and land productivity on the long term (Collard and Zammit, 2006). In intensive grazing systems, vegetation cover is decreased and soil compaction through trampling results in high bulk density, leading to lower SOC stocks compared to extensive systems (Cha et al., 2020). As we used average values per land system, we did not distinguish between different types of intensification, such as sustainable intensification, climate-smart agriculture or organic agriculture, which could reduce degradation within agricultural land.

Intensification of forest management described changes in harvest regimes and species selection. Land productivity and SOC stocks in planted forests and afforestation sites is often lower than in natural forests, due to insufficient accumulation processes in the soil or higher bulk densities (Cha et al., 2020; Ngaba et al., 2020). Wood harvest can decrease SOC stocks in the forest floor when residues are harvested as fuelwood (Achat et al., 2015). Discontinued irrigation leads to lower productivity (NPP) due to water scarcity and can decrease SOC, especially in arid environments (Trost et al., 2013). Discontinuation of land management is similar to extensification (land improvement mechanism), but results here in degradation of land. This is the case, for example, for cropland abandonment with subsequent extensive grazing, which negatively impacts vegetation cover, land productivity and carbon stocks (Ries, 2010). Another example is discontinuation of forest management, which can include the termination of practices that artificially increase NPP and SOC levels, for example nitrogen fertilization (Mayer et al., 2020). Increased grazing pressure in forests due to less competing objectives and less control can be another reason causing land degradation when forest management and timber harvest is discontinued (Keleş et al., 2017; Mayer et al., 2020). Urban expansion leads to soil sealing and loss of land productivity and organic carbon.

Conversions classified as land improvement that result in gains in land-based natural capital included seven categories: (1) afforestation, extensification of (2) annual crops, (3) permanent crops, (4) livestock or (5) forest management, (6) increase in multifunctionality and (7) started irrigation (Fig. 3b). These categories are thereby mainly the opposite of the corresponding land degradation mechanism. Increase in multifunctionality describes the provisioning of additional ecosystem services, which can increase land quality and productivity over monoculture approaches (Organisation for Economic Co-operation and Development (OECD), 2016). Urban contraction was not included as a way to improve land, as we prohibited urban land from converting to other systems. It needs to be noted that we only included sustainable land management practices in broad terms through the intensification level. However, in reality there is a broader and specific range of measures which could improve land in agricultural systems and forests without land use change.

3. Results

3.1. Changing land system patterns

Our results show that it is possible to achieve LDN next to fulfilling demands for food, timber and housing. However, this is accomplished through considerably more land system changes in the LDN scenario as compared to the business-as-usual scenario. These are required to balance losses in natural capital as a result of intensification driven by increasing demands (Fig. 4). Compared to the business-as-usual scenario, where LDN is not pursued, the amount of losses in land-based natural capital is similar in the LDN scenario. However, gain in land-based natural capital is projected to occur only on a small area in the business-as-usual scenario, while in the LDN scenario the extent of areas with natural capital gain is much larger, about the same extent as the area with natural capital losses due to the counterbalancing requirement. Our results furthermore indicate that even while the mitigation hierarchy, which aims at avoiding losses under LDN, was implemented in the model, the high demand for land-based goods leads to large areas that experience losses in natural capital that need to be compensated by land improvement.

The main cause for land degradation in both, the business-as-usual, as well as the LDN scenario is the intensification of land use, primarily of annual croplands, driven by an increasing demand for annual crops (Fig. 5). To a lesser extent, intensification of livestock and permanent crop, urban expansion and discontinuation of management are found as causes of degradation. To achieve LDN, land degradation has to be counterbalanced with land improvement, which is mostly achieved by afforestation and to a lesser extent by extensification of annual crops.

We observe distinct land system trajectories for each biogeographical region. Annual cropland intensification is the most prevalent cause for land degradation in all three regions in the business-as-usual scenario.

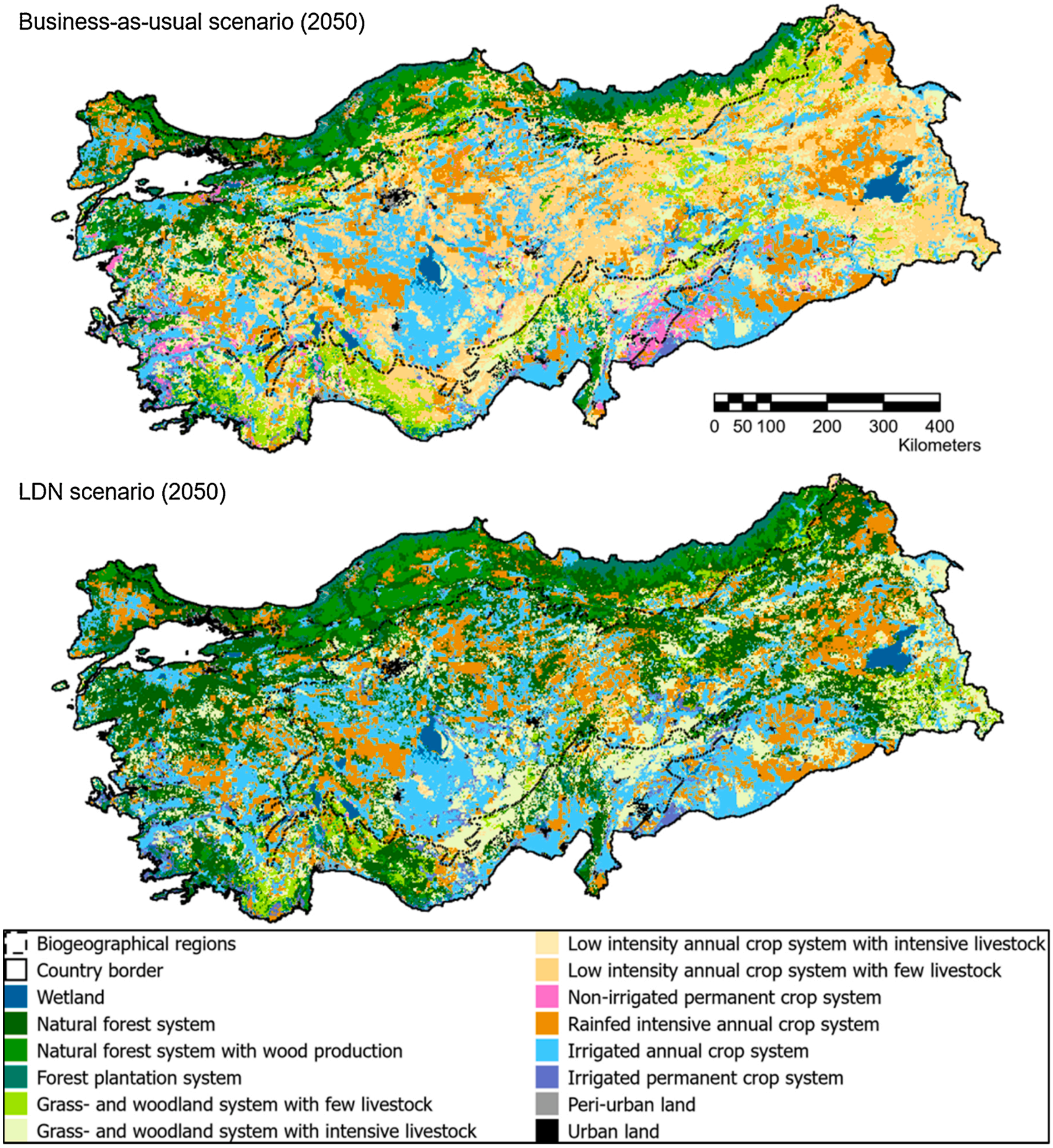


Fig. 4. Comparison of land system projections for 2050, following the business-as-usual scenario (without LDN) and the LDN scenario. Initial land systems can be found in Fig. 1.

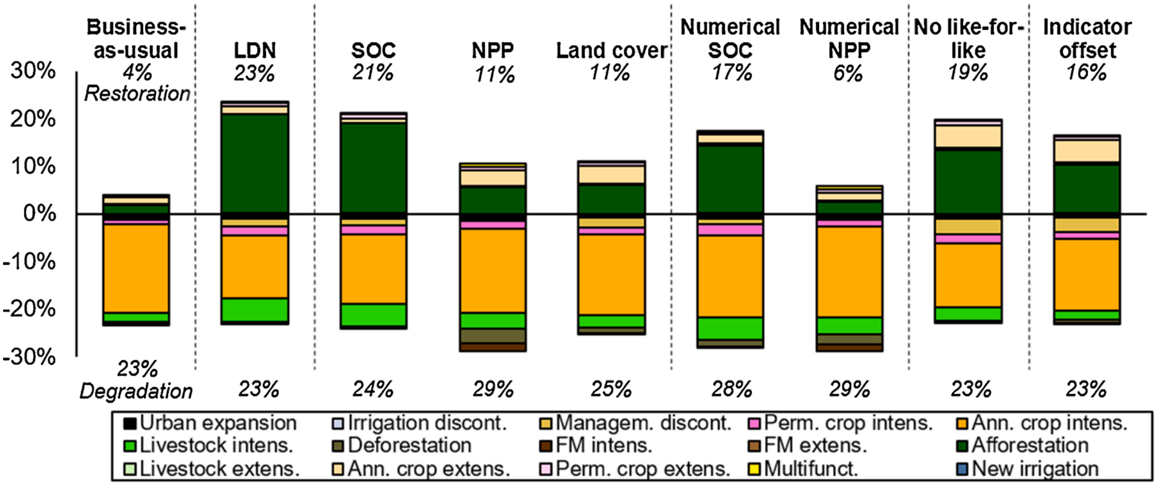


Fig. 5. Relative size of areas of that experience losses and gains in land-based natural capital, distinguished in their underlying conversion causes. For the business-as-usual scenario and the sensitivity analyses, the area of land degradation and improvement were calculated based on the land conversion matrices of the LDN scenario for an easier comparison. The values used in sensitivity analysis differed (e.g. because just one indicator was used to determine if a land conversion should be considered land degradation or improvement). Hence, it might seem in this figure, that no-net-loss was not achieved, which is, however, not the case. Percentages of degradation and restoration area are given in relation to the whole national extent of Turkey.
Abbreviations: intens. – intensification, extens. – extensification, ann. – annual, perm. – permanent, FM – forest management, discont. – discontinuance, managem. – land management, Multifunct. – increase in multifunctionality.

When implementing LDN, this trend reciprocates in the Mediterranean and Anatolia, while in the Black Sea region, discontinuation of land management is the main cause for degradation (Fig. 6). Discontinuation of land management refers here mostly to converting natural forests used for wood production to non-productive natural forests. The change is driven by constant wood demands, but increasing wood production efficiencies. NPP and SOC values are lower in non-productive than in productive forests in this region, hence the conversion is classified as land degradation. Degradation is likely caused by increasing grazing pressure in forests, which are no longer used for timber production. It is also possible that lower NPP and SOC values in non-productive forests are an indication for unfavourable growing conditions for wood production, rather than an effect of land system change. In the Mediterranean, intensification of permanent cropland is more frequently observed than in the other regions. Due to climatic conditions, the region already initially has the largest supply of permanent crops (Fig. S8). Compared to Anatolia, which produces only slightly less permanent crops, there is less competition with other resources, such annual crops and livestock, in the Mediterranean.

3.2. Sensitivity analysis and impact of the LDN principles

When only accounting for a single indicator for loss/gain in land-based natural capital the area of degradation is larger than in the LDN scenario, as decrease of other indicators is not avoided. This indicates that using multiple indicators has added value over the use of a single indicator and that each indicator has an effect on the results. Comparing the single indicator sensitivity analyses with each other suggests that the

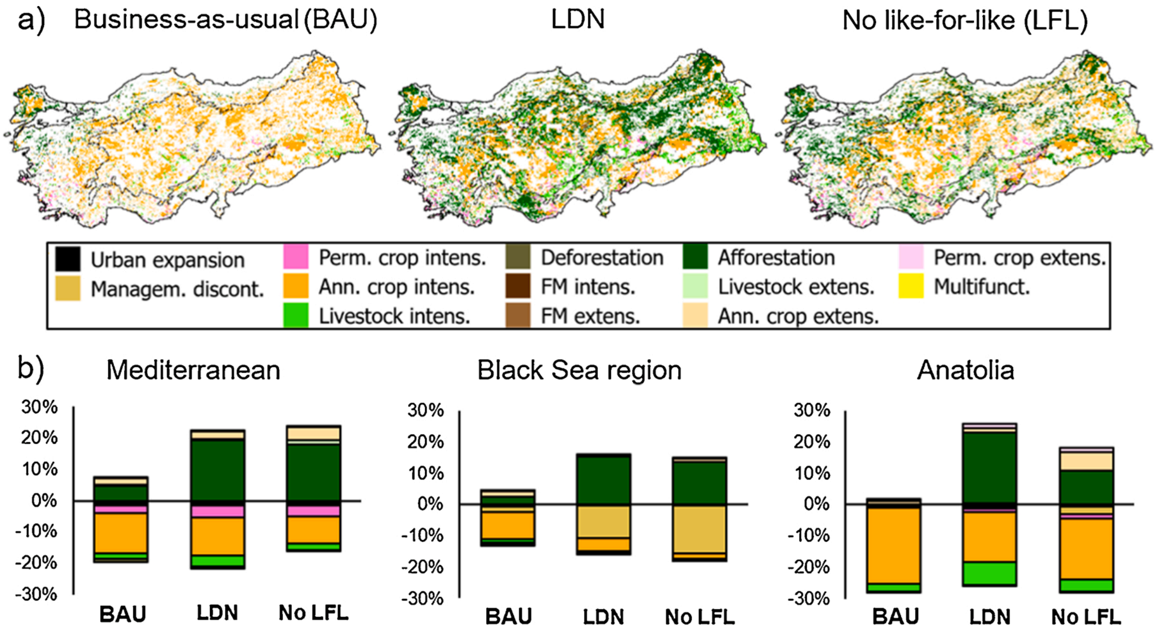


Fig. 6. Spatial patterns of land conversions (a) and relative amounts within different regions (b) compared between the business-as-usual scenario, the LDN scenario and the no like-for-like test.

LDN scenario is largely driven by achieving neutrality in the SOC indicator, as the results of the LDN scenario and the SOC sensitivity test show more similarity in terms of area size of land degradation and restoration, conversion mechanisms and resulting land use patterns, compared to the other single indicator tests (Figs. 5 and S5b & e). The single indicator tests that only include NPP or land cover have the smallest expansion of restoration areas. Land use intensification, a dominant process, increases NPP values of crops systems and has a less negative impact on land cover conditions. Therefore, less counterbalancing is required.

To avoid complex bookkeeping and quantification that requires extensive measurements, LDN uses a binary approach for calculating counterbalancing needs. A numerical approach, balancing real gains and losses on the indicators is an obvious alternative. For Turkey, we find that in the single indicator (binary) tests a larger area of land improvement was required to counterbalance land degradation, than when using numerical values (Fig. S5e - h). In the numerical approach, it is possible that an area of land improvement counterbalances more (or less) than an area of land degradation with the same extent. The values of SOC and NPP for forests are up to double of those for agriculture, while the differences between extensive and intensive agriculture are considerably smaller, often around 20%. The degradation mechanisms in the offsetting test are similar to the LDN scenario, but, as expected, less areas of gains are required to counterbalance losses in land-based natural capital (Fig. 5).

The ‘like-for-like’ principle, which forces counterbalancing within the same biogeographical region, has a large impact on the results. While at the national level the extent of areas experiencing loss and gain in land-based natural capital is similar with and without the like-for-like principle, the regional division is strong. In the ‘no like-for-like’ test we observe considerably less afforestation and more extensification of annual cropland, compared to the LDN scenario (Fig. 6a). In Anatolia, more degradation is caused by intensification of annual crops and less improvement occurs in the test without like-for-like. In the Mediterranean, on the other hand, more areas with gains in land-based natural capital are observed, with more extensification of annual crops than in the LDN scenario. Additionally, the region shows fewer land degradation in the test without like-for-like mostly due to less annual crop intensification (Fig. 6b).

4. Discussion

4.1. Feasibility of LDN implementation

We present the first scenario assessment of future land system change with LDN embedded as a core principle, demonstrated in the example of Turkey. Our results show that it is technically possible to achieve LDN in Turkey by 2050 while fulfilling the demands for food, timber and housing. However, with the assumptions of our model and under such conditions, achieving LDN might require large land system changes. Overall, the model projected as a most likely future trajectory intensification of annual croplands, simultaneously counterbalanced by afforestation. Although other strategies, such as extensification of land use and increase in multifunctionality were included, their impact towards achieving LDN was relatively minor. This was a direct result of the pressure on land systems, where insufficient lands are available to supply the demand with extensification strategies. Agricultural intensification and sustainable land management approaches that limit land degradation were not distinguished in our study. Novel trajectories of intensification could avoid the need for extensive counterbalancing, making the feasibility of achieving LDN a lot higher. Sustainable intensification, climate-smart agriculture and organic agriculture are promoted as alternatives to conventional intensification trajectories (Helfenstein et al., 2020) and could make achieving LDN and meeting increasing food supply more realistic. However, the potential of these forms of intensification for meeting the ‘double objective’ is still debated (Struik and Kuyper, 2017) and may be location dependent (Prestele and Verburg, 2020). The drastic reorganization of land systems and the very high investments needed for counterbalancing confirm that in order to achieve LDN the avoidance priority should also address the demand for land resources (Verburg et al., 2019). Demand-side solutions, such as dietary change or reduced waste can help to avoid the projected increases in demand, leading to less counterbalancing needs and making achieving LDN a lot more feasible (Malek et al., 2018).

Our results are difficult to compare to most of Turkey’s voluntary LDN targets set in the pilot project (Ministry of Forest and Water Affairs, Republic of Turkey (MFWA), 2016). As compared to the small scale of the pilot project, our approach did not include enough detail, for example, in making a distinction between degraded and rehabilitated pastures, as well as the impact of sustainable land management approaches. For the case of Turkey, the Global Sustainable Land Management Database (World Overview of Conservation Approaches and Technologies (WOCAT), 2021) lists several sustainable land management approaches, including strip farming to reduce wind erosion and land degradation in rainfed crop production, woven wood fences to protect soils from water erosion or rotational grazing to support the regeneration of herbaceous plant cover in pasture lands. Preferably, satellite trends on degradation and land improvement should be validated with ground-truth data by local experts (García et al., 2019). However, a methodology on how to do this on national scale is currently lacking. Our projections of land degradation and improvement therefore only considers major land systems changes, but not nuances of sustainable land management within the same land use system. For the Turkey’s voluntary targets that we could compare to our simulated land system changes, our projections exceeded the anticipated areas of the LDN report (Ministry of Forest and Water Affairs, Republic of Turkey (MFWA), 2016). For example, the anticipated increase of irrigated systems is about 4 times lower than the increase we projected (66%). A recent study found that irrigation in the southern part of Anatolia increased by more than 6 times in the last 30 years (Rufin et al., 2021) and a similar trend can be expected for other arid areas in the country, depending on available resources. It has to be noted that the voluntary targets are until 2030, while our projections were for the year 2050. For forest cover, the difference between the LDN targets (5%) and our results (167%) indicates that the trajectory is unlikely to be realized in the future, even when accounting for the different time scale.

The magnitude of afforestation which we projected to be necessary for counterbalancing, would be challenging to achieve in the future and very costly. Multiplying the budget numbers from the LDN report for afforestation (150,000$/km^2) with our projected area of afforestation (173,488 km^2) would sum up to over 26 billion $, not including additional land consolidation or other necessary expenses. This would already substantially exceed the costs that were estimated for achieving the entire LDN voluntary targets until 2030 (Ministry of Forest and Water Affairs, Republic of Turkey (MFWA), 2016). Afforestation by planting single, non-native species should furthermore be avoided, for the sake of biodiversity and resilience (Cowie et al., 2018; Schulze et al., 2020). Natural regeneration on abandoned fields would come at lower costs and has been found to be better for biodiversity, soil conditions and climate change resilience (Chazdon et al., 2020), while at the same time making the target more achievable. Almost all of Turkey’s forest increase over the last decades is due to natural regeneration on abandoned agricultural land (Atmiş and Günşen, 2018). However, the large increase of forest cover in the currently forest-poor Anatolia is unlikely to be achieved with natural regeneration only, as seed sources would be too far away. Assisted regeneration with deliberate planting of tree groups could be an alternative in areas where forests used to occur naturally (Chazdon et al., 2020), while in some regions, grassland restoration might be a more sensible policy (Veldman et al., 2015).

Compared to the business-as-usual scenario, we observe in the LDN scenario land sparing in terms of agricultural land use to make space for increasing forest areas. This is a direct result of the increased competition for land due to the need for counterbalancing the potential degradation of increasing food production. Land sparing can lead to increased competition between farmers and increased dependency on off-farm resources, such as inorganic fertilizers, to increase productivity (Kohler et al., 2018; Rey Benayas and Bullock, 2012). Agriculture is the main employer for the rural population in Turkey, which often has a low-level of education and off-farming employment (Aksakal et al., 2016). Following our results, many extensive small and family-owned farms would be lost due to intensification or afforestation. This could lead to more rural unemployment and migration from rural to urban areas (Kapović Solomun et al., 2018). Already in the last years, migration, mostly driven by economic reasons, has been an increasing issue in Turkey (Öztürk et al., 2018). The Turkish government has addressed this by subsidizing crop production and livestock farming (Gökbulak et al., 2018). This policy support would not be sufficient to limit future migration, if low intensity agricultural land is used for land degradation offsetting, and only high intensity agriculture remains. A people-centred restoration approach, taking local needs into account, can lead to more sustainable land use, while creating new opportunities to avoid and reverse poverty in rural areas (Mansourian et al., 2020). Future research could include participatory scenario development to consider the needs of local land users and respect local land tenure. Large scale tree planting in unsuitable habitats, like natural grasslands, can furthermore diminish ecosystem services, such as biodiversity or carbon storage and landscape planning should consider synergies with other policy priorities and national targets (Fleischman et al., 2020; Quatrini and Crossman, 2018).

4.2. LDN indicators and principles

Our results suggest that the SOC indicator mostly drives the observed land system projections in the LDN scenario. Through our sensitivity analysis with single indicators, we found that intensification of land systems decreased the SOC contents more often than it affects NPP or land cover. The effects of land use on SOC levels are not always well-known and depend also largely on precedent land cover and land use (Cha et al., 2020; Mayer et al., 2020). Furthermore, SOC stocks adapt rather slowly after restoration efforts while decreasing fast upon increased land management (Cha et al., 2020). Wind erosion is additionally depleting SOC stocks of land systems with a larger fraction of uncovered soil surfaces, such as intensive grazing systems (Chappell et al., 2019). More effort is required to support countries in monitoring changes in soil carbon stocks. Careful management and long-term monitoring is necessary to assess the success of restoration efforts. Additionally, although counterbalancing is pursued following the LDN bookkeeping approach, the carbon balance might be negative in the shorter term as a result of the large amount of land system changes.

Fertilizer application in intensive agricultural fields may result in an artificial increase of productivity, hence NPP, thereby masking land degradation (Nkonya et al., 2011) and is also used as a remedy against productivity decline caused by land degradation (Crossland et al., 2018). Nevertheless, increasing fertilizer use is not the optimal solution for pursuing LDN, as it can cause soil pollution and could lead to more land degradation in the long-term (Bajocco et al., 2012). Similarly, irrigation increased NPP values of annual cropland in most arid parts (Anatolia). However water scarcity is limiting the extension of irrigated areas in the Mediterranean without considerable improvements to irrigation efficiencies (Malek and Verburg, 2018). To exclude the effect of artificial modification of the NPP indicator, it could be considered with regard to the inputs, including fertilizer and water. When comparing the binary, single indicator tests for SOC and NPP with the respective numerical tests, less counterbalancing was required in the latter, as losses in land-based natural capital due to agricultural intensification required less afforestation compared to the binary tests. Our results confirm that the binary approach is more strict in terms of achieving LDN (Orr et al., 2017) and the concern that it could lead to marginal improvements of land counterbalancing areas of severe degradation, did not eventuate in our case study.

Our results showed that the implementation of the like-for-like principle better represents local characteristics and ensures a more equal distribution of losses and gains in land-based natural capital. On the other hand, it exacerbated competition between food production and land restoration, especially in the agriculture dominated region of Anatolia and resulted in a larger amount of land system changes. The representation of the like-for-like principle in our model does not fully follow the LDN framework. However, the LDN framework offers little guidance on this principle and a more strict and local implementation may limit the possibilities to counterbalance strictly, disabling the achievement of all objectives. Given the large competing claims that have driven our results, land use planning might need larger regions to accomplish the counterbalancing in being able to optimally use the differential capabilities across the landscape. When the like-for-like principle is applied in even smaller regions, or at the landscape scale it may further exacerbate competition due to the more restricted possibilities within smaller regions.

4.3. Conclusion

The scenario and simulation approach of this paper can help to identify potential consequences of LDN and demonstrates how pursuing LDN can be supported with land use modelling. Our projections should be considered as an exploration of possible implementation pathways instead of future predictions. Land use modelling can supplement other approaches when planning for LDN, such as the assessment of the current conditions of land, degradation drivers and affected stakeholders. Model-based exploration of LDN can provide valuable insight into what the implementation of LDN principles means in a dynamic land use change context. While LDN has so far been mostly implemented in small-scale projects, the intention is to achieve neutrality on a national scale and to strive for full counterbalancing of degradation globally. Our model simulations at the scale of a large country indicate that achieving LDN might require transformative changes in land systems and policy. The scale of counterbalancing under continuous growth of demands for land-based projects supports that LDN must also address the demand site. Lower demands by more sustainable consumptions can reduce the need for counterbalancing degradation and release pressure on land resources, enabling different LDN compliant solutions. Additionally, novel sustainable land management approaches to avoid degradation upon intensification can make the scale of counterbalancing more realistic. Land use modelling can provide a boundary object for discussing the different pathways of achieving land degradation neutrality and provides a virtual laboratory for testing the impact of different principles included in the LDN framework. Future work could include participatory scenario analysis to identify pathways that are more realistic and support the local community. This will not only support land use planning and LDN implementation strategies, but also aid a further refinement of the LDN principles in order to optimize outcomes.

Authorship_Statement

Katharina Schulze: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft; **Žiga Malek**: Conceptualization, Methodology, Resources, Supervision, Writing – review & editing; **Peter H. Verburg**: Conceptualization, Funding acquisition, Methodology, Software, Supervision, Project administration, Writing – review & editing

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.envsci.2021.06.024.

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