Received: 2 September 2022 | Revised: 9 January 2023 | Accepted: 7 February 2023

DOI: 10.1002/ldr.4645

RESEARCH ARTICLE

WILEY

An interactive system to map land degradation and inform decision-making to achieve land degradation neutrality via convergence of evidence across scales: A case-study in Ecuador

Ingrid Teich[1,2] | Nicole Harari[2] | Pablo Caza[3] | Juan Pablo Henao-Henao[1] | Juan Calles Lopez[1] | Eugenia Raviolo[1] | Ana María Díaz-González[1] | Hernán González[1] | Soledad Bastidas[1] | Cristian Morales-Opazo[1] | César Luis García[1]

[1]Food and Agriculture Organisation of the United Nations, Viale delle Terme di Caracalla, Rome, Italy

[2]Centre for Development and Environment (CDE), WOCAT, University of Bern, Bern, Switzerland

[3]Ministry of Environment, Water and Ecological Transition, Quito, Ecuador

Correspondence
Ingrid Teich, Centre for Development and Environment (CDE), WOCAT, University of Bern.
Email: ingrid.teich@fao.org

Funding information
Global Environment Fund

Abstract

One of the core challenges to achieve land degradation neutrality (LDN) is to spatially identify, and strategically prioritise, the areas to implement actions to avoid, reduce and reverse land degradation. To achieve this, a tool for a participatory and data-driven assessment considering both the biophysical and socio-economic dimensions of land degradation across scales was developed for Ecuador. In this paper, we present the methodology and results obtained, including the spatially explicit interactive tool developed to integrate indicators that support the scaling-up of sustainable land management (SLM). The process involved specialists from various national and international institutions, as well as decision makers from the public sector and other relevant stakeholders. Cloud computing allowed the integration of five main sources of data: (1) the results of a participatory land degradation assessment based on an expert knowledge questionnaire following the land degradation assessment in drylands (LADA) and world overview of conservation approaches and technologies (WOCAT) methodology; (2) the Hand-in-Hand Initiative Ecuador typology maps based on poverty and estimated agricultural potential and efficiency scores from household surveys; (3) National datasets on land cover and land use, soil properties, and hydro climatic indicators; (4) global satellite-derived LDN indicators, such as land productivity dynamics; and (5) documented SLM practices from WOCAT Global SLM Database. The tool is based on a Google Earth Engine application and allows decision makers to easily compare results and obtain statistics at different spatial scales and landscapes, including land use systems delimited by experts. It also includes a multi-criteria module to identify areas with specific characteristics to prioritise different types of interventions to achieve the Country's LDN targets. Convergence of local and global evidence allowed the identification of hotspots of degradation as well as areas of false positives/negatives—if only global or remote sensing indicators were considered. The participatory process contributed to strengthening multi-sector cooperation mechanisms and to guaranteeing ownership of the tool and the results. The system will support Ecuador's efforts to monitor and report progress towards LDN to the United Nations Convention to Combat Desertification. The system's code is shared as a repository at Earth Engine and can be adapted to and used by other countries and regions.

KEYWORDS
cloud computing, land degradation neutrality, land productivity, participatory participatory mapping, poverty, remote sensing

1 | INTRODUCTION

Mapping land degradation (LD) is a challenging but necessary task, particularly at large spatial scales (Gibbs & Salmon, 2015). The impacts of LD on ecosystem services as well as the drivers and processes involved are spatially diverse and change over time, and so does the social perception of the severity and effects of degradation. Therefore, it has been recognised that LD cannot be globally mapped by a single indicator or a combination of variables (Prince, 2016) and that a unique map cannot take into consideration all views or needs at global scale (Montfort et al., 2021). However, mapping LD is necessary to achieve land degradation neutrality (LDN), which is target 3 of the Sustainable Development Goal (SDG) 15 “Life on Land” (Jensen, 2022). LDN aims to preserve the natural capital provided by land, by avoiding, reducing and reversing LD (Orr et al., 2017). To reach a status of not net loss of productive land, it is necessary to estimate the effects of land use and counterbalance projected losses through the rehabilitation or restoration of areas of the same land type (Cowie, 2020). In this process, mapping and quantifying LD are crucial to spatially identify, and strategically plan actions to counterbalance LD, as well as to monitor and report progress towards LDN at landscape scale.

The United Nations Convention to Combat Desertification (UNCCD) is the custodian agency for SDG Indicator 15.3.1 (proportion of land that is degraded over total land area) and provides a methodological approach to map and quantify LD (Sims et al., 2021). SDG target 15.3 is closely related to strategic objective (SO) 1 of UNCCD 2018–2030 Strategic Framework, which aims at “…improving the condition of affected ecosystems, combating desertification/land degradation, promoting sustainable land management (SLM) and contributing to LDN”. To track progress towards SO 1 and SDG target 15.3, a set of three (sub)indicators were identified by country parties. These were defined as the trends in (1) Land cover, (2) Land productivity, and (3) carbon stocks aboveground and belowground. The metrics proposed for these indicators are land cover change, land productivity dynamics (LPD) and changes in soil organic carbon (SOC) stock.

Earth observation (EO) science provides key information to obtain these metrics and most countries rely on global products of satellite derived data for their estimation. However, the complexity of LD, including its intensity and driving forces cannot be completely captured by these three indicators and global assessments are difficult to interpret at local scale. Therefore, to strengthen interpretation of the LDN processes, UNCCD encourages countries to use meaningful national or sub-national datasets and knowledge together with a participatory approach to validate results from EO analysis (Sims et al., 2021). LD has been mapped at global, national, and local scales, through different approaches, including the use of experts´ opinion (e.g. Oldemann et al., 1990; Bot et al., 2000). This type of approach has advantages over using only satellite-derived data, since it provides a more comprehensive assessment that includes drivers and types of LD, as well as recommendations to apply SLM. However, they are subjective and qualitative and are often perceived as less reliable. Other limitations include not being globally consistent and combining actual and potential degradation. Satellite derived approaches to map LD are quantitative, readily repeatable, and globally consistent but also have serious limitations and can lead to a counterintuitive degradation assessment (Gibbs & Salmon, 2015; Yengoh et al., 2015; Sims et al., 2020). The integration of EO data with experts´ opinion through participatory processes that include local knowledge is, therefore, crucial in the process of LDN (García et al., 2019; Teich et al., 2019), as is considering the local context and the inclusion of socio-economic indicators. Process indicators that track measures taken along the LDN implementation pathway are also necessary to monitor progress towards LDN (Cowie et al., 2018). This requires identification of indicators of the enabling environment in terms of policies and institutions supporting LDN, land use planning, and monitoring systems for LDN.

In Ecuador, LD is a long-standing problem whose direct causes include deforestation and loss of native vegetation cover, overgrazing and unsustainable management of crops and pastures, urban development and infrastructure, and other causes related to mining and industrial activities and contamination of water resources. The country has been making important efforts to address these causes and the challenges related to achieving LDN. Ecuador, through the Ministry of the Environment and with the support of FAO, implemented the Project “Decision Support for Mainstreaming and Scaling up of Sustainable Land Management” (DS-SLM) to evaluate and map the status, trends, impact, causes, and effects of degradation at national level based on expert opinion (Liniger et al., 2019). In addition to the results of the participatory assessment of LD that resulted from this project, Ecuador has many outstanding national maps and monitoring systems, such as the Unified Environmental Information System (SUIA: Spanish acronym) of the Ministry of Environment, Water and Ecological Transition (MAATE: Spanish acronym), and the Agricultural and Public Information System (SIPA: Spanish acronym) of the Ministry of Agriculture and Livestock (MAG: Spanish acronym). However, Ecuador still has to set National Voluntary LDN targets and needs integrating the different existing sources of information to reliably map and assess LD at national scale, as many other countries do.

To contribute to the establishment of a comprehensive baseline, and support the process of setting LDN targets, an innovative tool for an evidence based and participatory assessment that includes both qualitative and quantitative indicators was developed for Ecuador. It allows the application of the principle of 'convergence of evidence' to map LD, by finding areas where particular core issues related to the biophysical and the socio-economic dimensions of LD simultaneously occur (Cherlet et al., 2018). This approach also allows the country to integrate and compare different sources and types of information to reach a 'most likely explanation', about the status of LD at a given location. The 'most likely explanation' can change in time as more reliable information becomes available. It simultaneously provides information on the effects, type, and causes of LD. When various maps that provide information on change of state, stress reduction, and process indicators are integrated, the identification of areas where the convergence of different issues related to LD co-occur, can provide key information and support decision making towards LDN. In this paper, we present the methodology and results obtained, including Ecuador's LDN Decision Support System (LDN DSS), a spatially explicit interactive tool developed to integrate indicators that support mapping LD and decision making, to progress towards LDN through a participatory process that involves decision makers from the public sector together with other relevant stakeholders. The workflow, the tool, and the codes developed are available and can be applied in different contexts and regions of the world to integrate, facilitate, and improve assessing, mapping, and achieving LDN.

2 | MATERIALS AND METHODS

2.1 | Interactive LDN decision support system

An interactive system to integrate data and support decision making was co-developed with national experts, stakeholders, and decision makers both in Spanish and in English. The system is based on cloud computing and is a Google Earth Engine (GEE) Application. GEE is a platform for Earth science data and analysis that provides access to a catalogue of satellite imagery and public geospatial datasets, and allows users to perform geospatial analyses using Google's Cloud and computational infrastructure (Mutanga & Kumar, 2019). The GEE App was built with the Earth Engine Code Editor at code.earthengine.google.com. The Earth Engine Code Editor is a web-based IDE for the Earth Engine JavaScript API. The code for the tool consists of two main scripts: the App script and the statistics calculation script. The statistics calculation script performs statistical computation using the Earth Engine ee.Reducer package over different relevant images. In order to offer a more fluid experience for the user, the computation to obtain statistics is done prior to the publication of the app for predefined areas (such as country, provinces, cantons, basins, sub-basins, mapping units, and land use systems). When this precalculation is done, statistics are added to each feature in the original feature collection assets as properties (columns) that are later queried in the app script. For user-drawn polygons, the calculation is done on the fly using the same script but it can take time and has limitations because it is a computationally demanding process. The system includes four main functionalities: (1) visualisation, comparison and calculation of statistics of relevant ld and additional indicators; (2) multicriteria analysis; (3) land cover transitions analysis; and (4) participatory mapping.

The layers incorporated in the system include the results of: (1) the participatory LD assessment of Ecuador carried out in 2018; (2) three socio-economic maps derived from the FAO Hand-in-Hand initiative; which include poverty, agricultural potential, and efficiency in Ecuador; (3) national datasets on land cover and land use and soil and hydro-climatic maps; (4) satellite derived Maps of LPD, Fire Recurrence and precipitation Trends for the period 2001–2020 developed for the country through cloud computing and other EO products; and (5) Ecuador's official SLM practices documented in WOCAT's Global SLM Database. These layers were selected due to their relevance and quality and their final selection was defined by a group of stakeholders, including experts from the Ministry of Environment, Water and Ecological Transition of Ecuador. The layers are described below:

2.1.1 | Layers derived from the participatory LD assessment of Ecuador

As a result of the DS SLM project, Ecuador applied the WOCAT-LADA-DESIRE mapping tool at national and subnational scale (Liniger et al., 2013), known as the mapping questionnaire (QM), which is in line with current FAO's "Guidelines for the National Assessment and Mapping of Land Degradation and Conservation" (Petri et al., 2019). Through the QM, different aspects of LD (extent, type, degree, causes, and impacts) and the actions to address degradation in terms of SLM are assessed by experts using a questionnaire. The database and outputs can be mapped to obtain an overview of LD and SLM in a landscape, country, or region. For this assessment, different land use systems (LUS) were defined and combined with administrative borders, obtaining 647 mapping units which were assessed by experts. The QM results included in Ecuador's LDN DSS are a selection of the whole dataset obtained through the QM, and include the following layers:

- *Degradation extent*: area affected by all degradation (percentage).
- *Degradation type*: main/dominant degradation type that affects one mapping unit. There are descriptions for 31 LD types grouped in 6 categories (FAO, 2011).

- *Degree of degradation*: intensity of the LD process, assessed using qualitative categories (light, moderate, strong and extreme).
- *Direct causes*: selection from a list of 60 types of drivers of LD, grouped in 12 categories (FAO, 2011).
- *Impact on ecosystem services*: the effect of LD on ecosystem services (ES) as defined from the Millennium Ecosystem Assessment (World Resources Institute, 2005), identified by experts from a list of 24 ES and 6 levels of impact (degrees).
- *Recommendations*: experts´ opinion on the best type of SLM intervention to combat LD in that mapping unit. Types are grouped into four categories: adaptation, prevention, mitigation, and rehabilitation.

2.1.2 | Socio-economic layers derived from FAO Hand-in-Hand Initiative

Hand-in-Hand is FAO's flagship initiative to eradicate poverty (SDG1) and end hunger and all forms of malnutrition (SDG2) by accelerating agricultural transformation and sustainable rural development (FAO, 2019). In Ecuador's LDN DSS, the layers used for the construction of typology maps under the framework of the implementation of the aforementioned initiative in Ecuador were included. The resulting maps are available at FAO's Hand-in-Hand Geospatial platform (FAO, 2022a) where the full methodology for the elaboration of these maps is described. The included layers are:

- *Rural poverty*: Based on rural poverty maps from the Ministry of Livestock and Agriculture (MAG), this layer illustrates poverty at the canton level using household surveys on Unmet Basic Needs and Consumption.
- *Agricultural potential*: the maximum achievable income given the observed market prices, climatic conditions, and land uses.
- *Technical efficiency*: Observed income given the current conditions, as a proportion of the maximum achievable income (potential).

The last two layers were estimated by the Hand-in-Hand initiative using data from national surveys on agricultural production that provide information on diverse variables including household income, market prices, agro-ecological zones, climatic variables, market access, technology adoption, access to extension services, and agricultural assets. The three layers correspond to categorical variables with three levels: low, moderate, and high.

2.1.3 | Layers derived from national datasets

Ecuador has a long-standing tradition in producing land cover maps and other spatial datasets using an inter-ministerial task force and making the products available via different spatial data infrastructures (SDI). For this publication, national data were accessed using the SDI of Ecuador's Ministry of Water, Environment and Ecological Transition (MAAE), (2022). Several layers of key information, to understand LD processes and correlate with indicators from other sources, were produced by national teams and published as official datasets. The national datasets integrated into Ecuador's LDN DSS are:

- *Administrative borders*: national, provincial, and cantonal borders were key variables to derive statistics and aggregate information in administrative units that coincide with land management decisions at political level.
- *Land cover*: National land cover data for the years 1990, 2000, 2008, 2014, and 2018 from the official MAAE SDI in shape format were converted to a 30 m resolution raster. All maps had a level 2 legend with 16 categories, with the exception of 2018, which had 12 categories, since the different types of agricultural categories in 2018 were not subdivided. An analysis of the main degradation processes due to land cover change was performed and categories were grouped into 8 classes: native forest, planted forests, grassland, paramo, cropland, artificial, other land, and water bodies, which can also be grouped into the UNCCD/IPCC categories (Table 1). This dataset was integrated into many sections of the LDN DSS including the land cover transition toolbox (for analysing LC change over different periods).
- *Soil organic carbon*: The second edition of the SOC map (MAG et al., 2021) was provided by the government. It was produced at 1 km resolution by Ecuador experts of an inter-ministerial team led by the Ministry of Agriculture and Livestock of Ecuador (MAG) with support from FAO and the Global Soil Partnership (FAO, 2017).
- *Water basins and sub-basins*: Data were obtained from the official MAAE SDI on hydro-geographic units (level 3) and used to define main water basins. Sub-basins required a combination of Level 4 and 5 units in order to have more homogenous subdivisions, due to the uneven size of the level 3 basins.
- *Biogeographical units*: Data were obtained from the official MAAE SDI on the National Classification System for continental ecosystems of Ecuador (MAAE, 2013), and subdivided into 15 biogeographical sectors. These sectors represent areas at landscape scale (10–200 km) that share common bioclimatic, physiographic, and geomorphological characteristics, as well as vegetation associations and pools of species including endemism.
- *Protected areas*: All official protected areas mapped by the National System of Protected Areas were included.

2.1.4 | Layers derived from EO data

Through the analysis of satellite images, diverse products were developed for Ecuador's LDN system. These are based on open and globally available data and the codes developed for their creation are also publicly available. The code for the calculations is available both in the system's dataset description and/or in FAO (2022b) as GEE Java scripts. The goal of these indicators is to provide key information to understand the intensity and underlying pressures of LD, and to apply

TABLE 1 Re-categorisation of land cover classes from national land cover datasets.

Level 2 category	National categories (1990, 2000, 2008, 2014)	National categories (2018)	LDN DSS code	LDN DSS categories	UNCCD reporting categories
1	Native forest	Native forest	1	Native forest	Forest Land
2	Planted forest	Planted forest	2	Planted forests	Forest Land
3	Shrubland	Shrubland	3	Grassland	Grassland
4	*Páramo*	*Páramo*	4	*Páramo*	Grassland
5	Grassland	Grassland	3	Grassland	Grassland
6	Annual cropland	Agropecuary mosaic	5	Cropland	Cropland
7	Semi-permanent cropland	Agropecuary mosaic	5	Cropland	Cropland
8	Permanent cropland	Agropecuary mosaic	5	Cropland	Cropland
9	Grass	Agropecuary mosaic	5	Cropland	Cropland
10	Agropecuary mosaic	Agropecuary mosaic	5	Cropland	Cropland
11	Populated area	Populated area	6	Artificial	Artificial
12	Infrastructure	Infrastructure	6	Artificial	Artificial
13	Bare areas	Bare areas	7	Other lands	Other lands
14	Glaciar	Glaciar	7	Other lands	Other lands
15	Natural water bodies	Natural water bodies	8	Water bodies	Water bodies
16	Artificial water bodies	Artificial water bodies	8	Water bodies	Water bodies

the principle of convergence of evidence to inform decision making processes.

- *Land Productivity Dynamics Map* (*LPD*): is one of the three main LDN indicators and was the most informative one according to previous UNCCD reporting exercise (PRAIS 3). Its calculation is based on the analysis of time series of vegetation indices derived from remote sensed imagery, which are a proxy of the total above-ground net primary production (NPP). The LPD indicator summarises changes in ecosystem functioning and reflects changes in the productive capacity of the land. A decrease in the productive capacity of land indicates degradation, so usually (but not necessarily), areas with declining trends in LPD are considered degraded. The algorithm used to calculate LPD in Ecuador for the 2001–2020 period was developed by FAO and WOCAT and is based on the methodology applied in the *World Atlas of Desertification* (Cherlet et al., 2018; Ivits & Cherlet, 2013; Ivits et al., 2013) which was updated using GEE (FAO, 2022b). Time-series of annual NDVI from MODIS MOD13Q1 v6 were analysed using a linear regression and the multi temporal image differencing (MTID) algorithm, at 250 m resolution. The resulting trends were classified according to their performance by comparing a baseline of 15 years and the current state, considering and initial biomass.
- *Fire recurrence*: The spatio-temporal pattern of fires provides key information to better understand plausible underlying causes of LD, and inform land use planning processes to achieve LDN. The fire hotspots yearly recurrence for the 2001–2020 period was estimated as the proportion of years with burning over a period of 20 years. Values near to 1 indicate at least one burning event every year whereas values of 0.05 indicate one year with burning during the 20-year period. The index was calculated using data of the Fire Information for Resource Management System (FIRMS) database (NASA, 2022), and combined with the MCD64A1 version 6 burnt area dataset (Giglio et al., 2015), using GEE computing power.
- *Precipitation trends*: Climatic information is key to understand possible causes of observed changes in land productivity, so maps of annual precipitation trends for the period between 2001–2020 were produced for Ecuador using the non-parametric Mann-Kendall test and 3 global databases: TerraClimate (Abatzoglou et al., 2018), ERA5 (Hersbach et al., 2018), and Global Precipitation Mission (GPM) (Huffman et al., 2019). Trends were classified as not significant, positive, or negative and the results obtained with each dataset were compared to show areas of agreement by calculating an index that varies from −3 to 3 indicating the level of confidence in both types of trends (negative or positive).
- *Mountain and topography layers*: Mountain layers were sourced from the Global Mountain Explorer (Kapos et al., 2000) which follows the mountains definition adopted by the UN and the Global Mountain Partnership. The Topography layer was created in GEE using NASA's Shuttle Radar Topography Mission (SRTM) Digital Elevation Model processed at 30 m resolution to create a 3D visualisation of the terrain, by rendering a hill-shade with artificially coloured height levels. Topography layer can be used for visual interpretation of the landscape.
- *Key Biodiversity Areas* (*KBA*): This map was produced by the KBA Partnership (BirdLife International, 2020) and shows the location of areas that significantly contribute to the persistence of biodiversity at global scale.

2.1.5 | Sustainable land management data

The WOCAT Global SLM Database (WOCAT, 2022) is recommended by the UNCCD as the primary dataset to report the best SLM practices. Ecuador's SLM practices were included in the LDN DSS, including (1) technologies, which are land management practices that control LD and enhance productivity and/ or other ecosystem services; (2) approaches, which are defined as 'the ways and means used to implement an SLM Technology, including the stakeholders involved and their roles; and (3) UNCCD practices (best practices in SLM previously documented through the UNCCD PRAIS reporting system).

- *SLM practices*: A total of 60 points were included corresponding to the reported locations where SLM technologies and UNCCD practices documented in the WOCAT SLM database were applied in Ecuador (https://qcat.wocat.net/en/wocat/list/?q=ecuador&type=wocat). Each SLM practice (point) can be queried by clicking on it to generate a short description and a link to its full documentation.

2.2 | Data integration and analysis

A multicriteria analysis and a land cover transitions analysis at different spatial scales (national, canton and LUS) were performed as an example of the capacities of the LDN DSS to support decision making processes to achieve LDN. All the maps, charts, and statistics included were produced automatically by Ecuador's LDN DSS with only a few clicks. No GIS software was used to obtain the results and maps at national and subnational scale. To combine and compare indicators, the multi-criteria toolbox was used. It offers two options: simple (only allows users to combine two layers: land cover and LPD) and advanced (allows combining all layers available in the tool). Results consist of a map that shows the areas (pixels) that meet all the criteria selected by the users, as well as the estimation (in hectares) of the area. Charts and statistics combining land cover, LPD, and SOC data are also obtained for any spatial unit. To use this toolbox, users select the categories they are interested in and click Run, which allows them to map areas where, for example, accumulated evidence that certain core issues related to LD co-exist. For the land cover transition analysis, the tool enables users to select the initial year and calculates land cover change metrics until the latest year with land cover data (2018). Results are shown in maps of gains or losses, bar charts of land cover change, and tables with the estimation of areas that underwent different land cover transitions.

3 | RESULTS

3.1 | Ecuador LDN DSS

Ecuador's LDN DSS was published and is accessible from a specific URL (https://wocatapps.users.earthengine.app/view/ldn-ecuador). It is not required to have an account to access the system. Ecuador's LDN DSS was used by experts and non-experts, including decision makers, and their feedback and suggestions were incorporated. The App script was structured in sections to facilitate the organisation of the code (about 2800 lines of code) where the ui components were created and the interactions between them and with the user were defined. The source code containing the data layers is published as a public repository for anyone to use and modify at https://code.earthengine.google.com/?accept_repo=users/wocatapps/Ecuador (GEE users); at https://earthengine.googlesource.com/users/wocatapps/Ecuador (Git users) and at the Zenodo open repository (García et al., 2022).

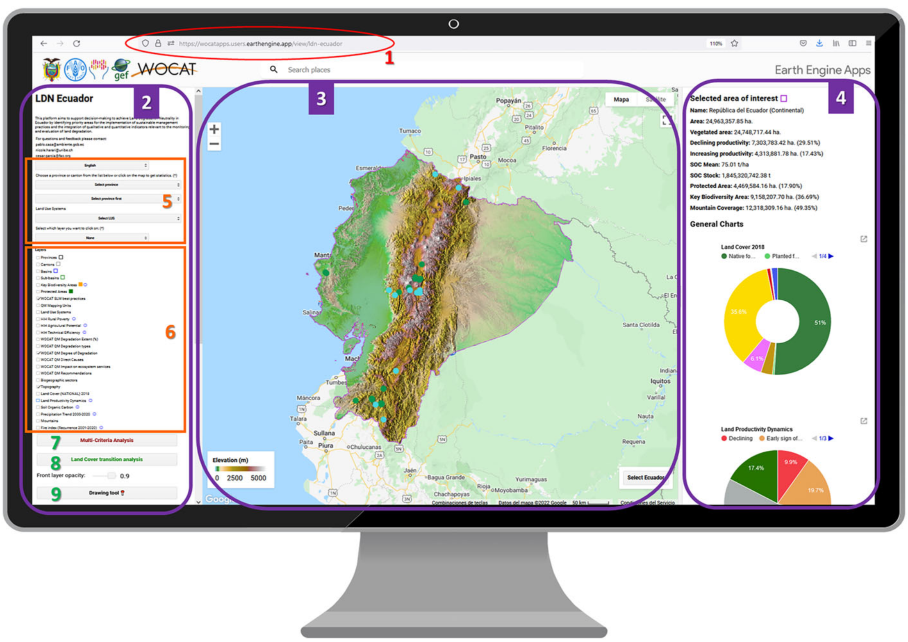

FIGURE 1 General view and main components in Ecuador's LDN DSS framework: (1) URL to access the system; (2) Layers and tools panel; (3) Map view panel; (4) Statistics and chart panel; (5) Section where users can choose Language and query areas from Drop-Down Menu or on-Click function; (6) Layers; (7) Multi-criteria Analysis Toolbox; (8) Land Cover Transition Analysis Toolbox; (9) Drawing Toolbox. [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 2 HiH typologies in Ecuador and associated recommended interventions adapted from Maruyama et al. (2018).

Typology	Recommended intervention
High poverty and low potential	Long-term investments in agriculture: Research and development and significant investments in infrastructure Short-term investments for social protection: assistance programs such as conditional cash transfers and investments in human capital
Moderate poverty and low potential	
Low poverty and low potential	
High poverty, high potential, and low efficiency	Short-term investments in agriculture: • Promote market access, reduce costs and improve roads and price information systems • Improve access to supplies and extension services • Generate innovative and inclusive financial instruments to allow savings from harvest income and invest in production • Generate and strengthen credit and insurance mechanisms to increase capital, adopt new technologies, and mitigate risks • Strengthen institutions to better access to markets for small farmers • Invest in small and medium-scale productive infrastructure (e.g. irrigation, water management projects, land management projects)
Moderate poverty, high potential, and low efficiency	
Low poverty, high potential, and low efficiency	
Low poverty, high potential, and high efficiency	Short term investments in agriculture: • Generate mechanisms for reaching international markets (increase exports) • Promote certification schemes to obtain higher income from agricultural production (e.g. environmental and health friendly production labels. Participatory guarantee systems) • Promote financial inclusion to allow higher returns on savings and credits to expand farm and non-farm businesses

The layout is structured in three main panels: (i) the layers and tools panel, where users interact and define the spatial units they would like to query (whole country, province, canton, land use system, QM mapping unit, basin, sub-basin or biogeographic unit); (ii) the Map View Panel, where the maps are shown; and the (iii) statistics and charts panel, where summary statistics and charts appear according to the spatial selected by the user (Figure 1). All tables and charts can be downloaded as .png and .csv files.

3.2 | Convergence of evidence across scales to support decision making to achieve LDN

As described above, the Ecuador LDN DSS system includes various layers, including rural poverty, agricultural potential, and efficiency for different territories in Ecuador. These maps were included to consider socioeconomic variables for decision making. The combination of these three layers (rural poverty, agricultural efficiency, and potential) allows the classification of territories into different classes (typologies) in FAO's Hand-in-Hand platform. This approach allows the differentiation and prioritisation of interventions and investments so that their impacts are higher in reducing poverty and enhancing rural productivity (Table 2). Combining these layers with biophysical variables such as land cover, LPD and/or SOC provides even more valuable information to spatially identify, and strategically prioritise the areas to implement actions to achieve LDN, a purpose that goes beyond reporting to UNCCD. As a result of the multicriteria analysis, it was possible to estimate and locate those croplands with declining or stressed LPD, where rural poverty is high, agricultural potential is high but agricultural efficiency is low (Figure 2). At national level, there are 130,400 ha with these characteristics. Following recommendations provided in Table 2, it would be recommended to make short-term investments in agriculture, such as strengthening

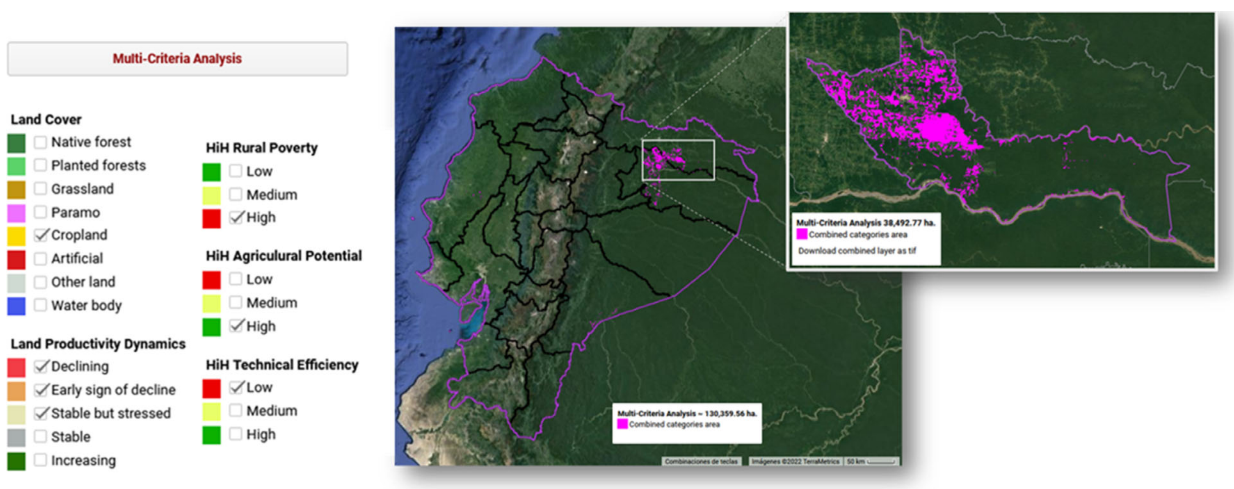

FIGURE 2 Results of a combination of 5 maps at national and subnational level using the multi-criteria toolbox of Ecuador LDN DSS. Areas that meet the criteria selected (croplands with declining or stressed productivity, high rural poverty and high agricultural potential but low agricultural technical efficiency) in Ecuador and in Shushufindi Canton are shown in pink. Black and grey lines represent province and canton borders, respectively. [Colour figure can be viewed at wileyonlinelibrary.com]

institutions for better access to markets for smallholder farmers and investing in small and medium-scale productive infrastructure (e.g. irrigation, water management projects, and land management projects).

The areas that meet these criteria in Ecuador are mostly located in the provinces of Orellana and Sucumbio, in the north of the Country. Within Sucumbio province, in the canton of Shushufindi, there are approximately 38,500 ha (15% of its territory) with these characteristics. A deeper analysis with the Land Cover Transition toolbox shows that these areas have undergone major land cover changes since 1990, particularly due to the conversion from native forests to croplands. According to the LDN DSS, in Shushufindi, there has been a net loss of approx. 56,000 ha of native forests since 1990 and a net gain of approx. 55,000 ha of croplands (Figure 3).

According to the LPD analysis at canton level, in Shushufindi, there are 89,000 ha with early signs of decline or declining land productivity. These areas represent approximately 37% of its territory. When the distribution of LPD categories for the different types of land cover is analysed, it is clear that the main land cover of the canton (native forests and croplands) is far from achieving neutrality, with more than 30% declining and less than 3% improving (Figures 4 and 5). This agrees with the expert assessment, according to which most of the area of the Canton (154,000 ha; 64%) was classified as suffering from severe or extreme LD (Figure 5).

When the maps derived from the QM are analysed in Shushufindi Canton, there is a particular area that meets the chosen criteria (croplands with declining or stressed LPD where rural poverty is high, agricultural potential is high but agricultural efficiency is low) that stands

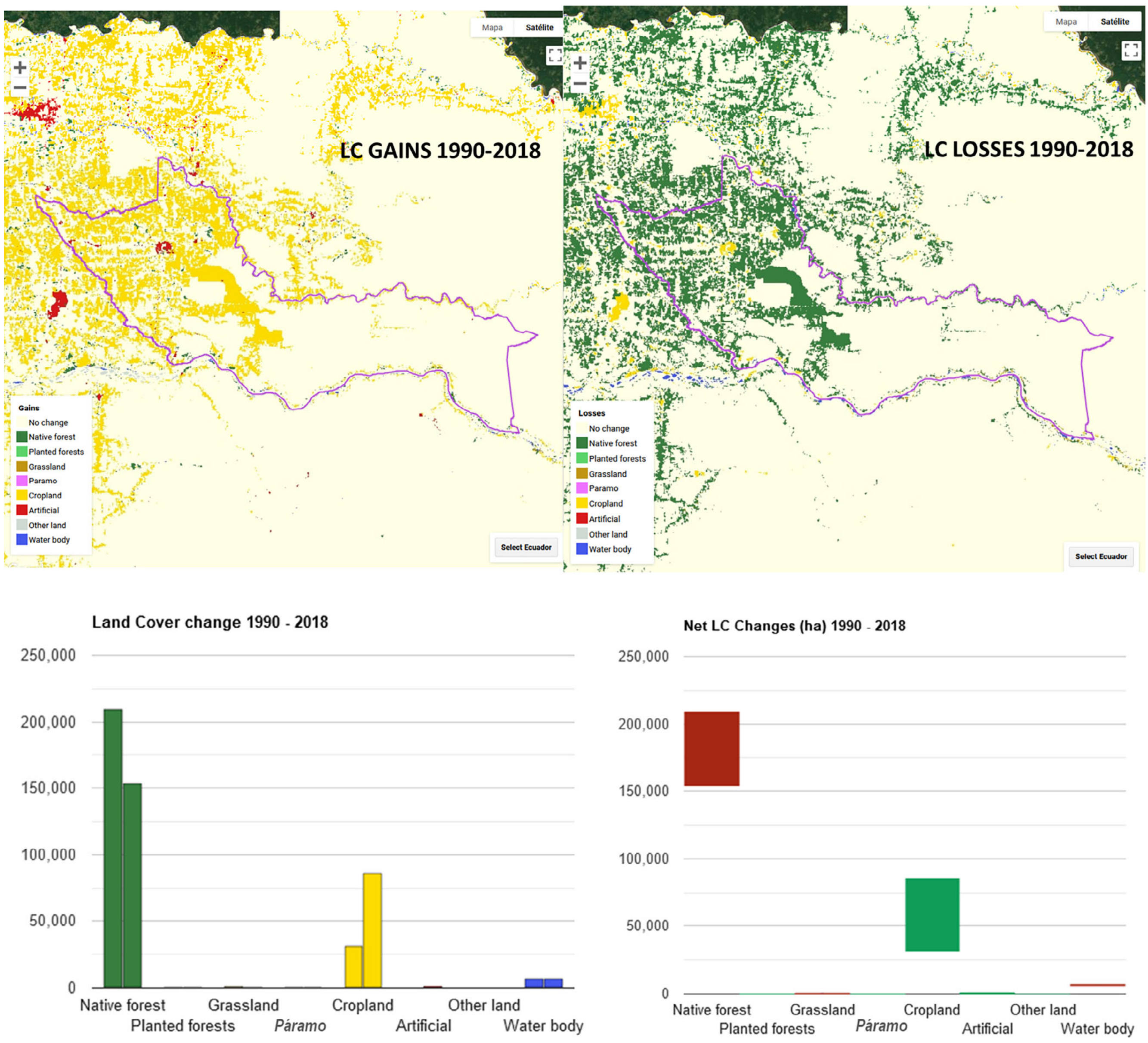

FIGURE 3 Results of the Land Cover Transition toolbox at canton level (pink polygon corresponds to Shushundi Canton), using national land cover maps for the period 1990–2018. Resulting maps of land cover gains and losses (above) and charts provided by the LDN DSS for any chosen period and study area (below) are shown. [Colour figure can be viewed at wileyonlinelibrary.com]

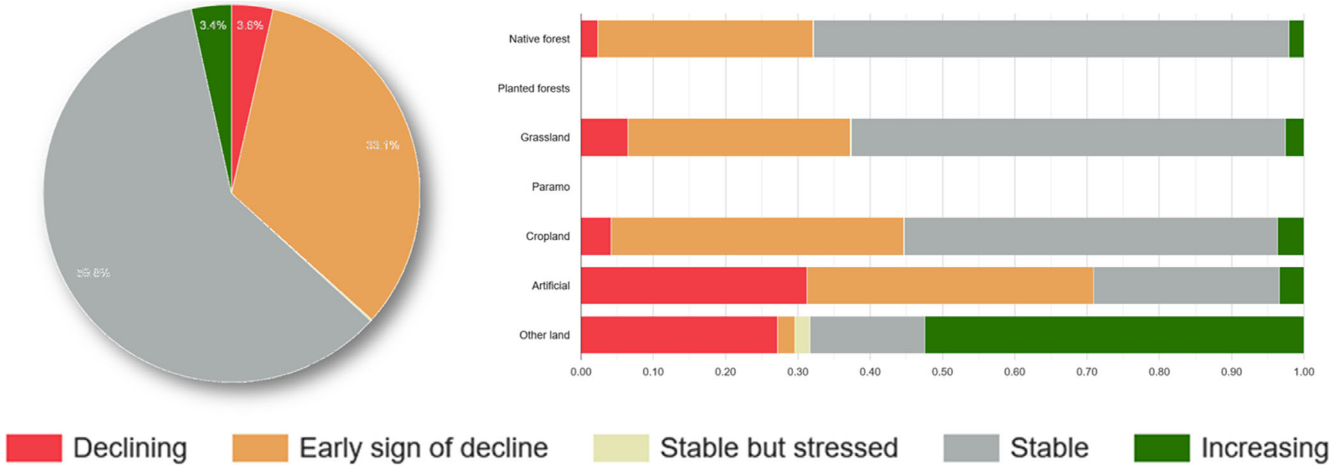

FIGURE 4 LPD statistics for the period 2001–2020 and LPD distribution by land cover classes for Shushufindi Canton as provided by Ecuador LDN DSS. [Colour figure can be viewed at wileyonlinelibrary.com]

out from the rest (Figure 5). This area corresponds to a particular land use system: "african palm oil plantations". Almost all plantations of oil palm are located in areas which were converted from tropical moist forests. The demands of palm oil are projected to increase substantially in the future and the current rate of conversion of forests to plantations, as well as the projected in the future, threatens biodiversity (Vijay et al., 2016). According to mapping experts, this mapping unit demonstrates a strong degree of degradation, with an impact on productive ecosystem services. The main cause of LD in this QM mapping unit is land management and the recommended type of intervention to combat LD in that mapping unit was Mitigation, to reverse LD. When the high-resolution images are analysed, it is clear that the magnitude of the land cover change due to the expansion of palm oil cultivation constitutes a major degradation process in Ecuador (Figure 6). According to the LUS map, there are 347,600 ha that correspond to the african oil palm plantation LUS in Ecuador. In this particular area (Shushufindi Canton), it would be regarded as a degraded area following the LDN "One Out All Out" (1OAO) principle, because LPD trends are negative, in agreement with expert opinion. However, at national level, according to Ecuador LDN DSS multicriteria analysis, there are 46,650 ha of oil palm LUS that correspond to improving LPD but that, according to experts, have either a severe or strong degree of LD. These areas are mostly located in the Northeast of Ecuador in Esmeraldas Province. These areas were identified as potential false positives.

4 | DISCUSSION

Mapping temporal and spatial processes, such as LD, is challenging but the results presented in this case study show that contemporary EO data and their processing capability in powerful cloud processors such as GEE facilitates the application of the principle of convergence and, therefore, improves the LD mapping results by facilitating a more comprehensive assessment. However, verification at field scale and through experts' consultations to validate remotely sensed indicators remains crucial. Bottom-up approaches that involve participatory mapping with land users and specialists are key to select the most suitable methodologies and meaningful results. The same EO data can produce different results, depending on the algorithms and methodologies used for its analysis (Teich et al., 2019), stressing the relevance of considering different sources of information, such as experts' knowledge (García et al., 2019). In addition, understanding the local context for the interpretation of maps contributes to the identification of false negatives and positives (Sims et al., 2020). In Ecuador, the LDN DSS is currently being used to map not only hotspots of degradation but also false positives and negatives for PRAIS4 UNCCD reporting process. According to the analysis performed, non-native tree species invasion of biodiverse grasslands and wetlands or their afforestation could be the reason for a high proportion of false positives. The tool allowed decision-makers in Ecuador to easily compare results and obtain statistics at different spatial scales and landscapes, according to their needs. The multi-criteria module was useful to identify areas with specific characteristics, to prioritise different types of interventions to achieve LDN using the principle of convergence of evidence. The participatory processes contributed to strengthening multi-sector cooperation mechanisms and to guarantee ownership of the tool and the results. This approach has already been adapted for other countries in Latin America, Central Asia, and Europe with similar results (FAO, 2022b).

The use and integration of national maps represented a significant comparative advantage for LDN decision making in comparison with the default use of global data sources. Limited availability of national information has led to the use of default datasets provided for LDN target setting by UNCCD in most countries (Gilbey, Davies, et al., 2019; Gilbey, Davies, et al., 2019). However, in countries where relevant national information is available, such as Ecuador, it remains a challenge to integrate it to other global datasets. In Ecuador, LC and SOC were modelled and ground-truthed by national teams, thus ensuring accuracy and local representativeness. In addition, national

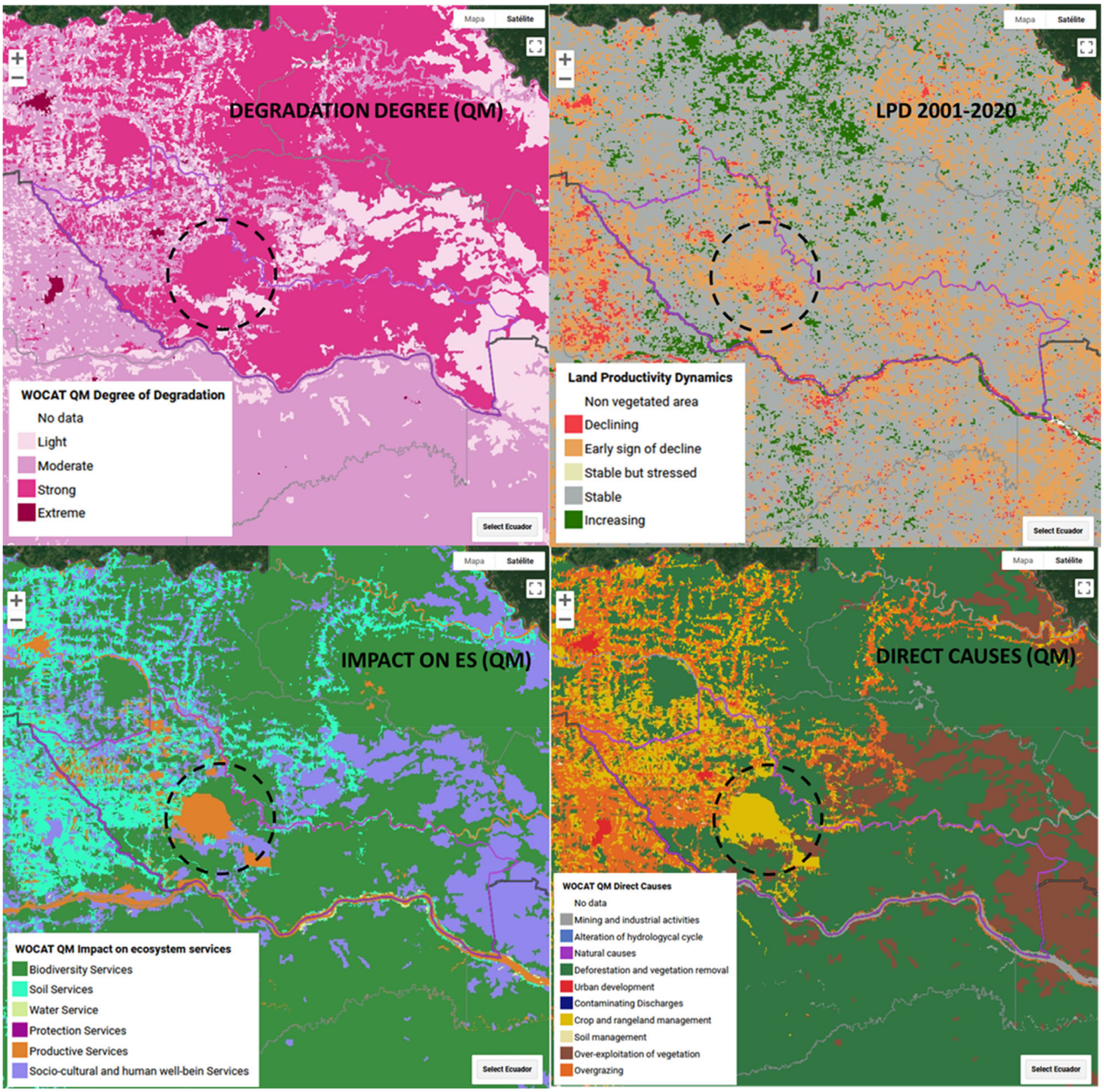

FIGURE 5 Land degradation maps of Shushufindi Canton and surroundings in Ecuador obtained by expert knowledge through the QM methodology (LD degree, impact on ES and direct causes) and satellite derived LPD for 2001–2020. The black circles indicate the location of a particular land use system: african oil palm. [Colour figure can be viewed at wileyonlinelibrary.com]

spatial units (polygons) provided better ways of integrating the spatial information in meaningful management units for decision making. While administrative borders are key for decision makers, other natural borders may be used in an LDN decision support system to evaluate neutrality, and assess gaps and issues in specific sectors of the country. For Ecuador LDN DSS, river drainage areas and the biogeographical sectors were selected by experts as the most significant. Drainage basins represent areas where the water mostly moves from the sources to the outlet, transporting energy, nutrients, sediments, pollutants, etc. They normally exhibit a mosaic or combination of different land uses that share a common biophysical border which makes them ideal for applying the landscape approach required in LDN (Cowie et al., 2018).

To achieve LDN, it is necessary to enhance productivity and improve farmer incomes by promoting evidence-based investments in agri-food systems that can lead rural households out of poverty in targeted territories. Socio-economic information provides clear opportunities to further understand drivers and impacts of LD, build synergies, and avoid trade-offs between SDG 15 and other objectives such as SDG 1 of no poverty and SDG 10 for reduced inequalities (Pradhan et al., 2017). In particular, rural poverty is a crucial indicator to prioritise territories, investments, and interventions to achieve LDN and contribute to the reduction of poverty. Also, estimations of the agriculture potential and current technical efficiency provide useful information to optimise investments, and add crucial information for the analysis of 'land sharing' versus 'land sparing scenarios. Applying

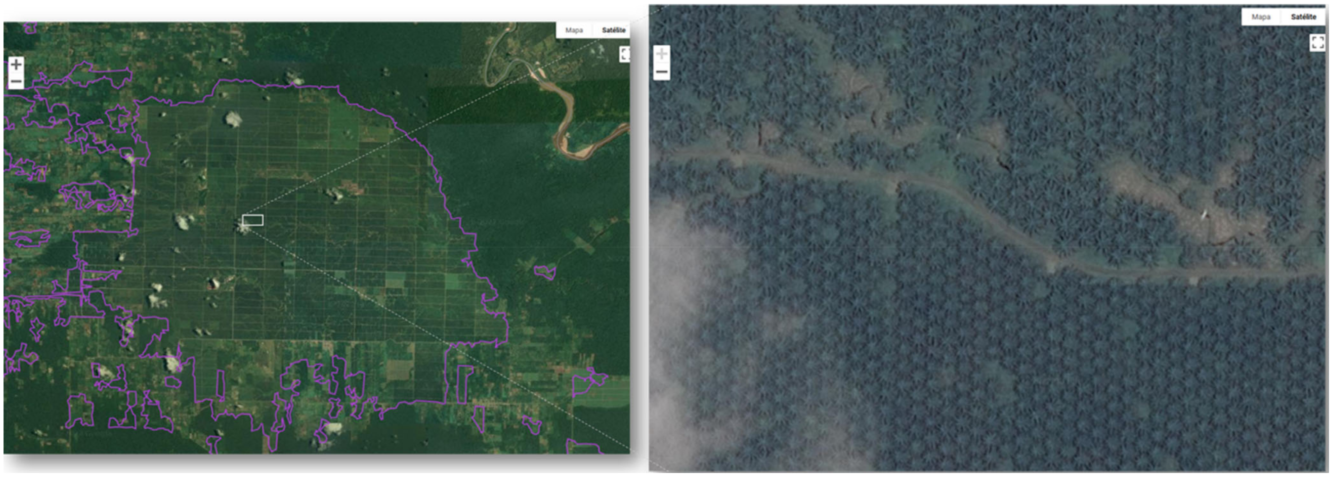

FIGURE 6 High resolution images of the selected african oil palm LUS in Shushufindi Canton, Ecuador. [Colour figure can be viewed at wileyonlinelibrary.com]

the principle of convergence of evidence also facilitates creating synergies with other SDG 15 targets. In addition to socio-economic data, Ecuador LDN DSS includes maps of mountain areas and key biodiversity areas. Mountain areas hold unique ecosystems that supply services of extreme importance for Ecuador. These areas are particularly fragile due to their environmental and topographic characteristics and such vulnerability to erosion and degradation is aggravated by climate change. Considering mountain areas and KBAs when planning interventions, creates an opportunity to accelerate synergies with other targets of SDG 15 and the three Rio Conventions by focussing efforts in areas that maximise the positive impacts to conserve biodiversity and mountain ecosystems (SDG 15.4).

Consensus mapping, both in the statistical and participatory sense, contributes to better knowledge, enhanced awareness, and well-informed strategic decisions. Successful and sustainable use of EO data and knowledge platforms by decision makers involves medium/long term processes with all level stakeholders and includes discussions, negotiations, capacity building, and adaptation of the methodologies to the end users' needs. Conclusions derived from the convergence of evidence approach are intended to be flexible in order to consider the different perceptions of LD (Crossland et al. 2018) and needs of stakeholders. The LDN DSS enables users to apply this concept and its flexibility. The co-development of the LDN DSS with government officers and experts was in itself an activity for the development of national capacities that strengthened the science policy interface.

5 | CONCLUSION

Cloud computing and EO data facilitate the implementation of the principle of convergence of evidence to map LD, as demonstrated in Ecuador. To effectively monitor LD and SLM at national and subnational scale, it is necessary to combine different types of indicators, including global products as well as national systems and indicators. Data transparency and knowledge sharing were crucial for integrating and using available resources, particularly national indicators. The LDN DSS developed for Ecuador represents a flexible tool for decision making and resource allocation that has already been tested and adapted in other countries and contexts to support achieving LDN. Any LDN programme or project should reserve/invest enough resources to guarantee a participatory process for the generation and co-development of sustainable tools and results.

ACKNOWLEDGEMENTS

This paper builds on the efforts of multiple initiatives, institutions and stakeholders at national and international scale. At the broadest level, the authors would like to thank the development of the GEF financed project "Decision support for Mainstreaming and Scaling Up of Sustainable Land Management" and FAO's Hand-in-Hand initiative whose results in Ecuador allowed the gathering of baseline data and results for the creation of the interactive system on which this paper is based. More specifically, the authors would like to thank all the efforts at the national level from the Ministry of Agriculture and the Ministry of Environment whose personnel and contributions were essential for the successful development of the aforementioned initiatives. Open access funding provided by Universitat Bern.

DATA AVAILABILITY STATEMENT

The data and codes that support the findings of this study are openly available in Zenodo at https://doi.org/10.5281/zenodo.6348037, reference number 6348038.

ORCID

Ingrid Teich https://orcid.org/0000-0002-7305-2923
Nicole Harari https://orcid.org/0000-0002-3730-5030
Ana María Díaz-González https://orcid.org/0000-0002-5452-1851
César Luis García https://orcid.org/0000-0001-8310-753X

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How to cite this article: Teich, I., Harari, N., Caza, P., Henao-Henao, J. P., Lopez, J. C., Raviolo, E., Díaz-González, A. M., González, H., Bastidas, S., Morales-Opazo, C., & García, C. L. (2023). An interactive system to map land degradation and inform decision-making to achieve land degradation neutrality via convergence of evidence across scales: A case-study in Ecuador. *Land Degradation & Development*, 1–13. https://doi.org/10.1002/ldr.4645