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Medium- (MR) and Very-High-Resolution (VHR) Image Integration through Collect Earth for Monitoring Forests and Land-Use Changes: Global Forest Survey (GFS) in the Temperate FAO Ecozone in Europe (2000–2015)

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Abstract: Monitoring of land use, land-use changes, and forestry (LULUCF) plays a crucial role in biodiversity and global environmental challenges. In 2015, the Food and Agriculture Organization of the United Nations (FAO) launched the Global Forest Survey (GFS) integrating medium- (MR) and very-high-resolution (VHR) images through the FAO's Collect Earth platform. More than 11,150 plots were inventoried in the Temperate FAO ecozone in Europe to monitor LULUCF from 2000 to 2015. As a result, 2.19% (VHR) to 2.77% (MR/VHR) of the study area underwent LULUCF, including a 0.37% (VHR) to 0.43% (MR/VHR) net increase in forest lands. Collect Earth and VHR images have also (i) allowed for shaping a preliminary structure of the land-use network, showing that cropland was the land type that changed most and that cropland and grassland were the more frequent land uses that generated new forest land, (ii) shown that, in 2015, mixed and monospecific forests represented 44.3% and 46.5% of the forest land, respectively, unlike other forest sources, and (iii) shown that 14.9% of the area had been affected by disturbances, particularly wood harvesting (67.47% of the disturbed forests). According to other authors, the area showed a strong correlation between canopy mortality and reported wood removals due to the transition from past clear-cut systems to "close-to-nature" silviculture.

Keywords: land-use change monitoring; forest monitoring; disturbance monitoring; temperate FAO ecozone; Collect Earth platform; Global Forest Survey

1. Introduction

Monitoring of land use, land-use changes, and forestry (LULUCF), as well as their disturbances, plays a crucial role in the response to global environmental challenges such as climate change (CC) mitigation and diversity conservation. LULUCF can disturb the biosphere–atmosphere exchange of carbon, water, and energy fluxes, can modify the ozone concentration [1], or can become a driving force of land and biodiversity degradation [2]. In this regard, land-cover disturbances associated with extreme events and CC, such as wildfires and insect outbreaks, can lead to carbon storage losses in a feedback pattern [3]. Therefore, land-cover disturbances, land-use changes, and CC are interrelated [4]. Forest mitigation capacity has been specially recognized in the second commitment period of the Kyoto Protocol and the Paris Agreement on CC [5] because it involves relevant carbon storage. National and international carbon reporting systems require terrestrial assessment systems such as forest inventory data combined with carbon estimation methods [6]. In addition, LULUCF inventory data play a crucial role in biodiversity assessment and ecosystem conservation [7].

LULUCF patterns and cause–effect processes are not fully defined in Europe since most studies of landscape consider medium-term timescales and local spatial scales. Moreover, most of the studies analyzed only one case study area and one spatial scale, among other factors. However, LULUCF are compromising the landscape's environmental sustainability and its capacity to deliver ecosystem services [8]. Furthermore, LULUCF datasets are critical for integrating socioeconomic, political, cultural, and environmental factors that influence land-use decision making [9].

Therefore, updated LULUCF resource inventories and indicators are required, i.e., forest extent and stock species composition [7,10]. This information is especially necessary at the forest level to encourage pan-European harmonization [11]. Additionally, forest-type monitoring may address other forest biodiversity conservation issues, e.g., the level of protection/landscape fragmentation of different forest types [12]. Therefore, accurate LULUCF monitoring, at appropriate scales and during significant periods, is essential to understand impacts on biodiversity, landscape ecology, and/or CC predictions [13].

Remote sensing performs a significant role in monitoring LULUCF [14]. The 30 m pixel Landsat image series has been a reference source for several land-cover mapping products at different scales. Thus, in the European Union (EU), from 1985, the European CORINE Land Cover (LC) project, based on photointerpretation of false-color Landsat scenes, has been the standard pan-European land monitoring system [15]. More recently, GlobeLand30, based on a pixel-object-knowledge operational approach over Landsat images, has provided global land-cover type maps for 2000 and 2010 [16].

However, medium-resolution (MR) images, such as the 30 m Landsat resolution and Sentinel 2A resolution (i.e., 10 m), may be insufficient for monitoring heterogeneous forests, mapping forest types, and recording LULUCF. In addition, there are few operative approaches with very-high-resolution (VHR) images to map mixed stands across forest landscapes, e.g., some studies focused on a European Forest Type classification approach or mapping forest type and tree species using VHR images [7,17].

The EU and other international institutions are looking for new land-use monitoring strategies. The European LUCAS project has implemented a comprehensive ground observation system that, every 3 years since 2006, has provided land-cover and management information based on the number of field points surveyed (i.e., 500,000 in 2012) and photo-documented by field surveyors [18]. However, the LUCAS original dataset needs harmonization to overcome some inconsistencies related to "subjectivity in legend interpretation, and complexity of the field survey because of the large number of surveyors (>700), complex documentation for the enumerators, and translations to 20 languages" [19].

In this framework, the 2015 Data Revolution proposal launched by the United Nations boosted the Global Forest Survey (GFS) project developed by the Food and Agriculture Organization of the United Nations (FAO) and supported by its Collect Earth open tool based on VHR and MR image integration [20,21]. The FAO aims to collect and release forest ecosystem data at the global level to potentially increase our understanding of forest health and has features that should facilitate global policies for CC mitigation. The first successful milestone of the GFS and Collect Earth approach has been monitoring 1327 million hectares of dryland around the world, which led to finding 467 million hectares of forest (equivalent to the size of the Amazon tropical rainforest) that was never previously reported. This finding could mean an increase of at least 9% over previous estimations of global forest cover, although this estimate is being debated [22].

In the framework of the GFS project in the EU, Martín-Ortega et al. [23] used the Collect Earth tool, supported by VHR/MR image integration, for monitoring 14,957 plots (0.5 ha) located in the drylands of the European Mediterranean region from 2000 to 2015. These authors concluded that only 0.97% of the study area changed from one land use to another. The net increase in forest was 0.02% in this region, in contrast with other studies, such as the Global Forest Resources Assessment (FRA) of FAO [24], which reported an increase of 0.93% in these Mediterranean forests.

Regarding European temperate forests, they are relevant ecosystems with a positive impact on socioeconomic aspects. These forests play a prominent role in timber production, nature protection, water conservation, erosion control, and recreation [25]. However, their interactions with global CC and their resilience to disturbances such as storms, floods, fires, and diseases are not well known. [26]. García-Montero et al. [27] monitored the "trees outside forests" (TOFs) in the Temperate FAO Ecozone in Europe. TOFs are an important sustainable source of ecosystem services and products, with significant impacts on forests and landscape management. These authors used a photo-interpretation approach supported by VHR images and the Collect Earth platform. Thanks to these technologies, they concluded that TOFs accounted for 22% of the inventoried area.

In this framework, the main objective of the present study is the temporary monitoring of LULUCF in the Temperate FAO Ecozone in Europe [28], using the Collect Earth tool supported by VHR and MR image integration. The development of this objective was in the framework of the GFS project to improve approaches to monitoring European LULUCF.

Raši [29], the LUCAS Inventory [30], and the Common Agriculture Policy [31,32] show differences in the European forest cover, with values ranging from 33% in 2015 to 41.1% in 2018. Moreover, the distribution of these forests is heterogeneous, i.e., Sweden, Finland, Spain, France, Germany, and Poland take up two-thirds of the EU's forested areas. According to the EC [33], the European forest area has increased by 9% over the past 30 years. However, Barbati et al. [11] highlighted that the net growth rate of the European forest area has slowed, increasing by around 0.2% per year in the period 2000–2010. These authors also indicated that new approaches to improve the monitoring of forest biodiversity are urgently needed. The reason is that biodiversity is at risk due to intensive silviculture, higher wood prices, higher harvests (notably for energy use), and the CC-related degradation of forest resources.

Senf et al. [34] analyzed the forest canopy mortality of temperate forests in Europe between 1984 and 2016. They concluded that forest mortality had doubled since 1984, mainly associated with land-use changes and CC. Biotic (insects, pathogens, and wildlife herbivory) and abiotic (wildfires, storms, floods, and drought) disturbances can also alter the forest ecology and ecosystem services [35]. Cohen et al. [36] highlighted that, in recent decades, patterns of forest disturbance have begun to shift both regionally and globally. However, monitoring these forest disturbance impacts is limited by a lack of reliable and timely disturbance data at large spatial scales [35].

In this context, the specific objectives of the present work, which is supported by VHR and MR image integration through Collect Earth (in the framework of the GFS project), were (i) to monitor the surface and temporary evolution of LULUCF in the Temperate FAO Ecozone in Europe, (ii) to analyze forest type diversity and disturbances that are altering these forests, and (iii) to propose a methodology to explore the LULUCF network structure in this study area.

2. Materials and Methods

2.1. Study Area

The study area comprised over 2.9 M km^2 between 38° and 54°N latitude and between 8°E and 28°W longitude (Figure 1). As part of the GFS sampling design, the sampled area mainly covered the European Temperate FAO Ecozone: 45% of the surface belonged to the temperate oceanic forest FAO ecozone, 40% belonged to the Temperate Continental Forest FAO ecozone, and approximately 15% belonged to the Temperate Mountain System (7%) and Mediterranean areas equivalent to the Subtropical Dry System FAO Ecozone (8%) [27].

Figure 1. Study area. Temperate FAO Ecozone sampled in Europe, including temperate oceanic area (45%), temperate continental area (40%), temperate mountain systems (7%), and Mediterranean areas (8%) [27]. This figure is based on the global image of the Earth by Google Earth in July 2016 (38–54°N latitude and −8° to 28°W longitude) [20,22].

According to the FAO [24,28], in the European Temperate FAO Ecozone, "the temperate domain, equivalent to Koppen–Trewartha climatic groups, is characterized by an average temperatures above 10 °C in 4–8 months of the year. Particularly in European temperate oceanic areas, the average monthly temperature is always above 0 °C and annual rainfall may vary from (400) 600 to 800 (1700) mm, with up to 2000–3000 mm in lowlands on windward lower coastal mountain slopes. More specifically, this average annual temperature ranges from 7 to 13 °C, while, in coastal areas, the temperature of the coldest month does not fall below 0 °C; however, the inland mean temperature is locally below 0 °C. The climate is influenced by the Gulf Stream and the proximity to the ocean, but their influence decreases inland. Various types of beech forests (*Fagus sylvatica*) and mixed beech forests are the dominant vegetation. In oceanic areas, *Ilex aquifolium* is a characteristic species of the shrub layer. On nutrient-poor, acidic soils, beech is partly mixed with *Quercus robur* and *Q. petraea* in the canopy. These stands are poor in species."

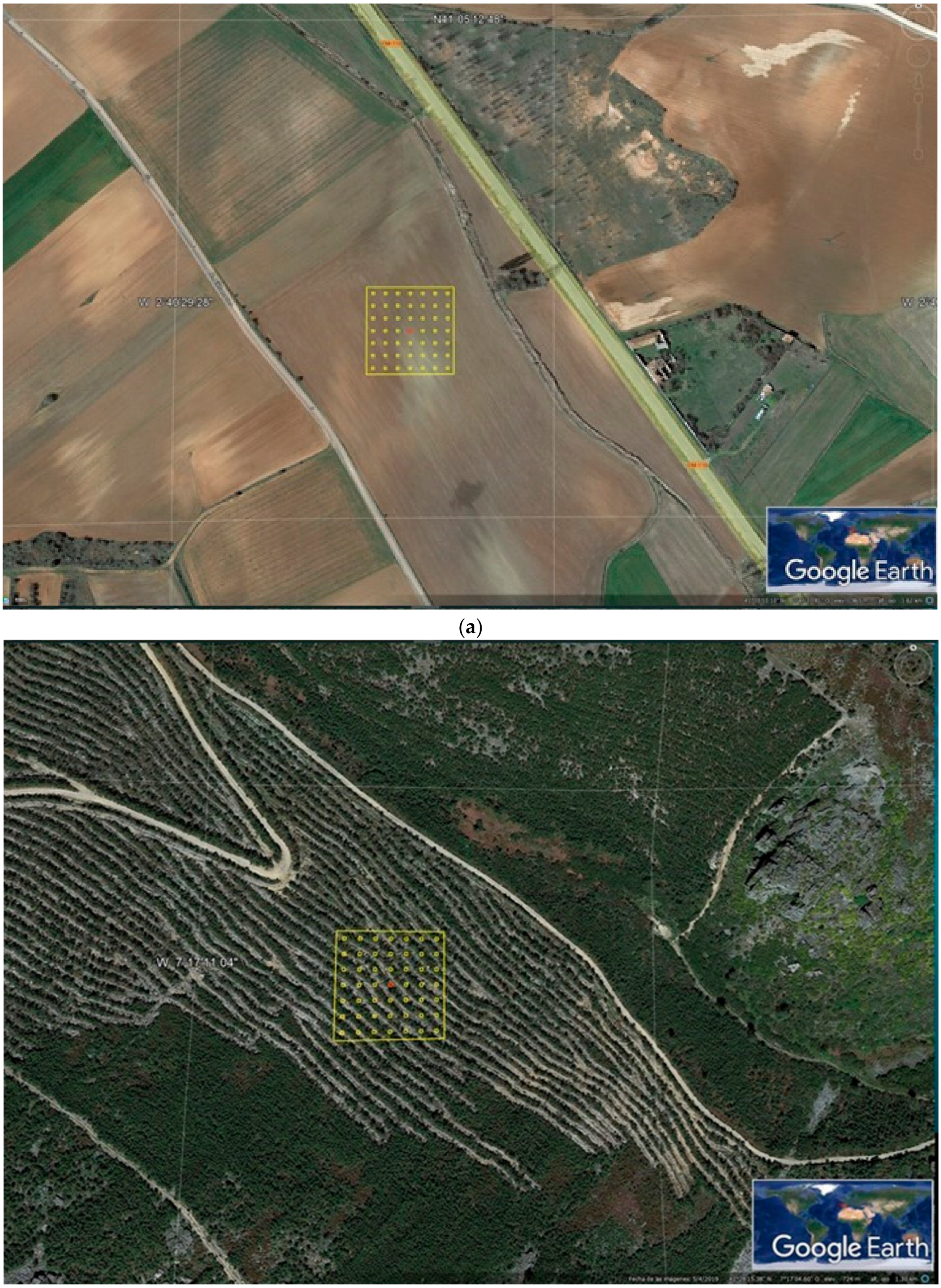
In European temperate continental areas, however, "winters are colder, with at least 1 month having average temperatures below 0 °C. Rainfall generally decreases with distance from the ocean and also at the higher latitudes. More specifically, summers are warm, and winters are cold in most of this region. Mean annual temperature is about 6 to 13 °C in the west and decreases to 3 to 9 °C in the east. The temperature of the coldest month ranges from below 0 °C in Scandinavia and around 0 °C in the Balkans to below −10 °C in the Ural Mountains. In the northern areas, more than 2 months of the year have a mean temperature below 0 °C. Owing to less influence of the Gulf Stream, annual rainfall gradually decreases from the west/northwest (greater than 700 mm) to the east/southeast (about 400 mm). Locally, in the foothills of the Caucasus, rainfall is very high. The zone has various forest types, distributed along local and regional gradients of climate and nutrient availability. In the northern parts, mixed coniferous broad-leaved forests form a belt parallel to the circle of latitude. Spruce forests (*Picea abies*) constitute most of the forest cover. On more acidic and drier soils, pine forests replace spruce. Further south, deciduous broad-leaved forests are represented by mixed oak–hornbeam, dominated by *Quercus robur*, *Q. petraea*, *Carpinus betulus*, and *Tilia cordata*, as well as associated species such as *Fraxinus excelsior* and *Acer campestre*. To the east of mixed oak–hornbeam forests, mixed lime–oak forests are found, dominated by *Quercus robur* and *Tilia cordata*. In southeastern Europe and the Balkan countries, *Quercus petraea* and Balkan oak (*Quercus* spp.) forests occur mainly, including mixed forests dominated by *Q. cerris* and *Q. frainetto* in central Balkan Peninsula" [24,28].

The European temperate mountain system includes "areas over 800 m of altitude. As the highest altitudinal belt of the temperate domain the mountain region is characterized by generally greater precipitation and lower temperature, and the climate is extremely varied. Precipitation varies from <500 mm to >3000 mm. The average annual temperature ranges from −4 to 8 °C (12 °C) and the average January temperature at the highest altitudes fluctuates between −10 and −4 °C. Beech (*Fagus* spp.) forests, particularly mixed beech forests with *Abies alba*, *Picea abies*, *Acer pseudoplatanus*, *Fraxinus excelsior*, and *Ulmus glabra*, comprise the vegetation of the lower belt in this region. As in the oceanic region, pure beech forests at higher altitudes are relatively dense. At higher altitudes, other tree species become more prominent. To the east, *Fagus sylvatica* (subsp. *sylvatica*) is replaced by *F. sylvatica* subsp. *moesiaca* and, further eastward, by *F. sylvatica* subsp. *orientalis*. At even higher altitudes, fir and spruce forests (*Abies alba*, *A. borisii-regis*, *A. nordmanniana*, *Picea abies*, *P. orientalis*, and *P. omorika*) replace the beech forests. Either *Abies* or *Picea* may dominate. *Pinus sylvestris*, *Fagus sylvatica*, some *Quercus robur*, and pioneer species such as *Sorbus aucuparia*, *Populus tremula*, and *Betula pendula* play a minor role. Around the timberline, pine scrub (*Pinus mugo*) or *Rhododendron* spp. may occur. This scrub and krummholz transitions at higher altitudes into alpine grasslands, various dwarf shrub vegetation, and rock and scree vegetation of the alpine to nival belt. In the Urals, the altitudinal zonation starts with lime–oak forests (*Quercus robur*, *Tilia cordata*) at the lowest level, followed by herb-rich fir–spruce forests (*Abies sibirica*, *Picea obovata*) with broad-leaved trees such as *Ulmus glabra* and *Tilia cordata*, as well as pine forests (*Pinus sylvestris*) with *Larix sibirica*" [24,28].

2.2. Data Collection

The data were collected through a stratified systematic survey in the Temperate FAO Ecozone in Europe under the GFS framework [28]. The Forest Assessment, Management, and Conservation Division (FOM) of the FAO designed this survey on the basis of the methodology proposed by Bastin et al. [22]. The grid in the systematic sampling was of the same order as that used in forest assessments by FAO and in national forest inventories (see Figure 2 in [27]). The aim of the survey was to map vegetation and land uses in this area of Europe. The international land-use guidelines set by the Intergovernmental Panel on Climate Change (IPCC) were used to assign the type of land use to each plot. The sample consisted of 11,159 plots of 0.5 ha (70 × 70 m) (Figure 2). Half a hectare is the minimum plot size that the FAO-FRA indicates in its definition of a forest [24]: "Forests are lands of more than 0.5 hectares, with a tree canopy cover of more than 10%, which are not primarily under agricultural or urban land use, as well as areas in which tree cover is temporarily <10% but is expected to recover".

Twenty-five master's and PhD students and two professors of Forestry and Agricultural Engineering and Environmental Sciences were involved in the survey implemented in Collect Earth in July 2016 [20,37,38]. Collect Earth is a system developed by the FAO to collect and analyze georeferenced data using Google geospatial tools, including free VHR images. It allows for free access to several remote sensing databases such as DigitalGlobe, SPOT, Sentinel 2, Landsat, and MODIS imagery, and it provides graphical representations of vegetation evolution indices from Landsat and MODIS imagery in Google Earth Engine (GEE) [20,39]. These features ensure robust land-use assessments by interpreting MR and VHR satellite imagery [40].



(**a**)

(**b**)

Figure 2. Two examples of the location of the sample plots of 0.5 ha (70 m × 70 m) that were assessed by means of a stratified systematic sampling design: (**a**) Spanish plot of cropland; (**b**) Portuguese plot of plantation linked to forest land.

2.3. Data Processing

The data sources mentioned above were automatically geosynchronized in each 0.5 ha plot to allow researchers to record several parameters. The chosen parameters were IPCC land-use types, land-use change, and types of disturbances. Each plot was assigned to one of the six IPCC land-use types: cropland, forest, grassland, settlement, wetland, and other land [41]. The assigned land-use type was that use whose surface was more than 0.1 ha and fulfilled a hierarchy rule that established the following order: (1) settlement, (2) cropland, (3) forest, (4) grassland, (5) wetland, and (6) other land, following a conservational principle: (i) less conservational land use results in a higher rank; (ii) if the forest area is more than 0.1 ha, then this land use is inconsistent with another dominant non-forest activity [42].

According to the IPCC classification, land-use forest subtypes were identified using VHR images (where available), which included: mixed conifers and broadleaf, conifers, broadleaf, mixed deciduous broadleaf, plantation, riparian forest, and gallery forest. In addition, different kinds of disturbances, i.e., tree felling, pastoralism, wildfire, and flooding, according to the FAO–FRA [43,44], were also inventoried.

The authors also evaluated land-use change following the same "predominant land use" criterion and using the available imagery stored in the Google Earth platform. The comparison between 2015 VHR imagery with the oldest 2000 (MR images) and 2000–2014 (VHR/MR images) information available on land-use changes (in this case, medium-resolution images, such as Landsat) allowed us to identify land-use changes. Potentially inconsistent plots were automatically identified through semiautomated data cleaning and manually reassessed by FAO members [22,27]. The data associated with the 11,159 plots were analyzed with open-source data visualization and by querying the tool SaikuBI, which is integrated with the Collect Earth platform [20].

As the variables in this study express the frequency of qualitative variables, the sampling error was calculated according to the following expression [45]:

$$e = z_{\alpha/2}\sqrt{\frac{\hat{p}\hat{q}}{n}(1-f)}, \tag{1}$$

where $z_{\alpha/2}$ is the inverse standard normal cumulative distribution function for a confidence level of $1-\alpha$, p is the proportion of the number of plots with a specific characteristic, $q = 1 - p$ is the proportion of plots without that characteristic, n is the size of the sample, and f is the sampling intensity in terms of the area sampled compared to the total area.

The sampling errors of each IPCC type in 2015 were 0.009, 0.009, 0.006, 0.005, and 0.002 for forest land, cropland, grassland, settlement, and wetland, respectively. All were statistically acceptable at less than 0.05 [27].

We shaped a preliminary structure of the plots' land-use change from 2000–2014 to 2015. The social network analysis (SNA) approach was applied. In the network, the land-use structure matrix was filled with the number of plots that changed from the land use in the first column of the matrix to the land use in the first row to develop a directed weighted network [46]. The SNA application calculated the parameter density, degree, average degree, in-degree, out-degree, weighted degree, and average weighted degree to characterize the network. Density describes the portion of the potential connections in a network that are actual connections. A potential connection is a connection that could potentially exist between two nodes regardless of whether it exists (see Equation (2)).

$$Density\ (G) = \frac{K}{\mathrm{N}(N-1)} = \sum_{LUi,\ LUj\ \in\ \mathrm{G}} LUSM_{LUi,\ LUj}/N(N-1), \tag{2}$$

where G is the network, K denotes the existing relationships, N is the total number of land uses (nodes) in the dataset, and LU_i and LU_j are the interrelated land uses in the land-use structure matrix (LUSM). The degree of a node is the number of relations (edges) it has, whether it is an in or an out relationship (see Equation (3)).

$$Degree(LU_i) = \sum_{LU_j \in G} LUSM_{LUi-LUj}, \tag{3}$$

where LU_i is the land use and LU_j is the j-esimo LU_i interrelated land use in the LUSM. The average degree is the average number of edges per node in the graph (see Equation (4)).

$$AvD = \frac{\sum_{i=1}^{N} Degree(LU_i)}{N}, \tag{4}$$

where $Degree(LU_i)$ is the degree of land use I, and N is the total number of land uses (nodes). The in-degree of node i is the number of relations (edges) from any other node of the network to this node (see Equation (5)).

$$In_{Degree(LU_i)} = \sum_{LU_j \in G} LUSM_{LUj \to LUi}, \tag{5}$$

where LU_i is the In_{Degree} land use, and LU_j is the j-esimo LU_i interrelated land use in the LUSM with a directed relationship between node j and node i. The out-degree of node i is the number of relations (edges) from this node to any other node of the network (see Equation (6)).

$$Out_{Degree(LU_i)} = \sum_{LU_j \in G} LUSM_{LUi \to LUj}, \tag{6}$$

where LU_i is the Out_{Degree} land use, and LU_j is the j-esimo LU_i interrelated node in the LUSM with a directed relation from node i to node j. The weighted degree of a node is the number of edges for a node, multiplied by the weight of each edge. In this work, the weights are the number of plots that change for every pair of land uses (see Equation (7)).

$$W_{Degree(LU_i)} = \sum_{LU_j \in G} W_{LUi-LUj} LUSM_{LUi-LUj}, \tag{7}$$

where LU_i is the weighted degrees land use, G is the network, LU_j is the j-esimo LU_i interrelated land use in the LUSM, and $W_{LUi-LUj}$ is the number of plots interchanged between land uses LU_i and LU_j. The average weighted degree is the average number of weighted edges per node in the graph (see Equation (8)).

$$AvWD = \frac{\sum_{i=1}^{N} W\_Degree(LU_i)}{N}, \tag{8}$$

where $W\_Degree(LU_i)$ is the weighted degree of land use I, and N is the total number of land uses (nodes). Gephi 0.9.2 software was used to obtain the network and parameters.

3. Results

Table 1 shows the 2015 results of integrated VHR and MR images in Collect Earth used to analyze the distribution of IPCC land-use types in the study area. The predominant land-use types were forest and cropland, which accounted for 77.48% of the inventoried area, while grassland and settlements covered 19.48%. On the other hand, for 2000, Table 1 shows the results of MR images used to analyze the distribution of IPCC land-use types. Other predominant land-use types were forest and cropland, which accounted for 78.43%, while grassland and settlements covered 18.64%.

Table 1. Number of plots (and %) for IPCC land-use types in GFS for the Temperate FAO Ecozone in Europe, in both 2000 (using MR images) and 2015 (integrating VHR and MR images).

IPCC Land Use	Plot Count (2000)	Plot % (2000)	Plot Count (2015)	Plot % (2015)	Total Net Increase in No. of Plots, TC_L [2] (%)
Forest land	4568	40.94	4617 [1]	41.37 [1]	0.43
Cropland	4184	37.49	4030	36.11	−1.38
Grassland	1289	11.55	1323	11.86	0.31
Settlement	791	7.09	850	7.62	0.53
Wetland	154	1.38	158	1.42	0.04
Other land	173	1.55	181	1.62	0.07
Total	11,159	100	11,159	100	2.77 [3]

[1] Data published in García-Montero et al. [27]. [2] Percentage net increase in no. of plots in each land use, TC_L, between 2000 and 2015 compared to the initial value calculated by $TC_L = (b_L - a_L)/11{,}159 \times 100$, where b_L is the number of plots counted in 2015, and a_L is the number of plots counted in 2000 for a specific land use. [3] Land-use change frequencies observed in the study area, between 2000 and 2015 (calculated as a sum in absolute value).

LULUCF from both years were detected by analyzing all the plots, using the MR images in 2000 compared with the integration of VHR and MR images in 2015. The LULUCF frequencies observed in this data group show that 2.77% of the plots underwent net changes in land use in those 15 years. Table 1 also shows that there was a 0.43% relative net increase in forest land plots, as a result of the net balance between these forest lands and some other land-use types that would have decreased, such as cropland, which decreased by 1.38% when comparing 2000 and 2015.

Table 2 shows the frequency of subtypes for the IPCC land-use types, using only VHR images in Collect Earth in 2015 and during the period 2000–2014. Regarding the 2000–2014 data, the scarcity of VHR imagery in the study area made the results not applicable or comparable to the 2015 data. Table 2 shows that, in 2015, most of the plots classified as forest land belonged to mixed conifers and broadleaf (13.3% of the study area) and conifers (11.3% of the study area), followed by forest land plots classified as broadleaf (7.5% of the study area) and mixed deciduous broadleaf (4.9% of the study area). However, the most abundant land use relative to the total number of plots in our study area was rainfed farming (29.28% of the study area), also highlighting the grassland (10.02% of the study area) and irrigated crop (5.02 % of the study area) types.

Regarding forest biodiversity, Table 2 shows that, in 2015 (VHR), all forest types were significantly represented in the study area. Mixed conifer and broadleaf forests covered 32.4%, conifer forests covered 27.6%, and broadleaf forests covered 18.9% of the forest land use; the surface of other forest types was mixed deciduous broadleaf forests and gallery forests, which accounted for 11.9% and 0.9% of the forest land use, respectively.

We also integrated VHR images from 2015 and a number of interpretable MR/VHR images from 2000–2014 to see the specific LULUCF through Collect Earth. Table 3 and Figure 3 allow us to see this LULUCF evolution in 6948 plots (62.3% of the plot sample). Changes were detected by analyzing all the plots, using available and interpretable images from 2000–2014 and 2015. The land-use change frequencies observed in this data group show that 2.19% of this analyzed territory underwent LULUCF in those 15 years. Table 3 also shows that 0.71% of plots of some land-use types generated new forest land areas, although, simultaneously, 0.34% of forest land areas were changed into other land uses. Therefore, if we use Collect Earth, comparing 2000–2014 (interpretable MR/VHR images) and 2015 (VHR images), 62.3% of the plot sample showed a net increase of 0.37% in forest lands.

Table 2. Number of plots of IPCC land-use subtypes in 2015, and number of plots of subtypes that showed changes regarding the 2000–2014 period (only VHR images), in European Temperate FAO Ecozone.

Temperate FAO Ecozone	Type of Land Use	Plot Count (2015)	Plot Count (2000–2014)
Forest land	Mixed conifers and broadleaf	1488	7
	Conifers	1266	15
	Broadleaf	835	9
	Mixed deciduous broadleaf	548	6
	Plantation [1]	307	3
	Riparian forest	42	-
	Gallery forest	4	-
	Other plantations [2]	53	3
	Plantation of poplars (*Populus*) [3]	33	-
	Plantation of eucalyptus trees [3]	16	-
	Total forest land subtype plots	4592	43
Non-forest land use	Rainfed farming	3265	77
	Pastureland	1117	71
	Irrigated crops	560	9
	Village	329	1
	Urban area	240	-
	Scrubland	229	8
	Orchard	182	4
	Infrastructure	144	2
	Rocks	130	4
	Built area	120	2
	Lake or permanent pond	85	-
	Permanent river or inland delta	37	-
	Snow or glacier	32	-
	Cultivation in flood zone	21	-
	Mine	17	-
	Sand	11	3
	Riparian vegetation	9	-
	Swamp in inorganic soil [4]	8	-
	Seasonal river	7	-
	Delta coastal	6	-
	Seasonal lake	3	-
	Rice plantation	2	-
	Peat	1	-
	Plantation of acacia trees [3]	1	-
Available data		11,148	224
No data		11	10,935

[1] Plantation = plant forestation linked to the existing forests (Figure 2b); [2] other plantation = plant forestation different to the existing forests; [3] plantation sp. = plantations of eucalyptus, poplar, or acacia (tree species that could be identified by VHR images); [4] swamp in inorganic soil = swamp without peat or riparian vegetation.

Table 3. Land-use structure matrix with the number of plots changed (using only VHR images) from the land use in the first column (2000–2014) to the land use in the first row (2015), designed to build a network of land use changes.

Number of Plots	Forest Land	Grassland	Cropland	Settlement	Wetland	Other Land
Forest land	0	14	0	10	0	0
Grassland	22	0	0	22	1	0
Cropland	21	18	0	25	3	0
Settlement	2	0	0	0	6	0
Wetland	0	0	0	0	0	0
Other land	4	2	0	2	0	0

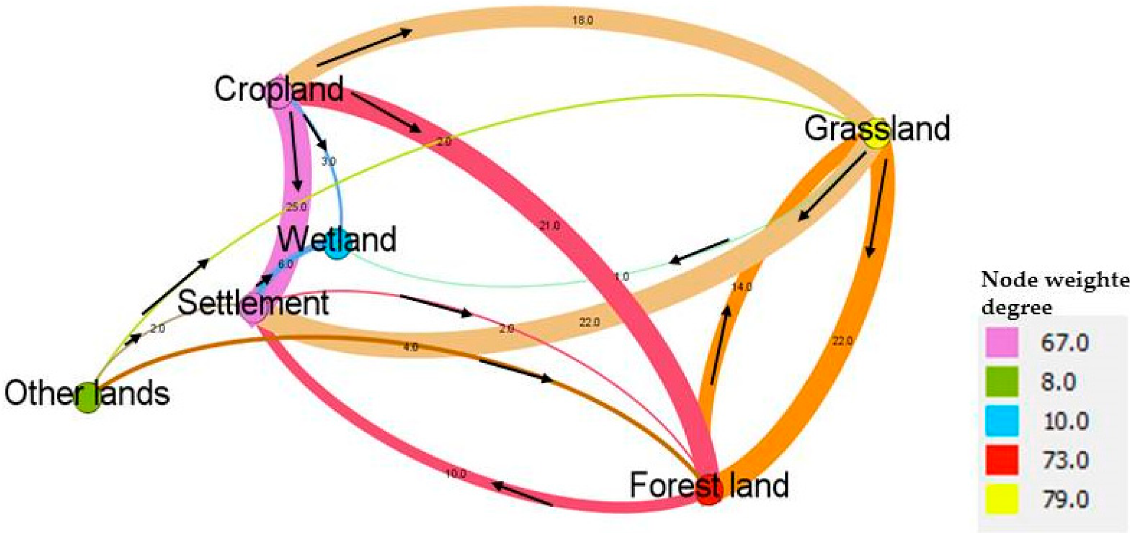


Figure 3. Graph of preliminary structure of network of the land-use interchange. The width of the lines is proportional to the weight (number of plots); the black lines indicate from which land use to which the plots changed, while the number of plots is indicated on the lines. The color of the nodes indicates the weighted degree.

The development of preliminary analyses (limited by the VHR availability) of the land-use network allowed us to identify which type of land uses present more changes and greater influence. Using only VHR images, Table 3 shows a land-use structure matrix based on the number of plots that changed land use, comparing 2000–2014 and 2015, designed to build the network of the land-use interchange. On the other hand, Figure 3 shows the network of these land uses (nodes), where the arrow width is proportional to the number of plots that changed from one use to another. The network density (0.46) indicates that fewer than half of the potential interconnections between land uses exist (14 out of 30). The average degree per node (4.65) shows that the network is minimally connected on average.

In the Temperate FAO Ecozone sampled in Europe, grassland, forest land, cropland, and settlement are the land uses with more frequent changes (see "weighted degree" in Table 4). In Table 4, the "degree" shows that forest land, grassland, and settlement are the types with more direct connections; thus, they have the highest impact on land-use management. However, no land-use type is connected with all the potential land uses. "In degree" values show that forest land and settlement have the highest value, 4; hence, there were plots from four different land-use types that changed into these two types. Most of the plots assigned to forest land use in 2015 were previously cropland or grassland. However, cropland is the land use whose initial plots changed into a higher number of land-use types (four), equally to grassland, forest land, and settlement. Regarding the "weighted degree" in Table 4, grassland shows the highest value; therefore, it is the type of land use with the highest number of plots that either changed from any other land use into grassland or from grassland into any other land use, followed by forest land. These are, thus, the land uses with the highest probability of changing their surface. Lastly, the results show that other land and wetlands have a small influence on the land-use change process observed in the study area.

In addition to the identified LULUCF, in Table 5, Collect Earth and VHR images show that, in 2015, 9.06% of plots were affected by different kinds of disturbances in the analyzed plots in the study area (10,340 plots). In the whole study area, the main disturbances observed in the plots with historically available data (10,340 plots) were tree felling and pastoralism, followed by flooding. In 2015, in the overall forest land areas, the disturbances were mainly tree felling, and, to a lesser extent, pastoralism and flooding, while fires disturbed very few forests. However, taking into account the IPCC land-use subtypes of forest land, Table 6 shows that, in broadleaf and mixed deciduous broadleaf forests, both tree felling and pastoralism had a similar impact. In riparian and gallery forests, the only disturbance detected was flooding.

Table 4. Value of the parameters degree, in degree, out degree, and weighted degree for each land use, and average degree and average weighted degree for the preliminary structure of network.

Land Use	Degree	In Degree	Out Degree	Weighted Degree
Forest land	6	4	2	73
Grassland	6	3	3	79
Cropland	4	0	4	67
Settlement	6	4	2	67
Wetland	3	3	0	10
Other land	3	0	3	8
Average per node	4.65	-	-	50.66

Table 5. Environmental disturbance kinds observed in the analyzed plots (VHR images) depending on the IPCC land-use types in the Temperate FAO Ecozone in Europe in 2015.

Type of Land Use (2015)	Disturbance Kind	Plot Count	% Relative to the Type of Land Use (2015)	% Total Available Data (10,340 Plots)
Forest land	None	3930	91.89	38.01
	Tree felling	237	5.54	2.29
	Pastoralism	41	0.96	0.40
	Flooding	14	0.33	0.14
	Fire	6	0.14	0.06
	Mining	5	0.12	0.05
	Storm	4	0.09	0.04
	Non identified	40	0.94	0.39
Cropland	None	3527	95.66	34.11
	Other	66	1.79	0.64
	Tree felling	53	1.44	0.51
	Pastoralism	30	0.81	0.29
	Flooding	9	0.24	0.09
	Mining	2	0.05	0.02
Other land	None	163	94.22	1.58
	Other	4	2.31	0.04
	Mining	3	1.73	0.03
	Tree felling	1	0.58	0.01
	Pastoralism	1	0.58	0.01
	Flooding	1	0.58	0.01
Grassland	None	950	76.18	9.19
	Pastoralism	236	18.93	2.28
	Tree felling	28	2.25	0.27
	Other	21	1.68	0.20
	Flooding	11	0.88	0.11
	Storm	1	0.08	0.01
Wetland	None	126	85.71	1.22
	Flooding	15	10.20	0.15
	Other	5	3.40	0.05
	Pastoralism	1	0.68	0.01
Settlement	None	707	87.39	6.84
	Other	61	7.54	0.59
	Tree felling	17	2.10	0.16
	Mining	16	1.98	0.15
	Pastoralism	8	0.99	0.08
All types	Disturbed plots	937	-	9.06
	Available data	10,340	-	100
	No data	819	-	-

Table 6. Environmental disturbance types observed in the analyzed plots (VHR images) depending on the IPCC land-use subtypes in the forest lands of the Temperate FAO Ecozone in Europe, in 2015.

Subtypes of Forest Land (2015)	Disturbance Kind	Plot Count	%
Conifers (11.23%) [1]	None	1065	91.73
	Tree felling	73	6.29
	Other	10	0.86
	Pastoralism	7	0.60
	Fire	4	0.34
	Mining	2	0.17
	Subtotal	1161	100
Mixed conifers (0.70%) [1]	None	68	94.44
	Tree felling	4	5.56
	Subtotal	72	100
Broadleaf (7.84%) [1]	None	765	93.97
	Tree felling	22	2.71
	Pastoralism	20	2.46
	Other	2	0.25
	Mining	1	0.12
	Flooding	1	0.12
	Subtotal	811	100
Mixed conifer and broadleaf (13.03%) [1]	None	1266	93.69
	Tree felling	55	4.08
	Other	14	1.04
	Pastoralism	5	0.37
	Flooding	4	0.30
	Storm	2	0.15
	Mining	1	0.07
	Subtotal	1347	100
Mixed deciduous broadleaf (4.85%) [1]	None	464	92.43
	Tree felling	24	4.78
	Pastoralism	6	1.20
	Other	6	1.20
	Mining	1	0.20
	Flooding	1	0.20
	Subtotal	502	100
Plantation of poplars (*Populus*) (0.83%) [1]	None	26	89.66
	Tree felling	3	10.34
	Subtotal	29	100
All forest subtypes	Available data	4174	-
	No data	443	-
Total number of analyzed plots in the study area	-	10,340	-
Subtypes of Forest Land (2015)	**Disturbance Kind**	**Plot Count**	**%**
Plantation of conifers (5.44%) [2]	Tree felling	42	21.99
	Fire	1	0.52
	Other	1	0.52
	None	145	75.92
	Storm	2	1.05
	Subtotal	191	100%
Plantation of *Eucalyptus* trees (0.46%) [2]	Tree felling	8	50.00
	None	8	50.00
	Subtotal	16	100%

Table 6. *Cont.*

Subtypes of Forest Land (2015)	Disturbance Kind	Plot Count	%
Riparian forest (0.40%) [2]	None	35	85.37
	Flooding	6	14.63
	Subtotal	41	100%
Gallery forest (0.04%) [2]	None	3	75.00
	Flooding	1	25.00
	Subtotal	4	100%
All forest subtypes	Available data	4174	-
	No data	443	-
Total number of analyzed plots	-	11,159	-

[1] Percentage related to the total of analyzed plots in the study area, in 2015 (10,340 plots). [2] Percentage related to the total of analyzed plots (11,159 plots).

4. Discussion

At the global scale, Goldewijk [47] summarized the historical data and patterns of LULUCF over the past 300 years, showing increases in cropland (5.6-fold) and pastures (6.6-fold) at the expense of forest lands and natural grassland. Thus, from 1700 to 1990, OECD Europe and Eastern Europe doubled their cropland area. However, LULUCF have shown differences between the different global regions and different temporary trends, i.e., for the period 1950–1990, the USA, OECD Europe, Eastern Europe, East Asia, and Japan showed a small decrease in cropland. Later, between 1990 and 2012, Naranjo et al. [9] described most of the EU territory as cropland, accounting for 35%. However, they also concluded that European agriculture and other land uses had changed during this period.

Nevertheless, as our results confirm, this decreasing trend of temperate forest area has been changing, at least in Europe, over the last few decades. The main reasons are the reforestation of abandoned cropland and woody encroachment resulting from wildfire suppression, especially in temperate regions [48]. Moreover, to counteract the historical overexploitation of European forests, in the last century, forestry management has been improved. This management has led to high growth rates and increased growing stocks in these forests [25].

In the 21st century, in the Temperate FAO Ecozone in Europe, our monitoring of 15 years of LULUCF using the Collect Earth platform and MR–VHR image integration has improved our knowledge of the land-use patterns in this region, especially for 2015. Collect Earth's efficiency is very high in years for which VHR images are available, such as 2015. On the other hand, our results have also shown that the Collect Earth platform has a similar efficiency to other monitoring methodologies when using medium-resolution images (i.e., the 30-m Landsat resolution).

However, our results showed differences when the image comparisons were based on (i) MR images (i.e., the 2000 data collection), (ii) VHR/MR integration of images (i.e., the 2015 data collection), or (iii) only VHR images (i.e., 2000–2014 data collection and 2015 data collection). In this regard, when Collect Earth integrated MR and VHR images (2000 and 2015 data), the results showed that the percentage of plots that had changed land use and increased in forest area, respectively, were 0.58% and 0.06% higher (with respect to the total territory) than the Collect Earth results when using only VHR images (2000–2014 and 2015 data). This comparison should be repeated in the coming years, when more VHR images are available.

On the other hand, the analysis of only VHR images through Collect Earth also suggested a preliminary structure of the land-use network structure associated with the 2.19% of the plots whose land uses changed between 2000–2014 and 2015. Thus, cropland was the land-use type that changed the most, and cropland and grassland were the main land uses that transformed to new forest lands in the study area in 2015. Notwithstanding the scarcity of VHR images for 2000–2014, these results at the European scale are consistent with previous trends found by European national studies, i.e., Václavík and Rogan [49] highlighted a 12% decrease in cropland, with 6% of it becoming new forest land and 3.5% arable land, in the Czech Republic between 1991 and 2001. Kuemmerle et al. [50] also showed cropland abandonment (at a rate of 21.1%), while forest lands remained stable from 1990 to 2005 in Southern Romania. Thus, although this land-use network gives a preliminary structure, because of the limited availability of VHR images before 2015, our results indicate that this methodology is already showing good LULUCF patterns. Therefore, in the future, this land-use network will be improved through an increase in VHR image availability, which will also increase the inputs into the SNA model.

In the European Temperate FAO Ecozone, Collect Earth also indicated that forest land was the second (VHR images) or third (MR/VHR images) most frequent type of land use that changed into any other land use. However, the LULUCF balance favored forest lands, which increased by between 0.37% and 0.43% during this period. This net forest growth rate was significantly lower than the 2% net growth rate of the overall European forests proposed in 2000–2010 [11]. Despite this, for 2015, Collect Earth and VHR images showed that more than 41.37% of the studied Temperate FAO Ecozone in Europe was forested (Table 1). This value exceeds the estimations of European forest proposed by other authors for 2015 [29–32].

In 2010, Forest Europe [51] reported that conifers covered 50% of European forests (excluding the Russian Federation), broadleaf covered 25%, and the remaining part comprised mixed conifer–broadleaf stands. When considering an equivalent Europe Temperate FAO Ecozone extension, the forest-type distribution amounted to 40%, 48%, and 12% for conifer, broadleaf, and mixed forests, respectively. For 2015, Forest Europe [52] reported that mixed European forest accounted for up to 70%, and the area of monospecific forests decreased in recent years. Therefore, there are large discrepancies in the state of Europe's forests between 2010 and 2015. These discrepancies are explained by (i) data availability, (ii) significant differences between national and international definitions of forests available for wood supply, and (iii) the different interpretations of these definitions by the various countries in their forest inventory reports [51]. Therefore, Alberdi et al. [5] highlighted that it is necessary to have harmonized European forest inventory datasets. In this regard, in the Temperate FAO Ecozone in Europe, using the Collect Earth platform and VHR images within the GFS framework in 2015, mixed forests represented 44.3% of the forest area, while monospecific forests (conifer or broadleaf forest) represented 46.5%.

On the other hand, Senf et al. [34] assessed canopy mortality in European temperate forests, finding that 0.79% of the forest area (240,000 ha) had been affected by canopy mortality per year since 1984, and this canopy mortality increased by 2.40%$\cdot$year^{-1} in 2016. They indicated that broad-scale processes due to past land use and CC are drivers affecting the ecosystem dynamics at large spatial scales, which can explain this mortality. These findings are in line with the annual net increase of forest lands due to the transformation of cropland and grassland that we found in the study area from 2000 to 2015.

Cohen et al. [36] highlighted that, in recent decades, disturbances affected northern temperate forests more frequently and with a higher spatiotemporal variability than harvesting. They indicated that, across Europe, wildfire, wind, and bark beetle disturbances have steadily increased since the early 1970s. However, our results, using Collect Earth and VHR images, confirm that, on average, in 2015, wood harvesting (associated with tree felling disturbance) was the most frequent forest disturbance in the six forest land subtypes. This disturbance represented 67.47% of the total forest land in the study area, with an impact (in terms of extent) six times greater than pastoralism, 13 times greater than flooding, and 40 times greater than wildfires. These results are consistent with the conclusions of Senf et al. [34]. These authors found (i) a strong correlation between canopy mortality trends and reported wood removals, and (ii) harvesting mainly being based on a transition from past clear-cut systems toward "close-to-nature" silviculture and retention forestry in the temperate forests of Europe.

Historically, the clearing of forests for firewood and agriculture has been a significant source of carbon emissions [48], in addition to wildfires and other forest disturbances.

Thus, burnt areas in temperate forests could lead to a mean reduction in the soil carbon stock of 35% [53]. Guo et al. [54] confirmed that a burnt area of 5 million ha in Russia generated 261.82–302.48 Tg of CO_2 emissions. On the other hand, a reduction in forest area and increase in forest isolation led to 20–75% decreases in the abundance of animals and plants, impacting ecological functions and reducing the ecosystem services of forests, such as carbon sequestration and nutrient cycling [55]. Therefore, as Goldewijk [47] suggested, it is necessary to improve land-use inventory methodologies and studies to increase the availability of LULUCF historical data. This improvement should imply collecting data at spatial and temporal scales since this is a requirement for validating models of global environmental change. In this regard, GFS, based on the Collect Earth platform and supported by VHR images, seeks to overcome the lack of forest inventory/information harmonization, as GFS provides a homogeneous sampling scheme independent of national borders.

Our work allowed us to conclude that the efficiency shown by the Collect Earth tool is clearly linked to its ability to manage free VHR images to analyze changes in land use. Although we cannot access multispectral bands, these VHR images allow for high-quality, direct photointerpretation of the analyzed scenarios, which provides greater definition of the elements and observable changes in the territory compared to the free multispectral images of lower spatial resolution (i.e., Landsat). However, the main limitation of the photointerpretation of these free VHR images is that they do not allow for the generation of spectral indices (NDVI, EVI, etc.). The spectral indices usually facilitate the diagnosis of certain states and/or ecological processes (humidity, vigor and phenology of plants, etc.) associated with the observed elements of an area (natural vegetation, crops, soils, etc.). Therefore, the high efficiency of Collect Earth and VHR images is limited to the inventory phase and directly observable changes and disturbances. A second limitation of the free VHR images is their low temporal availability in many areas, mainly in the early 2000s. However, since 2015, we confirmed a significant increase in the temporary availability of VHR images in the study area. If more VHR images are available, this will increase Collect Earth's capacity to integrate both VHR and multispectral MR images, with the aim of increasing knowledge about the cause–effect processes associated with the LULUCF evolution at different area scales.

However, as with the use of any other research tool, the first results obtained by Collect Earth and VHR images would be conditioned by other aspects of the used methodologies, such as the sampling procedures or the conceptual frameworks in which each work would be carried out. Following the example of forests recently located in drylands over the world (using Collect Earth and VHR images), Bastin et al. [22] suggested a figure of 9% of new forest, estimated at the global scale; some authors have discussed this estimation from different conceptual perspectives, e.g., (i) Griffith et al. [56] disagreed with the forest definition used by the authors [22] because it would not reflect the ecosystem function or biotic composition, which could have overestimated the extent of forest in the tropics and could have led to both unwanted changes in their conservation strategies and inadequate management practices of tropical pastures, (ii) Schepaschenko et al. [57] discussed the "novelty" of some additional forests located in drylands and thought that not all sources of uncertainty in the used methodology had been considered because, in Australia, they observed a 14% discrepancy in the forest/non-forest classification, instead of the 3.5% reported by the authors of [22], and (iii) De la Cruz et al. [58] disagreed with regard to the delimitation of dry forest distribution, the conceptual framework of drylands, and the sampling design used by the authors of [22].

Beyond the methodological problems and conceptual debates linked both to the diagnosis of cause–effect processes and to the policies of decision-makers on land-use management, our work highlighted the two main advantages of Collect Earth in monitoring European LULUCF. Firstly, they allow users to easily overlay and integrate VHR image information (with less temporary availability and without multispectral bands) with multispectral MR images (with lower spatial resolution and high temporary availability), with the aim of improving the cause–effect diagnoses of LULUCF, disturbances, and forest types evolution. Secondly, as suggested by Saah et al. [40], Collect Earth enables researchers and land-use decision-makers, with a minimal background in remote sensing, to monitor LULUCF of vast areas.

5. Conclusions

In summary, the FAO's Collect Earth platform, within the GFS framework, has improved the accuracy of our knowledge of land-use patterns in the Temperate FAO Ecozone in Europe. Collect Earth supported the monitoring of LULUCF comparing the 2000 and 2015 data, integrating VHR and MR images. Moreover, using only VHR images, it was possible to build a preliminary structure of the LULUCF network, comparing the 2000–2014 and 2015 data, in 62.3% of the study area. The LULUCF frequencies observed, comparing the 2000 and 2015 scenarios (VHR/MR images), showed that 2.77% of the territory underwent net change, including a 0.43% relative net increase in forest land plots. On the other hand, the LULUCF network comparing the 2000–2014 and 2015 scenarios (VHR images) showed that 2.19% of the analyzed territory underwent net change, including a 0.37% relative net increase in forest lands. The preliminary structure of the LULUCF network showed that cropland was the land-use type that changed most, and both cropland and grassland were mainly transformed into new forest land. Thus, during this period in the Temperate FAO Ecozone in Europe, there was a moderate upward trend of forest area, in contrast with the results found by other authors, who described higher increases in these forests during comparable periods. In the coming years, the greater availability of VHR images will improve LULUCF monitoring and network building through the Collect Earth platform. The analysis of available VHR images also showed that mixed and monospecific forests represented 44.3% and 46.5%, respectively, of the forest land area. These results indicate high discrepancies with other forest inventories, highlighting the need for the homogenization of forest inventories, which the GFS and Collect Earth could facilitate. Lastly, the analysis of available VHR images also showed that disturbances affected 14.9% of the study area. Wood harvesting (tree felling) was the most frequent disturbance (67.47% of disturbed forests), while fires only disturbed 0.14% of forests. However, considering broadleaf and mixed deciduous broadleaf forests, both tree felling and pastoralism had a similar impact; in riparian and gallery forests, the only disturbance was flooding. According to other authors, the study area showed a strong correlation between canopy mortality and reported wood removal when "close-to-nature" silviculture replaced the clear-cut system. In conclusion, the GFS project based on the Collect Earth platform supported by VHR images provides new opportunities for data collection and analysis at large scales. These data can help validate the models of global environmental change and guide land-use decision-makers.

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