D4.2

ASSESSMENT OF THE CLIMATE SENSITIVITY OF LAND-BASED MITIGATION TECHNOLOGIES

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Short Summary of results

The document provides an overview of the work that has been done on the sensitivity of Land-based Mitigation Technology (LMT) approaches to climate variations to better understand the climate conditions that favour or compromise biomass production and CO_2 sequestration potentials.

The objective of this deliverable is to identify climate-related risk factors and sensitivities that may affect the LMTs and their large-scale implementation. For that we present: 1) literature research on the climate-related risks and sensitivities; 2) Information on climate-related sensitivities extracted from the stakeholder surveys; and 3) Specific analysis based on Earth Observation (EO) data: regarding climate-related sensitivities of LMTs for the climate (change) risk assessment.

These three elements refer to similar (qualitative) risk factors, such as temperature (high extremes), drought (intensity and frequency) and precipitation (decreasing, unpredictability and/or strong). These key risks factors may constitute a limitation in the large-scale implementation of LMTs at the plant development level and consequent carbon uptake.

These results will be considered in the analysis of climate-related risks in Task 4.3 on ‘Systematic climate risk assessment for local LMT actions’, when analyzing climate change scenarios for risk factors relevant to LMT and its changes that partly already emerge and will be considered for global scale-up.

Evidence of accomplishment

This report includes documentation of our work from December 2020 until August of 2022 of the analysis to better understand climate conditions that favour or compromise the different LMT solutions in their effectiveness as carbon storage in the various LMT case studies, including data collected online and in the field, collaboration between technology partners, and our online brainstorming/discussion sessions.

Preface

Negative emission solutions are expected to play a pivotal role in future climate actions and net zero emissions policy scenarios. To date most climate actions have focussed on phasing out fossil fuels and reducing greenhouse gas emissions in, for example, industry, electricity, and transport. While zero emission trajectories in these sectors will remain a priority for decades to come, it is expected that residual GHG emissions will remain. To be able to fulfil the Paris Agreement and meet the world's climate goals, research, policy and markets are increasingly looking at negative emission solutions.

This is why the nineteen LANDMARC consortium partners work together in order to:

- Estimate the climate impact of land-based negative emission solutions, in agriculture, forestry, and other land-use sectors
- Assess the potential for regional and global upscaling of negative emission solutions
- Map their potential environmental, economic, and social co-benefits and trade-offs

LANDMARC is an interdisciplinary consortium with expertise from ecology, engineering, climate sciences, global carbon cycle, soil sciences, satellite earth observation sciences, agronomy, economics, social sciences, and business. There is a balanced representation of partners from academia, SMEs, and NGOs from the EU, Africa, Asia, and the Americas, which ensures a wide coverage of LMTs operating in different contexts (e.g., climates, land-use practices, socio-economic etc.) and spatial scales.

The LANDMARC project consortium:

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Executive summary

The purpose of this deliverable is to identify climate-related risk factors and sensitivities that may affect land-based mitigation technologies (LMTs) and their large-scale implementation. Proper recognition of the exposure and vulnerability of LMTs to climate variations and climate-related hazards, will help to better understand the climate conditions that can favour or compromise biomass production (vegetation growth) and the associated CO_2 sequestration potentials.

Ideally, we would like to be able to identify specific threshold values for these climatic risk factors. However, such values are difficult to obtain due to the complexity of interacting effects, e.g., the vegetation shows different responses at different locations due to the climatic conditions, plant species, plant genetics, soil, and hydrological conditions. Also, the availability of Earth Observation (EO) data can be severely limited (e.g., regarding the length of records of the EO data used in our initial assessment) to adequately understand the vegetation responses to climate variations. In this document, we try to find answers to the research questions associated with how key climate variables are related to biomass and vegetation sequestration potential.

In our efforts to better understand climate-related risk factors and sensitivities that may affect the LMTs and their large-scale implementation, we present in Section 1 results from a literature review on climate-related risks and sensitivities. In Section 2 we provide some qualitative information on climate-related sensitivities extracted from stakeholder surveys, while in Section 3 we provide – with the help of EO data – a more in-depth analysis on climate-related sensitivities of LMTs on the Iberian Peninsula (Dehesas and Montados) for the climate (change) risk and sensitivity assessment.

In the *first section*, we identify that the main atmospheric variables driving significant changes in carbon and land cover are temperature and precipitation. The temperature (range), drought (intensity, frequency), or possibly atmospheric CO_2 concentration are potentially the future strongest climate risks for LMTs. LMTs (in the form of lasting vegetation growth and subsequent carbon storage) show a reduced effectiveness with increasing temperatures and decreasing precipitation. In regions characterized by hot and dry climate, further temperature increases will increase vegetation respiration, and photosynthesis will decrease demonstrating that the plant will not adapt to this climate change. In climatic moderate regions, there will be a potential to improve the climate resilience of LMTs by selecting tree/vegetation species that are best fit for the purpose, i.e., selecting plant species that thrive better in a warmer or drier climate.

The *second section* provides some preliminary results on the climate sensitivity of LMTs in different countries. These results are derived from the stakeholder surveys carried out as part of task 4.1 (‘Qualitative climate risk assessment’). The full results of this survey will be presented in more detail in the D4.1 ‘Climate risk assessment and initial risk management plan’ (Publishing date: December 2022). The initial survey results show that for the LMTs, afforestation, agroforestry, peatland rewetting, soil fertility, dry seeded rice, forest management and pastures, heavy rainfalls (unpredictability and/or strong), temperature extremes (heat/cold waves) and drought appear to be identified as the dominant climatic risk factors.

In the *third section*, we present a quantitative analysis of site-specific data from WP3 ('Improving Earth Systems Observations: asses and measure potential to fix carbon')[1] and remote sensing data (e.g., from TROPOMI, Sentinel-1 and Sentinel-2) to link a proxy measure of biomass and carbon uptake to climate observations. Differences in the location of plant species are associated with precipitation and temperature. In the case of Cork oak we see that its climate resilience is related to the annual thermal accumulation and not so much to precipitation, while Evergreen oak shows to be more resistant to extreme conditions of water and thermal stress. In Portugal, the annual Solar-Induced Chlorophyll Fluorescence (SIF) maps (2018-2021) shows that regions with higher SIF values are correlated with best conditions for growing and hence with higher photosynthetic carbon uptake, i.e., plants with more photosynthetic activity and consequently with more biomass potential. Similar positive correlations between biomass and carbon uptake potential with SIF were observed in Colombia and in other case studies countries, where low and high values of SIF mean apparently correspond to low and high values of biomass and carbon uptake. These results are in accordance with the study in climate risk for reforestation in north-central China where positive correlations between the increased forest cover and SIF observation over most of the afforested regions were observed and in which the inter-annual variation in SIF is, besides by land use change, impacted by climatic factors.

In summary, SIF showed to be a very powerful tool to study plants biomass and CO2 sequestration potential and plants biomes for specific local interventions for climate change adaptation. SIF can potentially be used to define bioindicators for specific regions to help better design specific policies in terms of the species (i.e., plant genetics and their resilience to climate change in plant dependent LMTs) that must be considered for future plantations and climate change adaptation. Although this SIF approach showed to be promising, further studies/analyses between SIF and specific climate-related risks should be developed to achieve a robust quantitative understanding of the sensitivity of LMTs to carbon uptake.

Overall, the assessments performed in all three sections of this report produce similar sets of key climatic risk factors, including temperature (high extremes), drought (intensity and frequency) and precipitation (decreasing, unpredictability and/or strong) that can negatively affect the effectiveness of LMTs. As such, these key risks factors may constitute a limitation in the large-scale implementation of LMTs at the plant development level and consequent carbon uptake (emission reduction and carbon removal). Further, the analysis of climate change scenarios for risk factors relevant to LMT should not decouple temperature and precipitation.

These results will be considered in the analysis of the climate-related risks in Task 4.3 ('Systematic climate risk assessment for local LMT actions').

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[1] Notably Tasks 3.1 ('Remote sensing data collection') and 3.2 ('In situ measurements and data collection').

1. Literature research on the climate-related risks and sensitivities

Weather and climate extremes can have devastating socio-economic effects worldwide and at the same time they can also affect the environment, including land-based mitigation technologies (LMTs)[2] that either preserve existing land-based C-stocks (by avoiding CO_2 emissions) or absorb CO_2 from (removal) the atmosphere. By deteriorating the effectiveness of LMTs in storing carbon, such weather and climate extremes can cause unwanted feedbacks to climate that can exacerbate the ongoing anthropogenic climate change. In general, the main atmospheric variables driving significant changes in carbon and land cover are temperature and precipitation, although others may be relevant too.

The goal of this review is to extract from the current literature *what* are potentially the strongest climate risks for LMTs, and *how* sensitive the LMTs are to those climate risks, specifically to (a) future temperature (range), and (b) future drought (intensity, frequency), or possibly (c) future atmospheric CO_2 concentration. The outcome of this literature review should lead to an improved understanding of the resilience of various LMTs on a hotter planet, and be useful input to LANDMARC Task 4.3, which targets climate risks to and the climate sensitivity of LMTs and aims at setting up a 'climate atlas' to indicate where LMTs are most robust or less resilient against climate change.

Methodology

In our literature review, we followed these steps. We first discussed with WP4-lead (BSC) on what sort of papers would be useful for the literature study. We then executed a Google Scholar search with search keywords including 'reforestation', 'afforestation', 'carbon storage', 'climate change', 'robustness', 'climate risks' to find key papers. After reading the key papers, we scanned the reference lists from those papers to find further relevant studies. Our focus was on scientific articles from the last 5 years (2017-2022). Finally, we read the papers and isolated take-home messages, reported the main uncertainties for the LMT to be persistent into the future, and (if possible) document/quantify climate sensitivity of the LMT.

1.1 Climate sensitivity/risk of specific soil and vegetation of LMTs

From our reading of recent peer-reviewed papers (more than 15[3]), we found that the effectiveness of land management techniques in permanently capturing carbon is surrounded by many uncertainties. The LMTs under consideration in LANDMARC are classified as forestry (reforestation and afforestation), agriculture, soil, and ecosystem management, and BECCS and biochar, two 'additional' technologies dependent on land-based management practices in the AFOLU sector (Agriculture

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[2] LMTs: (land based mitigation technologies) are defined as land management techniques in AFOLU sectors (Agriculture Forestry and Other Land Use) that mitigate and/or sequester carbon and contribute to environmental and social sustainability

[3] Some of these papers were discarded as they were not sufficiently on topic.

Forestry and other Land use). Here our focus is on the capacity of vegetation growth in general to contribute to carbon capture through the above LMTs and we do not focus on the added technologies of BECCS and biochar on land use practices, noting that many of the climate sensitivities and risks that apply on forestry also apply on BECCS, which requires vegetation growth.

An overall conclusion that can be drawn from the literature review is that LMTs (in the form of lasting vegetation growth and subsequent C-storage) show a reduced effectiveness with increasing temperatures and decreasing precipitation. In more detail, the papers mentioned the below 5 factors as making lasting C-storage from LMTs particularly uncertain:

1) Uncertainty in climate change (especially temperature and precipitation) itself;
2) Uncertainty how soils (including soil moisture and soil carbon content) and available nutrients (nitrogen, phosphorus) will evolve;
3) Unclear if proper land management and vegetation species selection (including shifting biomes) can be sustainably achieved and how (increasing) erosion should be kept in check;
4) Unclear how extreme events such as droughts, wildfires, and plagues or pests will affect speed of recovery of LMTs in capturing carbon; and
5) The climate impact on litter and soil carbon turnover and saturation points (respiration).

The factors listed above show convincing correlation, which implies an obscure or sometimes unclear cause-effect relationship between these factors. For example, whether climate is on a RCP1.5, RCP4.5, or RCP8.0 trajectory (factor 1 above) is an important driver for the speed with which land management practices need to select appropriate species (factor 3) and consider fire management techniques (factor 4). Also, the growth rate of forests depends not only on future nutrient availability (factor 2) and future temperature (factor 1), but also very much on the success of vegetation selection and management practices (factor 3). One other, less crucial aspect of relevance to LMTs mentioned in the papers is the CO_2-fertilizer effect with higher atmospheric CO_2 concentrations, more carbon can be captured in otherwise similar circumstances (Le Noe et al., 2021; Wang et al., 2022).

Below we report on LMT-effectiveness and their climate risks for specific soil and vegetation types across the world.

Northern Hemisphere Forests

One study assessed carbon uptake in California and found that temperature and precipitation control aboveground live carbon (Coffield et al., 2021). For CMIP5 RCP8.5 and RCP4.5 scenarios, they found that increases in (average and extreme) temperatures cause biomass decline, and RCP8.5 is the scenario having the greatest loss of forest cover and changes in their forest typology, driven by wildfires, drought, and insect-driven mortality. Coffield et al. (2021) also computed the vulnerability of California forest carbon offset projects and found that most of the state is set to lose carbon under the RCP8.5 scenario, in line with Duffy et al. (2021) and with findings that frequently burned plots (likely under RCP8.5) experience a decline in surface soil carbon and nitrogen (Pellegrini et al., 2017). Such study could be useful in the future, for identifying regions where mitigation efforts and carbon uptake is appropriate, and to study the known hotspots where climatic risks occur, providing risk assessment to policy makers and policy executives to take better action to minimize climate risks. Another study focused on the southwestern USA created an index for assessing forest drought-stress since drought may reduce tree productivity and survival in many ecosystems (Park Williams et al., 2013). The index shows a change in forest structure and composition by the end of the 21st century and tree mortality may be caused by bark-beetle attack and wildfires.

The European summers of 2018 and 2019 were dry and hot compared to previous years. Bastos et al. (2021) analysed these two summers and their interactions in terms of impacts on ecosystems and vegetation response. They found one region dominated by grasslands and crops showing larger impacts because of high sensitivity to heat and drought, and a second region dominated by forests and grasslands that showed browning from summer 2018 to summer 2019. In the latter case, the former summer had a preconditioning role on the impacts of the latter. Bastos et al. (2021) conclude that European summers are projected to become drier and hotter, and this could pose a threat to European forests.

Tropical Forests

Bennett et al. (2021) argue that the response of tropical forests to environmental change are critical uncertainties in predicting future impacts of climate change. Therefore, they assessed the impacts of the 2015-2016 El Niño event on African tropical forests and found that drought decreased carbon uptake and vegetation growth and biomass accumulation of the forests. This is strongly in line with the findings from satellite and Eddy Covariance measurements over the Tropics in Duffy et al. (2021) and Huang et al. (2021).

A recent issue (18 August 2022) of the journal *Nature* included a collection of articles about forest resilience and tree mortality. Two papers highlighted the decreasing resilience (or increased mortality) of trees in tropical forests: Bauman et al. (2022) suggest that increased water stress, driven by global warming, may be the primary cause of increasing tree mortality in moist tropical forests. Forzieri et al. (2022) conclude, from a global analysis based on satellite-based vegetation indices, that tropical and arid forests go through a decline in resilience related to water shortage and climate variability.

Peatlands

Loisel et al. (2021) identified the main sources of change for carbon balance in peatlands as temperature, atmospheric pollution, sea level rise, fire, permafrost, moisture, and land use. Peatlands are still a very important sink of carbon (Loisel et al., 2021) but they may change and become a source in the near future due to fires, permafrost degradation and sea-level rise. Current climate models also do not include peatland ecosystems, making their study an even more important subject, since they store about 25% of global carbon stock.

Soils and ecosystems

Soils and ecosystems across the world are threatened by soil degradation with important impacts on crop yields, soil biota, biogeochemical cycles, and consequently also LMTs. Guerra et al. (2020) report on a decline in soil erosion protection leading to increasing soil erosion rates across the world in the last 15 years. The stronger erosion comes mostly from rainfall erosivity, in regions with large run-off (i.e., slopes, mountains) and threatens not only the functioning of ecosystems but also reduces soil biodiversity. Guerra et al. (2020) find that patterns of soil erosion protection varied significantly across space and time, with extensive areas of the Southern Hemisphere losing capacity to protect the soil over time. This reduction in global soil protection appears to be a systematic negative trend across all terrestrial biomes considered. This negative trend is strongest (-10% in 13 years) in flooded grasslands, temperate grasslands, and savannas (−7%), Mediterranean regions (−6%) and in temperate broadleaf and mixed forests. Most of the increased soil erosion risk comes from climate change (66%), and one third is caused by a reduction of vegetation cover.

Another concern for soils is that global warming is expected to accelerate soil carbon losses via microbial decomposition. Garcia-Palacios et al. (2021) argue that a strong positive carbon-climate feedback is imminent. Patoine et al. (2022) find that soil microbial carbon has been reducing over the past decades, mostly driven by higher temperatures. With a decrease in soil microbial carbon, dark CO_2 fixation is also likely to decrease, therefore reducing the climate mitigation effects of soil microbial communities. They propose that improvements in land management are required to be leveraged as a climate change mitigation strategy, to preserve microbial communities and to sequester carbon.

Some clear lessons and recommendations on LMT-effectiveness extracted from the papers:

- *Deforestation drove C emissions, enhanced growth rate drives net C sink. “Deforestation should be halted to turn global forests into a net forest C sink” (Le Noe et al., 2021).*
- *When planning (re)forestation, the full range of the future’s climate, soil and nutrient availability, and the selection of ‘feasible’ species needs to be considered. “Some species will be more appropriate [in a certain climate zone] than others in the new climate” (Mackenzie and Mahoney, 2020).*
- *The current climate is in the optimal range for C-uptake by plants. A FLUXNET meta-analysis suggests that in a warmer climate, photosynthesis will decline, and respiration increase (Duffy et al., 2021), especially in the Tropics.*
- *Efforts to protect soil from erosion, by locally managing rainfall extremes, will be ever more important to maintain crop yields, ecosystem services, and carbon-capture in a climate with more extreme precipitation events (Guerra et al., 2020). Conservation, rewilding, and reforestation efforts focused on vulnerable areas can strongly contribute to supporting soil ecosystem functions and services, and soil communities (Patoine et al., 2022).*
- *Especially carbon uptake in the Tropics and already arid regions are vulnerable for further climate change in the form of water shortages and high temperatures.*

1.2 Main threshold and/or quantitative climate sensitivities identified

One common driver of LMT sensitivity to climate change quantified from the papers above is the temperature dependence of the global photosynthesis and respiration (Duffy et al., 2021), as derived from the entire historical record of global FLUXNET-measurements. A similar study by Huang et al. (2019) has assessed at which range of temperatures, vegetation productivity is at its optimum.

Photosynthesis has a distinct maximum of temperature of 18 °C and 28 °C for C3 and C4 plants[1], respectively. Any increase in temperature beyond these levels leads to a decrease in photosynthesis. In stark contrast, respiration keeps increasing for currently observed temperatures up to 38°C (Figure 1). Current climate is in the regime where photosynthesis thrives, and respiration is still coupled to photosynthesis.

[1] C3 plants are plants that tend to thrive in areas where sunlight intensity is moderate, temperatures are moderate, CO_2 concentrations are around 200 ppm or higher, and groundwater is plentiful. This is often the case in mid- to high latitudes. In contrast, C4 plants have a higher rate of photosynthesis and a lower rate of photorespiration, which makes them fit to grow in warmer regions, so that they tend to dominate tropical grasslands and savannahs.

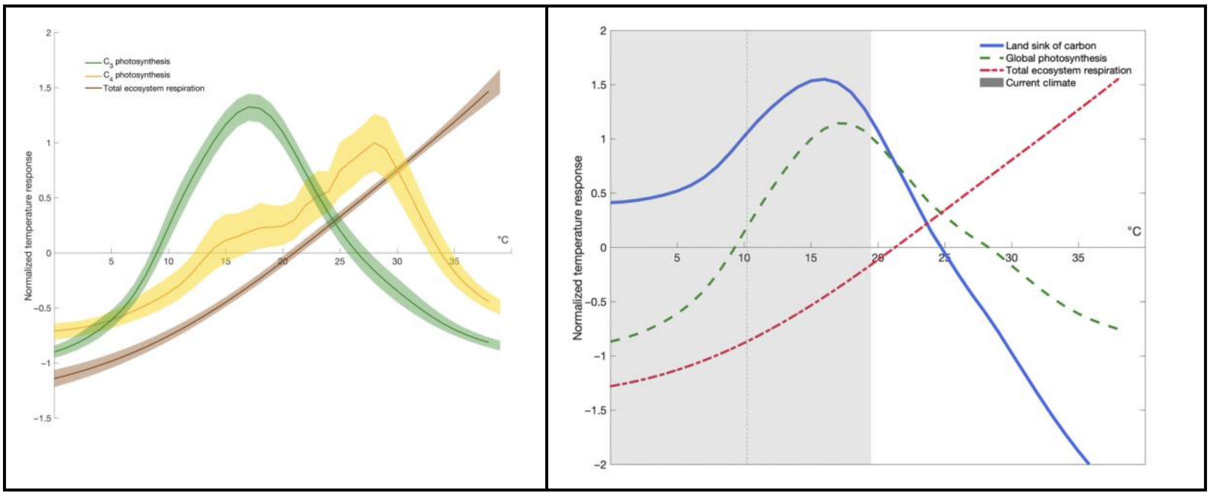

Figure 1: *Left:* averaged temperature-response of C3 (green) and C4 (yellow) plants to ambient temperature, as derived from global FLUXNET data in Duffy et al. (2021). The brown curve indicates the temperature sensitivity of respiration in the current climate as recorded in the 20-yr FLUXNET dataset. *Right:* calculated temperature dependence of the land carbon-sink. The grey area shows that in the current climate the FLUXNET-derived total land sink of C is large and positive, but that the uptake will decline because of reduced photosynthesis and increased respiration in the projected future climate.

With further temperature increases, however, photosynthesis and respiration will uncouple and move to a regime wherein respiration will increase and photosynthesis decrease. Thus, photosynthesis does not seem to adapt to a warmer and drier climate. Failure to account for sensitivities shown in Figure 1 will lead to a much too optimistic view of the effectiveness of land mitigation techniques in permanently storing carbon. This implies that there is potential to improve the climate resilience of

LMTs in moderate regions by selecting tree/vegetation species that are best fit for purpose (e.g., MacKenzie and Mahony, 2021), for instance, because they thrive better in a warmer or drier climate. For LMTs situated in already hot and dry (tropical) regions, maintaining carbon uptake will be jeopardized by increasing temperatures and reduced water availability, unless massive improvements in hydrological management are being put in place.

The right panel of Figure 1 shows that as long as the Earth's climate stays within the grey shaded area (the current climate) the FLUXNET-derived total land sink of C is large and positive. For temperatures higher than current (the white area), the C-uptake will decline because of reduced photosynthesis and increased respiration, as plants do not thrive under hotter circumstances. Large-scale adjustments or migration of vegetation, as discussed in MacKenzie and Mahony (2021), could help to maintain the C-uptake by plants in the future climate.

The results of the Duffy et al. (2021) study are in line with those from Huang et al. (2019). Based on Eddy Covariance and satellite GPP proxies across the world, they also conclude that there is an optimum temperature for vegetation growth and that climate warming beyond that optimum will lead to substantial decreases in the capacity of vegetation to take up carbon. This is particularly relevant in the Tropics, where the optimum temperature for plant growth has already been reached, and further warming will lead to a decrease in canopy photosynthesis. In Temperate or Boreal ecosystems, optimum temperatures for plant growth have not yet been reached, providing a safer margin for LMTs under climate change in those regions.

A recent study examined growth of deciduous trees in a warming climate (Dow et al. 2022). Their findings imply that any extra CO_2 uptake in years with warmer spring temperatures does not significantly contribute to increased sequestration in long-lived woody stem biomass. Rather (and contradicting projections from global carbon cycle models) their empirical results imply that warming spring temperatures are unlikely to increase woody productivity enough to strengthen the long-term CO_2 sink of temperate deciduous forests.

Other sensitivities: the FLUXNET-analysis does not suggest any effect of CO_2-fertilization on GPP. The net C-uptake is driven by temperature (and therefore water stress) rather than atmospheric CO_2 availability, at least in the current climate.

2. Information on climate-related sensitivities extracted from the stakeholder surveys

To validate the findings from the literature review we present the preliminary results of the stakeholders' views[4] (Table 1) about the climate sensitivity of LMT solutions to climate variations. Preliminary results on the following LMTs per respective countries are included:

1) Afforestation/Agroforestry in Netherlands, Kenya, Nepal and Vietnam;
2) Peatland Rewetting in Netherlands;
3) Soil Fertility in Kenya;
4) Dry seeded rice cultivation in Nepal.

This survey is designed as a semi-open interview, with a reach of 3 to 5 stakeholders consulted per LMT and Case Study country. The interviews were predominantly carried out as a video call, and the focus was on priming quality of the responses over quantity, with the average interview taking from 45 to 60 minutes.

To have a good representation of the opinions expressed, stakeholders from all profiles (land users, researchers/consultants, public administrators, NGOs) were interviewed, with focus on achieving gender parity and including interviewees from every age range.

The results shown in this paragraph reflect only the partial results[5] and should be seen as preliminary. Further, stakeholder consultations are being carried out for Task 4.1 (Qualitative climate risk assessment), with D4.1 'Climate risk assessment and initial risk management plan' (publication date December 2022). The results discussed in this section are based on 54 interviews from an expected total of 100 to 120. The main limitation is that not for all LANDMARC Case Study countries[6] results are represented, and the number of consultations carried out for some LMTs are not yet complete. Keeping this in mind, we find the currently available data relevant and supportive for this deliverable. Deliverable 4.1 will elaborate further on the findings of stakeholder consultations.

In Table 1, we can observe that the major concerns regarding the *climatic risks* for the LMTs afforestation/agroforestry, peatland rewetting, soil fertility, rice dry seeded, forestry and pastures are soil conservation, water and nutrient retention, heavy rainfalls (unpredictability and/or strong), water floods, landslides, fires, heat/cold waves, as well as drought and strong winds.

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[4] At the time of writing of this report the survey was still ongoing.

[5] The survey covered a broader spectrum of topics.

[6] The LANDMARC case study countries are: Germany, Indonesia, Nepal, Kenia, Vietnam, Sweden, The Netherlands, Venezuela, Canada, Spain, Portugal, Switzerland, and Burkina Faso.

Table 1: The main climate risks identified by stakeholders in selected countries

Country	LMTs	Soil conservation	Water and nutrient retention	Heavy rainfall	Water floods	Land-slides	Fires	Heat, Cold waves	Drougth	Strong wind
Netherlands	Afforestation	X	X		X					
	Agroforestry	X	X		X					
	Peatland rewetting			X					X	
Kenya	Afforestation	X		X		X			X	
	Agroforestry	X		X		X			X	
	Soil fertility			X					X	
Nepal	Aforestation						X			
	Agroforestry						X			
	Rice dry seed	X	X	X						
Vietnam	Aforestation	X		X		X		X	X	X
	Agroforestry	X		X		X		X	X	X
Portugal	Aforestation	X	X	X			X	X	X	X
	Agroforestry	X	X	X			X	X	X	X
	Forestry	X	X	X			X	X	X	X
	Pastures	X	X						X	

Source: *Preliminary results of 54 semi-open interviews of stakeholders from all profiles (land users, researchers/consultants, public administrators, NGOs) with focus on achieving gender parity and including interviewees from every age range for the LMTs afforestation/agroforestry, peatland rewetting, soil fertility, rice dry seeded, forestry and pastures in Netherlands, Kenya, Nepal, Vietnam, and Portugal.*

The main climate risks cited by the interviewees are *drought* and the *unpredictability of rains*, which is increasing, following the pattern of stronger rain concentrated in fewer days, leading to an increase in death rates of young trees, landslides, and erosion (a major concern in the area, as all interviewees emphasize it). *Erosion* is also a climatic risk for agroforestry, and planting trees can even be impossible in areas heavily degraded by soil erosion. *Landslides* are also cited as affecting the mountainous areas and flash floods, such as the one that happened in 2020 in the Quang Nam province of Vietnam[7], and the deadly floods that occurred in 2021 in Germany and Belgium[8]. *Strong winds* can affect agroforestry, as they are not naturally protected by mountains. Heat waves can also have a bad effect on coffee production. Overall, the results of the interviews with stakeholders show that heat/cold waves and heavy rainfalls and drought are the main climate risks identified in the LMTs.

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[7] See: https://e.vnexpress.net/news/news/floods-paralyze-traffic-submerge-houses-in-quang-nam-4199771.html

[8] See: https://www.nytimes.com/2021/07/15/world/europe/flooding-germany-belgium-switzerland-netherlands.html and https://www.science.org/content/article/europe-s-deadly-floods-leave-scientists-stunned

As a general observation we note that, while most LMTs indeed have a carbon uptake potential, it is perhaps their adaptation and climate resilience potential what makes their implementation more valuable. The non-climate effects of certain LMTs, particularly those related to forestry, such as avoiding desertification, soil erosion, improving water balance and restoring degraded ecosystems are remarkable. Switching to these systems would allow to improve resilience towards climate change and make land use more climate resilient in the long term, aside from contributing to climate change mitigation.

3. Specific analysis based on EO data: regarding climate-related sensitivities of LMTs for the climate (change) risk assessment

While in the previous points, we present the literature review and the local stakeholders' point of view of climate sensitivity of specific soil and vegetation types (i.e., LMTs), here we present a quantitative analysis of site-specific data from WP3 'Improving Earth Systems Observations: asses and measure potential to fix carbon'[9] and remote sensing data (e.g., from TROPOMI, Sentinel-1 and Sentinel-2) to link proxy measure of biomass and carbon uptake to climate observations. The goal of this analysis is to better understand climate conditions that favour or compromise the different LMT solutions in their effectiveness as carbon storage.

3.1 Quantitative analysis of site-specific data

In the period from December 2020 to August 2022, remote sensing (RS) data (Task 3.1), and *in situ* data and results from in-situ measurements have been collected (Task 3.2) for the development of tools for carbon measurement in (CS) case studies (>1ha in size). These CS sites include (Figure 2):

- CS01-Agroforestry (The Netherlands),
- CS02- Peatland rewetting (The Netherlands),
- CS03-Forest management (Germany),
- CS12-Agroforestry (Coffee and cocoa; Indonesia),
- CS13-Agroforestry (Spain),
- CS16-Pastures in Montado (Portugal) & Dehesas (Spain)
- CS17-the new CS-Agroforestry (Palma) in Colombia.

The collection of Earth Observation data will continue during the remainder of the LANDMARC project. The key results/findings will be compiled and included in additional reports and publications. In this report, we will focus on CS16 which includes farms in Montado, Portugal and Dehesa, Spain covering several LMTs (e.g., grassland management, forest management and agroforestry). CS16 also have the most complete set of *in situ* measurements and data collection.[10]

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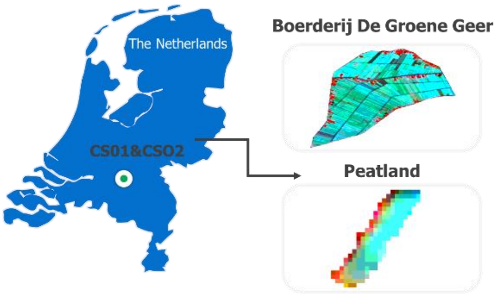
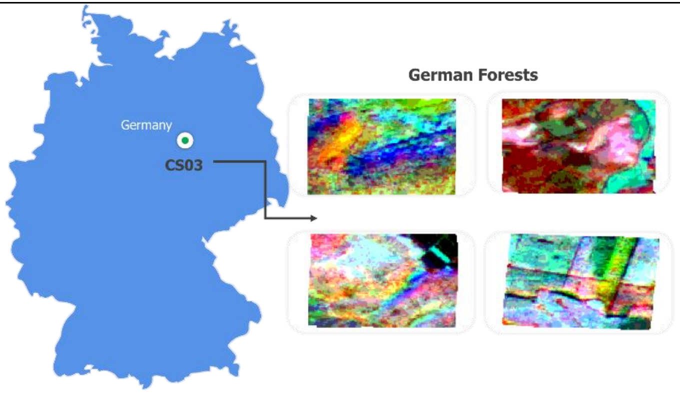
[9] Notably Tasks 3.1 ('Remote sensing data collection') and 3.2 ('In situ measurements and data collection').

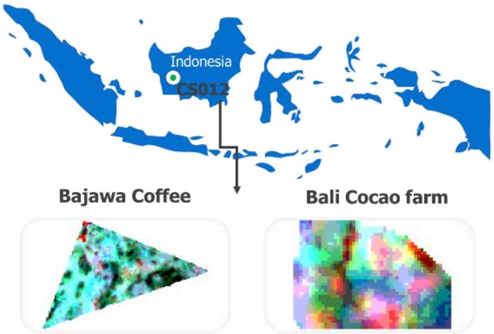
[10] See LANDMARC Deliverables:
D2.6 National LMT portfolio scaling narratives (publication date December 2022),
D2.8 CS Leaflets for further details on the CS (publication date February 2021) - report available via this link, and
D3.8 New Earth Observation Tools (publication date July 2022) – confidential report.



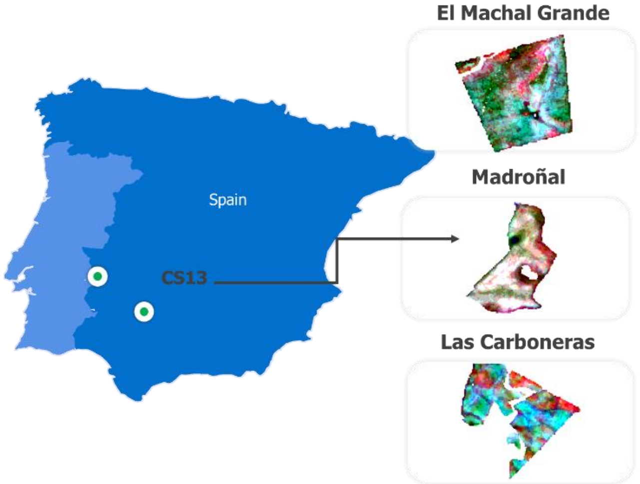
a) CS01 - Agroforestry & CS02 – Peatland rewetting in The Netherlands



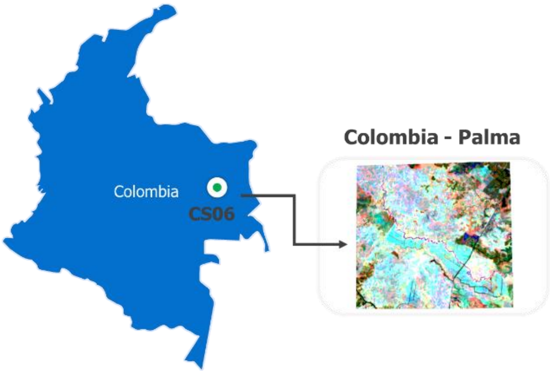
b) CS03 – Forest management in Germany



c) CS12 – Agroforestry (Coffee and cocoa) in Indonesia



d) CS16 – Pastures in Montado /Portugal) & Dehesas (Spain)



e) CS17 – Colombia Palma

f) CS16 - Pastures in Montado /Portugal) & Dehesas (Spain)

Legend of carbon maps:

Figure 2: Carbon measurement using Carbon Map Tool in the case studies (CS): a) CS01-Agroforestry & CS02- peatland rewetting in The Netherlands; b) CS03-Forest management in Germany; c) CS12-Agroforestry (coffee and cocoa) in Indonesia; d) CS13-Agroforestry in Spain; e) CS-Agroforestry (Palma) in Colombia; and f) CS16-Pastures in Montado (Portugal) & Dehesas (Spain).

The Montado in Portugal and Dehesa in Spain is one of the most characteristic landscapes on the Iberian Peninsula. They cover over four million hectares in Spain and around one million hectares in Portugal. The ecosystem was created by humans to meet their food needs in an environment where resources were scarce. By clearing the Mediterranean forest, a landscape was formed with scattered trees, mainly Cork oak (Figure 3a) and Evergreen oak (Figure 3b), which allowed the growth of grazing pastures and livestock to be raised, as well as agriculture and forestry. In addition to ensuring multiple productions, such as cork and firewood, beef, sheep, pigs and goats, mushrooms, aromatic herbs and honey, the Montado/Dehesa also supports a wide range of other ecosystem services, such as water cycle regulation, carbon fixation, erosion prevention, high biodiversity, recreational and leisure activities, and support of a local identity. Considered by the European Union to be of High Nature Value (HNV) system, Montado/Dehesa is a model of sustainable development which is of great ecological, economic, and social interest (Pinto-Correia et al., 2013).

a) *Quercus suber* (Cork oak)

b) *Quercus rotundifólia* (Evergreen oak)

Figure 3: a) *Quercus suber* (Cork oak) and b) *Quercus rotundifolia* (Evergreen oak).

Under standard conditions, vegetation presents optimal yield performance when it has optimally combined water, temperature, light, and nutrients to feed on. Therefore, the same LMT with the same species, but placed in different soil and climate conditions, can present different productive performances and resistance to change (in climate and other changes). In addition to these aspects associated with the controlling factors of biomass production, we have others, which go through the genetic variability of each species that makes up the LMT. For instance, in the specific case of Montado/Dehesa oak forests, we usually have annual species (pasture composed by grasses and legumes) and multi-annual species such as shrub species and forest species (Evergreen and Cork oaks).

The **annual species** (grasses and legumes) associated with the Montado/Dehesa pasture begin their vegetative cycle during autumn, after the first rains, producing seed during the spring and ending their life cycle around June, in the summer, when there is total absence of precipitation. For this type of species, which have thousands of individuals per hectare and that produce millions of seeds per year and per hectare, variations in the optimal climatic conditions can affect their reproduction and yield. However, given the high seed bank that they accumulate in the soil for a long time, they have the ability to be resilient when conditions change and even when change is very strong. For example, heat waves usually occur when annual species (grasses and legumes) have already ended their life cycle and therefore will not be affected strongly. These species may be affected more by the absence of precipitation and by very low temperatures in wintertime, which corresponds to the growth and reproduction period.

Multiannual species (like shrubs and forest species) may be more exposed to the pressures of inter-annual climate variations (Annex 1). However, they have other characteristics that make them more resilient than grasses/legumes, such as the possibility of: i) exploring a much greater volume and depth of soil when compared to species with an annual cycle (low root depth); and ii) having genetic adaptations to resist summer dryness (e.g., absorbing the relative humidity of the air through the leaves) and excess temperature (waxed and leathery leaves that reduce the effect of thermal radiation and decrease evapotranspiration). Cork and Evergreen oaks, the forest species that are associated with the Montado/Dehesa, are adapted to the extremes of the Mediterranean summer. Evergreen oak will grow in normal conditions when accumulated precipitation is normally greater than 300 mm, while Cork oak will grow in normal conditions in areas with annual accumulated precipitation greater than 500 mm. Both species resist maximum summer temperatures above 40°C.

Considering these different characteristics at the level of the genetic component, in Figure 4 we can see the potential and actual distributions of Cork and Evergreen oak in the Portugal mainland. Cork oak is predominantly located in the Southwest region and Evergreen oak is in the Southeast region. The differences in the location of these two species are essentially due to the characteristics associated with precipitation and temperature in these regions of mainland Portugal, i.e., more precipitation occurs in the Southwest than in the Southeast region.

Comparing Figure 4 and the analysis of the growing period (2018-2021) over mainland Portugal of **rainfall** annual accumulations (**Rain**, Figure 5a,d,g,j), **Land Surface Temperature** annual accumulations (**LST**; Figure 5b,e,h,k) and **Solar-Induced Chlorophyll Fluorescence** (**SIF**) annual mean of vegetation (Figure 5c,f,I,l), we observe that in the Southwest region of Portugal, i.e., the Montado Cork oak area, the annual thermal accumulation is lower compared to the corresponding Southeast region. Cork oak thus demonstrates a climate resilience that is related to the annual thermal accumulation and not so much to precipitation. On the other hand, the climate resilience of the current area of the Montado Evergreen oak, located in the Southeast area of Portugal region, shows to be more resistant to extreme conditions of water and thermal stress. These results of Montado distribution highlight the diversity of climatic situations to which the vegetation of these systems is subject to. Furthermore, these systems present a vegetation complexity since they include different types of species with different life cycles (e.g., grasses, legumes, shrubs, Cork, and Evergreen oaks) and with a high genetic diversity.

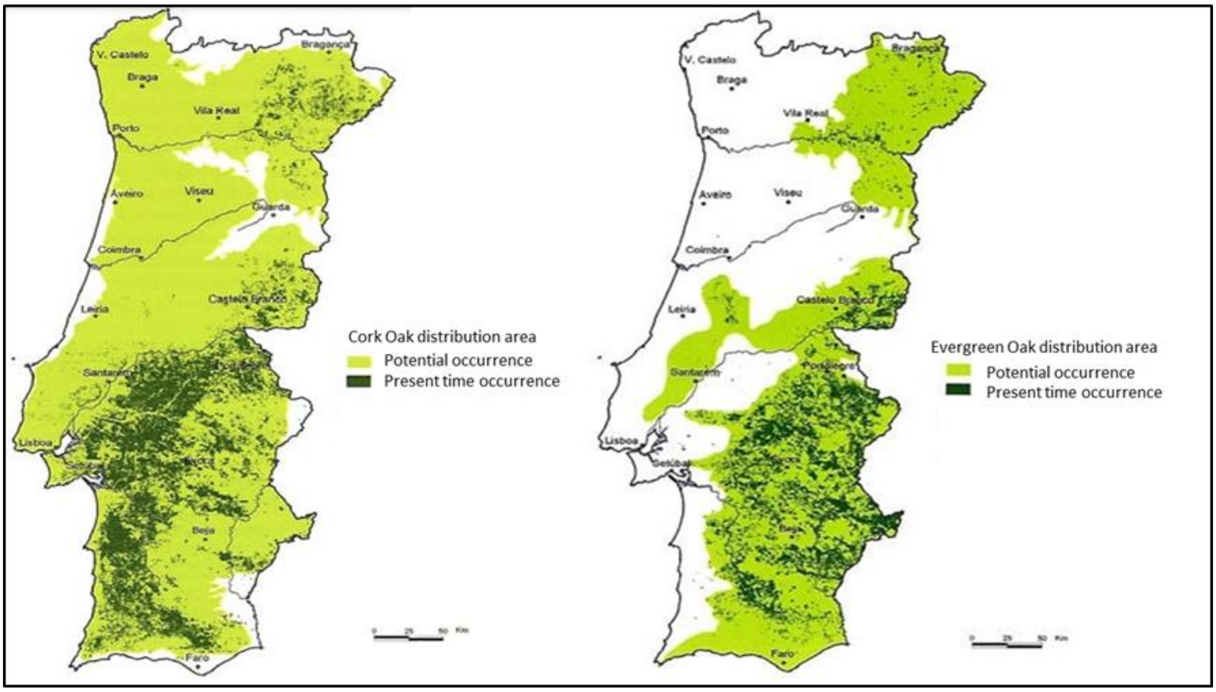
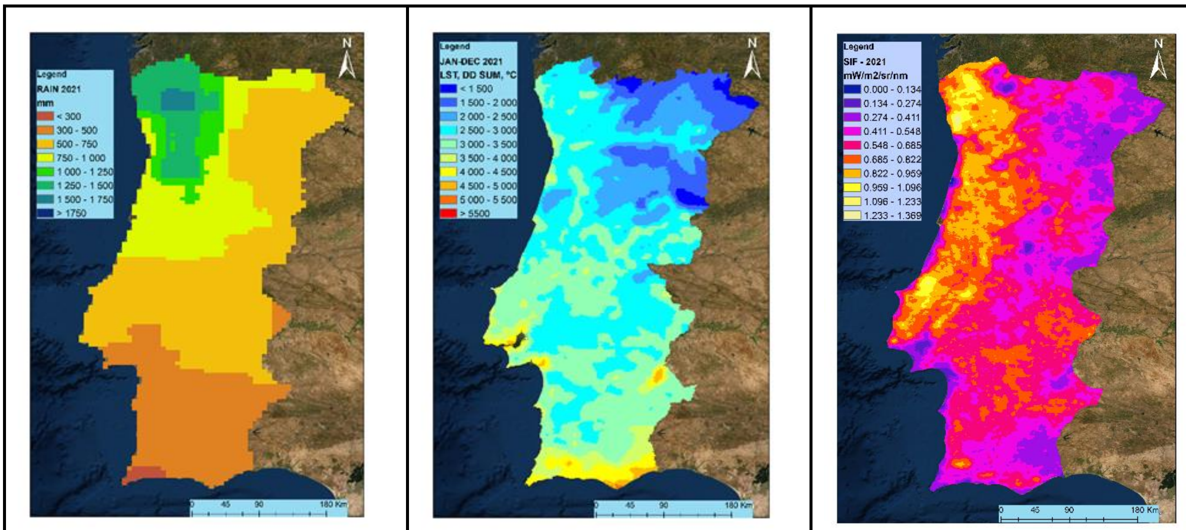


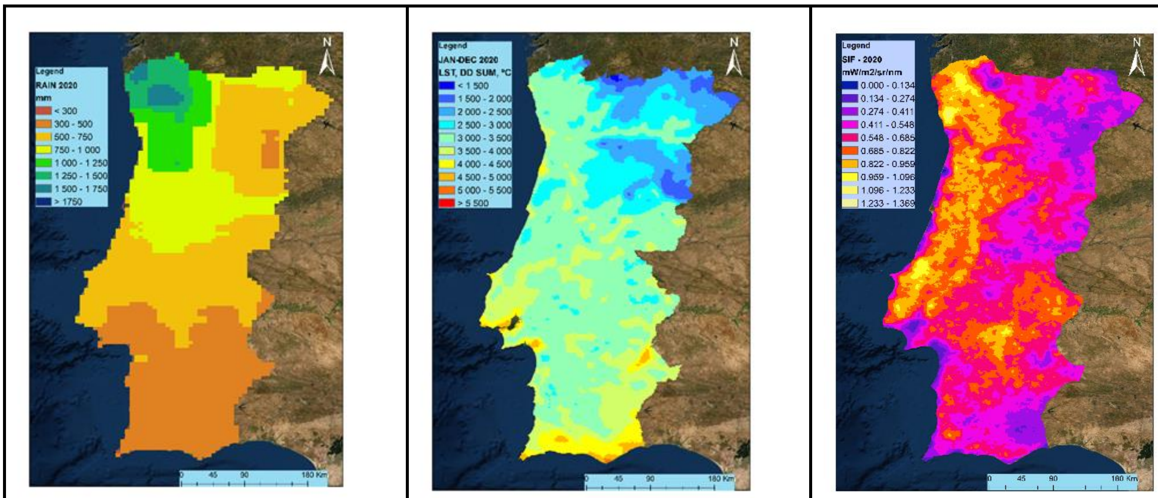
Figure 4: Potential and present time occurrence of Montado/Dehesa species distribution area (Cork oak and Evergreen oak) in Portugal (Vieira, 2007).



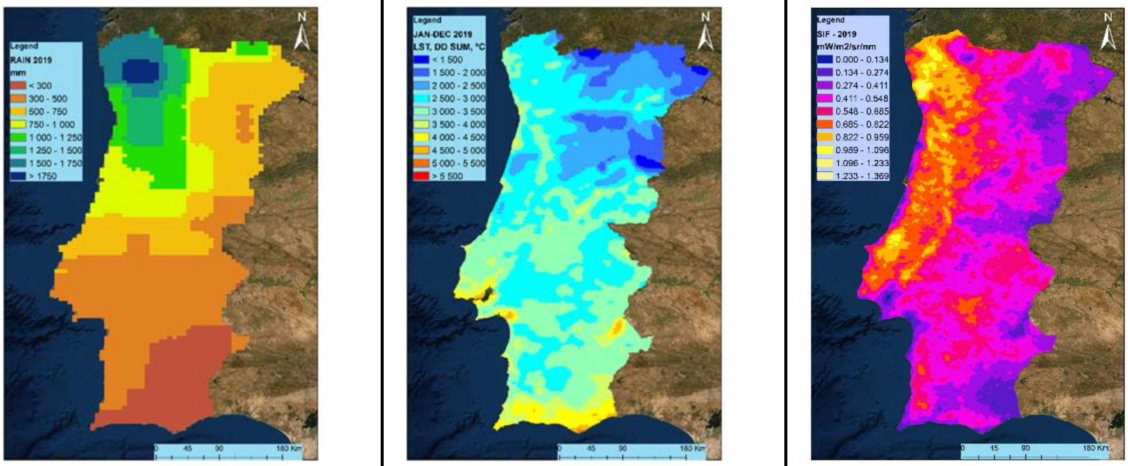
a) Rain 2021

b) LST 2021

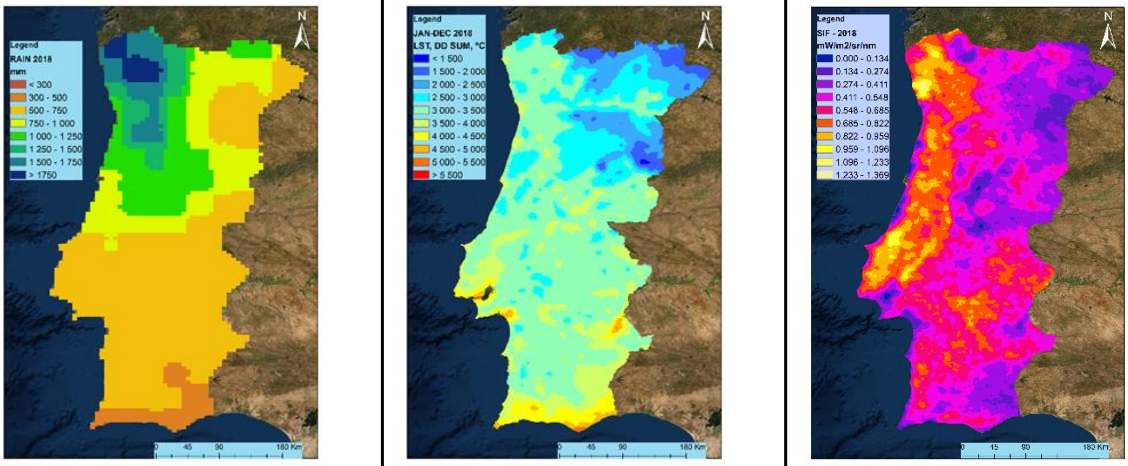
c) SIF 2021



d) Rain 2020 e) LST 2020 f) SIF 2020



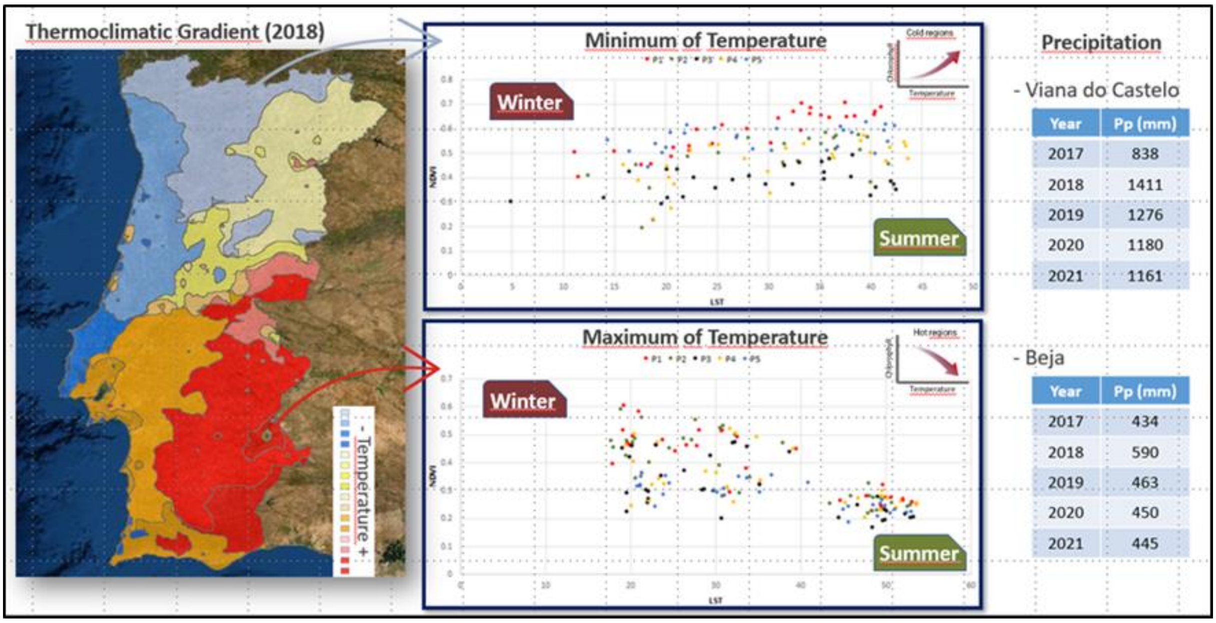
g) Rain 2019 h) LST 2019 i) SIF 2019



j) Rain 2018 k) LST 2018 l) SIF 2018

Figure 5: Growing period average from 2018-2021 of: i) rainfall annual accumulations (a, d, g, j); ii) Land Surface Temperature annual accumulations (LST, b, e, h, k); and iii) Solar-Induced Chlorophyll Fluorescence (SIF) annual mean of vegetation (c, f, I l), is presented for Portugal continent.

Based on the LST data, we built a thermo climatic gradient map and related the photosynthetic activity (NDVI) with the maximum and minimum temperature (LST) of Portugal in 2018 (Figure 6). The analysis of site-specific data show that raising the temperature in the North of the country, characterized by wet and cool winters and mild summers (Figure 5a,d,g,j; Figure 5b,e,h,k), stimulates photosynthetic activity, i.e., the biomass production, and hence the vegetation “comfortability” (i.e., plant photosynthetic activity). This is because in these regions, the low temperatures during winter (and not water) are a limiting factor for biomass production. On the other hand, in the South of the country, characterized by mild wet winters and warm to hot, dry summers, the high temperatures will reduce biomass production and vegetation “comfortability” because in these regions the low precipitation (and not temperature) is a limiting factor for biomass production.



- Viana do Castelo

Year	Pp (mm)
2017	838
2018	1411
2019	1276
2020	1180
2021	1161

- Beja

Year	Pp (mm)
2017	434
2018	590
2019	463
2020	450
2021	445

Figure 6: Photosynthetic activity (NDVI) and Land Surface Temperature (LST) behaviour in Portugal considering vegetation in the North regions (Viana do Castelo) and the vegetation in the South regions (Beja).

In order to measure the bulk vegetation “comfortability” considering grasses, shrubs and trees together, like in the Montado/Dehesa systems or other LMT portfolio sub-category (e.g., wetlands, croplands), TROPOMI SIF (Köhler and Frankenberg, 2020) maps were produced (Figure 5c,f,i,l) to detect the yearly (2018-2021) country variations vegetation “comfortability”. SIF, the Solar-Induced Chlorophyll Fluorescence emitted by plants, is highly correlated with Plant Gross Primary Productivity (PGPP), an indirect measure of plants “comfortability”.

The annual (2018 - 2021) SIF maps (Figure 5c,f,i,l) show a spatial trend presenting regions with higher SIF values when compared to other regions in the same country, which may be correlated with best conditions for growing and hence with higher photosynthetic carbon uptake, i.e., plants with more photosynthetic activity and consequently with more biomass potential. This is the case of the North coast which shows the highest SIF values because in this region the mild temperature and precipitation values do not limit vegetation growth throughout the year, including in the summertime, which are characterized by frequent foggy days. The high availability of water, temperature, radiation, and nutrients for plants causes this region to present high SIF values compared to the hotter and drier regions. In the Northeast and Southeast regions, vegetation face limitations due to low temperatures and low precipitation in the wintertime and low precipitation and high temperatures in the summertime (Figure 5). Because of that, the vegetation of these regions is more adapted for certain conditions than others. This fact shows the complexity and difficulty of evaluating vegetation resilience to climate change, not only due to different species variation but also due to intraspecies variation.

Considering the trees and shrubs zoning in Portugal (Annex 2) carried out by Cabral & Telles (2022), we observe that the local conditions influence the major species in a particular location as seen in the Montado/Dehesa areas. Trees species (e.g., *Quercus rotundifolia* and *Quercus ilex*) that are more resilient to low precipitation and high temperatures can exist very well in dry and hot regions or in other regions where the topography favours low water infiltration and poor soils. Trees species (e.g., *Quercus suber* and *Quercus pyrenaica*) that require more humid climates grow in more humid regions or in other regions where the topography favours water infiltration (bottom of the valleys). SIF maps shows (Figure 5c,f,i,l) that species adapted to hot and dry conditions, despite the fact that they can survive and grow there, will not have a very high Plant Gross Primary Productivity when compared to the species adapted to hot and humid regions. Interestingly the SIF maps Figure 5c,f,i,l also present a very similar distribution with the vegetation potential regions and vegetation series indicated in Cabral & Telles (2022) (see Annex 2). This reveals that SIF is a good indicator of:

i. edaphoclimatic conditions (temperature, radiation, nutrients, and water availability) for plant growth and biomass production;
ii. plant Gross Primary Productivity;
iii. carbon uptake;
iv. plant density;
v. plant photosynthesis;
vi. mineral/organic inputs concentrations for plants best performance and
vii. vegetation comfortability in time and space.

To illustrate the montado/dehesa climate resilience, i.e., vegetation potential regions of Cork oak and Evergreen oak, field inspections were carried out in July 2022 during a one-week heat wave (from 07/07/2022 to 13/07/2022) in the Iberian Peninsula (Figure 7). From the analysis of Figure 8 (photos taken during field inspection), we can see two *Quercus suber* trees close to each other with totally different behaviour. The left tree (Figure 8a) has a reduced canopy (i.e., losing leaves a genetic resilience strategy for Oak trees) contrary to the tree on the right. Several reasons could be responsible for that differential behaviour: i) intra specie genetic difference; ii) bigger and older tree needs more resources and because of that experienced a greater impact from the heat wave; iii) tree illnesses; iv) bigger and older trees are located in a ground position where soil resources are scarcer. This type of behaviour can be seen in a landscape perspective in which some Oak trees when compared to others show less and more brown leaves (Figure 9). Surely genetic variability and local soil and topography conditions play an important role in this Oak trees' behaviour. From the field inspection the Oak trees that were feeling more the heat wave were: i) old trees; ii) sick trees; and iii) trees where agriculture pressure was present (Figure 10).

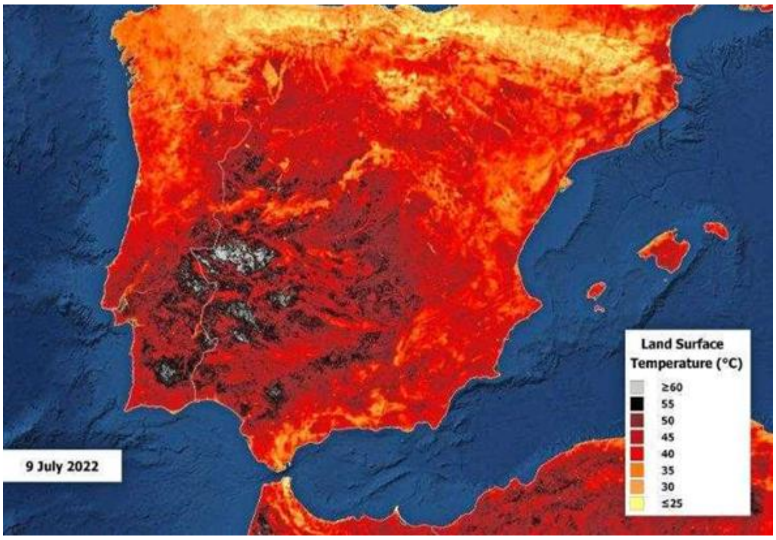


Figure 7: July 2022 heat wave mapping: Montado/Dehesa trees climate resilience.

Figure 8: Montado/Dehesa trees canopy adjustment (a resilience strategy): a) Two *Quercus suber* trees close each other, the left tree is reducing its canopy/losing leaves and the right tree is not; b) A detailed photo from a) left tree; c) A detailed photo from a) right tree; d) The ground under the a) left tree.

a) b)

c) d)

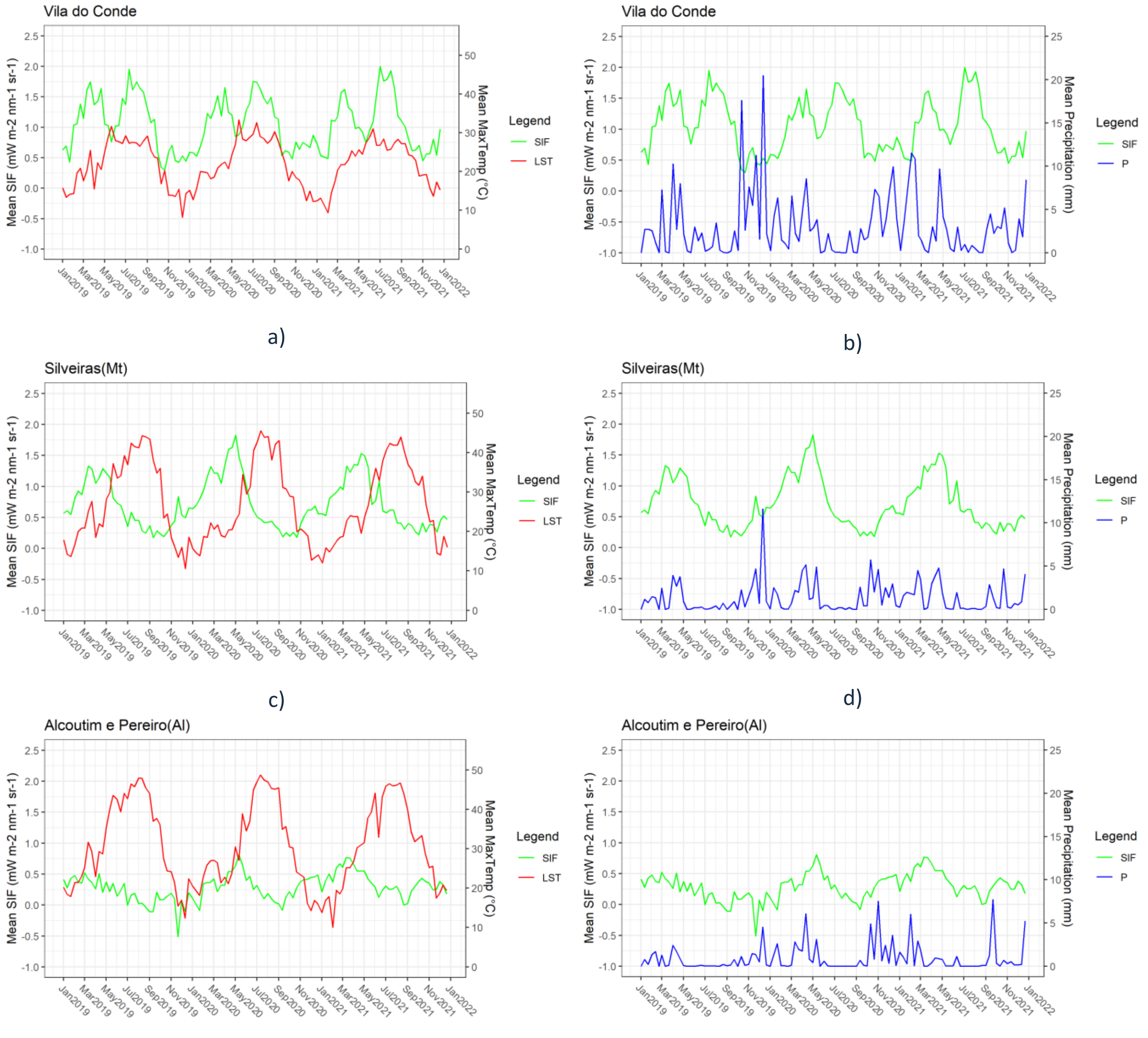
Figure 9: Montado/Dehesa trees genetic variability (a resilience strategy): Several trees seem greenish and do not seem to respond to the heat wave while other trees have a more brownish canopy (dead leaves) and with less leaves. The tress are almost the same locations but respond differently the heat wave conditions due to their genetic variability and due to local soil and topography conditions.

a) b)

c) d)

Figure 10: Montado/Dehesa degradation by agriculture intensification (a resilience bottle neck): a) Dying old Oak tree due to soil machinery implements cutting superficial roots; b), c) and d) Sick trees due to natural reasons and due to cattle intensification.

Regarding the Montado/Dehesa Plant Gross Primary Productivity and CO_2 sequestration, we analysed the relation between SIF and the mean maximum temperature and mean precipitation in three regions of North, Centre, and South of Portugal (Figure 11). The hot and dry regions (Figure 11e,f - Alcoutim e Pereira) appear to have lower sequestration potential when compared to humid and hot regions (Figure 11a,b,c,d – Vila do Conde and Silveiras) because of limiting factors for growth and sequestration.



a)

b)

c)

d)

e)

f)

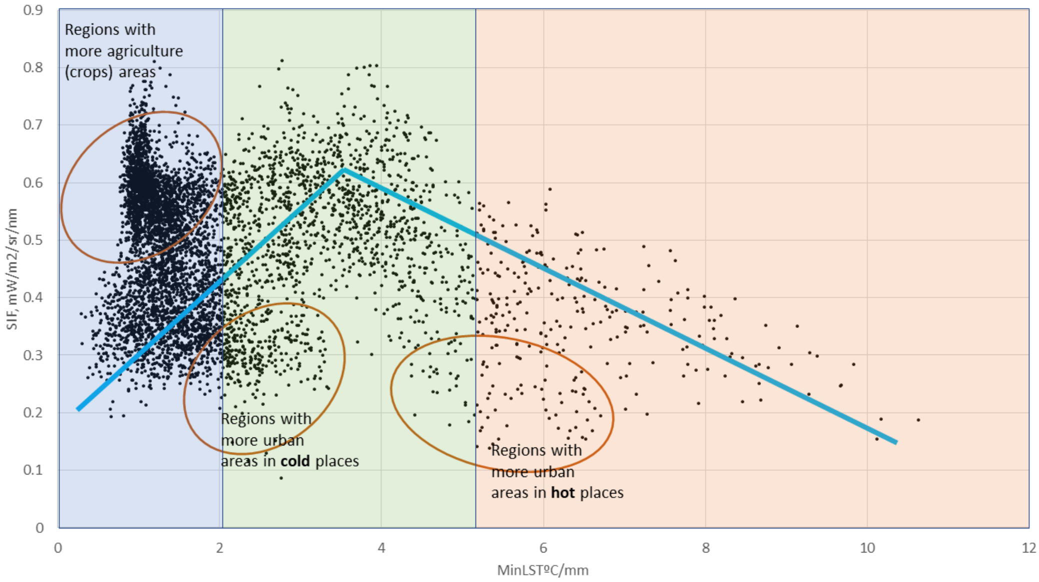
Figure 11: Vegetation comfortability (SIF) variation in time considering LST (a, c, e) and precipitation (b, d, f) in three different Portuguese regions: North of Portugal - Vila do Conde: Mild and humid; Centre of Portugal - Silveiras: Hot and humid; South of Portugal - Alcoutim and Pereiro: Hot and Dry.

In Southern Portugal, the increase of vegetation carbon stocks (Figure 11e,f) in the rainy season (<SIF on average) may be due to lack of temperature limitations. However, the vegetation of the South, due to its physiological characteristics adapted to dry and hot climates, is more adapted to the climate

change pressures than the vegetation of the North. Thus, plant diversity in the Montado/Dehesa structure is fundamental for both objectives (increase in stocks and climate resilience).

We also analysed the vegetation dynamics response of several regions of Portugal (North, South, Coast, Continental) by creating a graphical image (see Figure 12) to analyse the relationship between Solar-Induced Chlorophyll Fluorescence emitted by vegetation (SIF) and the Land Surface Temperature (LST) /Precipitation (P) ratio for the best period of vegetation growth (without irrigation) in the Mediterranean countries (October to June).

We observed that between 2 to 5 MinLST °C/mm (Figure 12a) and 8 to 15 MaxLST °C/mm (Figure 12b), it is possible to map the regions where the maximum biomass production and maximum CO_2 sequestration occur in mainland Portugal. The highest values of minimum and maximum LST/P ratio occur in regions where the limitations to growth and CO_2 sequestration are due to lack of precipitation and high temperatures. On the other hand, the lowest values of minimum and maximum LST/P ratio are found in regions where the limitations to growth and CO_2 sequestration are due to low temperatures. In these regions, the increase in temperature will have a positive effect on SIF and consequently on biomass production and CO_2 sequestration.



(a)

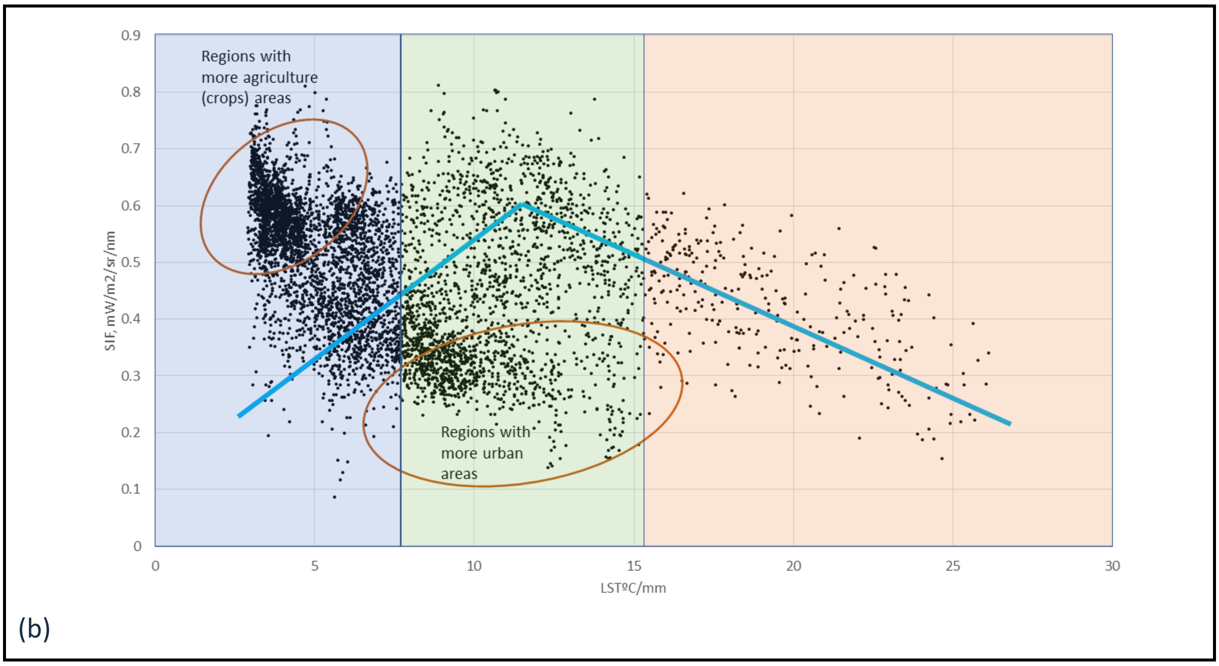
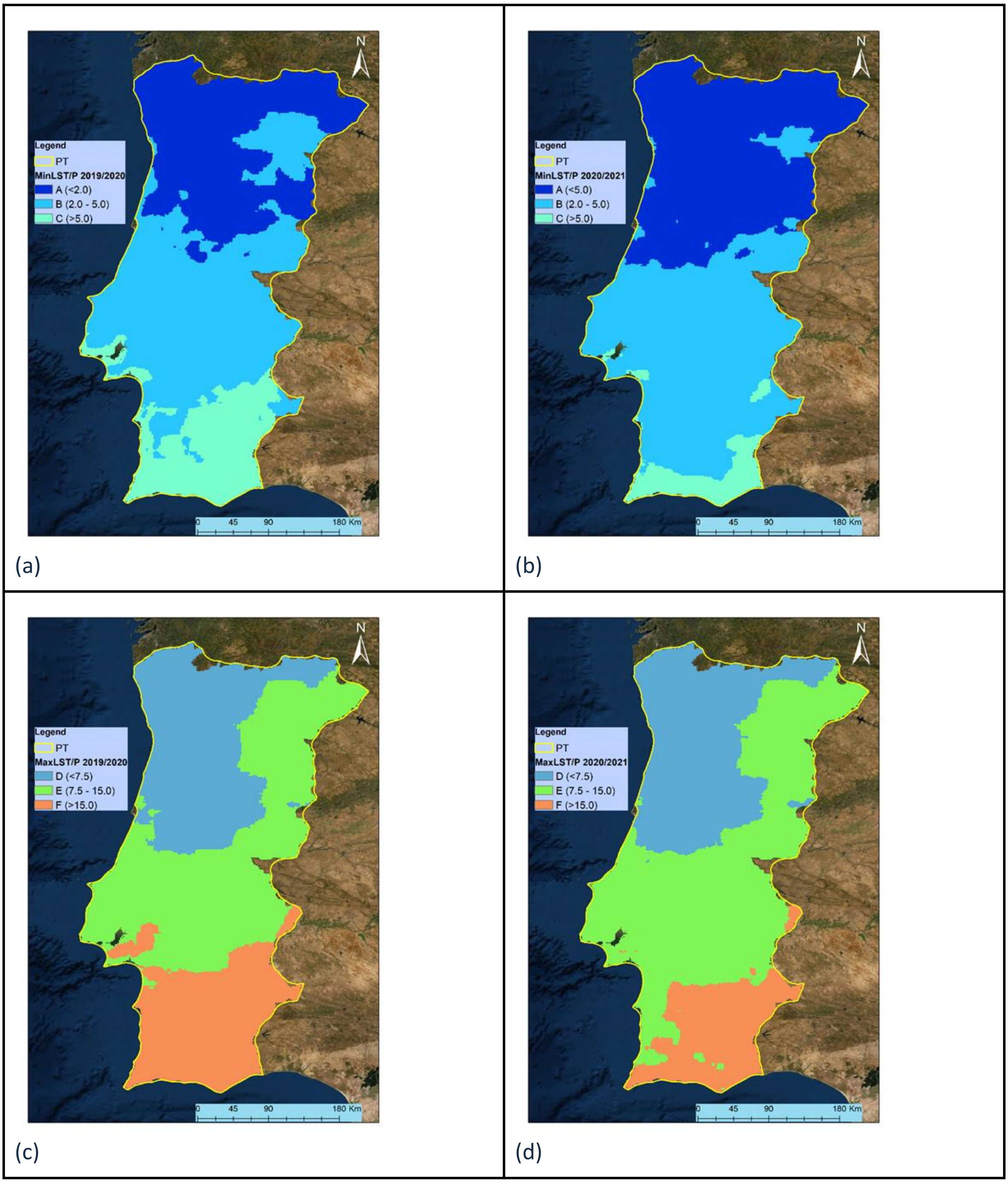


Figure 12: Relation of Solar-Induced Chlorophyll Fluorescence emitted by vegetation (SIF) mean and the Land Surface Temperature (LST) /Precipitation (P) ratio accumulated for all territorially administrative areas of Portugal between October and June (the main rainy/growing period in typical Mediterranean conditions) of 2019 to 2021 period: a) SIF vs "MinLST °C/mm"; b) SIF vs "MaxLST °C/mm".

Based on the ratio minimum and maximum of LST(°C)/Precipitation(mm) for the years 2019/2020 and 2020/2021, six climatic regions were defined for Portugal (Figure 13). Considering MinLST °C/mm: **A**) less than 2; **B**) between 2 and 5; and **C**) more than 5. Considering MaxLST °C/mm: **D**) less than 7.5; **E**) between 7.5 and 15; and **F**) more than 15.

In terms of optimizing the resilience of Montado/Dehesa to climate change, regions **A** and **D** prioritize the installation of the species shown in Annex 2, Figure 18A and present a potential positive increase in Carbon uptake with increasing temperatures; regions **B** and **E** prioritize the installation of the species presented in Annex 2, Figure 18B and Figure 18D and it will be the region where carbon uptake will always be greater but it will also be the region where increasing temperatures and decreasing precipitation can reduce its carbon uptake potential and therefore some of the most resistant trees should be planted in future plantations; the regions **C** and **F** prioritize the installation of the species shown in Annex 2, Figure 18E because these species are more resilient and adapted to hot and dry climates.

Also, Figure 13 shows that LST/P zoning is slightly different from 2019/2020 and 2020/2021 due to precipitation and temperature variations between years. However, in these zones, there is some geographical trend regarding LST/P zones and consequently, a trend in CO_2 sequestration/resilience. For instances, when planting the Montado species, it is necessary to consider that these young plants are more sensitive to high temperatures and lack of water when compared to mature plants. Therefore, regions **C** and **F** will be the regions that will have some difficulties in planting new Quercus trees in conditions of high temperature and low precipitation conditions in terms of the first years' survival through the summers. Thus, specific future plantations in these regions must be supported in the first years after planting with summer irrigation.



(a) (b) (c) (d)

Figure 13: Montado/Dehesa climate zoning towards optimization of CO_2 sequestration resilience in Portugal: a) MinLST/P - 2019/2020; b) MinLST/P - 2020/2021; c) MaxLST/P - 2019/2020; d) MaxLST/P - 2020/2021. Six climatic regions were defined considering MinLST °C/mm for the years 2019/2020 and 2020/2021: A) less than 2; B) between 2 and 5; and C) more than 5; and considering MaxLST °C/mm: D) less than 7.5; E) between 7.5 and 15; and F) more than 15.

Bearing in mind that the LMTs studied in Portugal and Spain are agroforestry systems, grassland management, forest management and afforestation/reforestation, these LMTs can play a significant role in adapting to climate change, as observed in the literature review (above point 1) and in the stakeholders' surveys (above point 2), especially those that can potentially reduce/delay desertification coming to the north. Due to their geographical location and socioeconomic characteristics, Portugal and Spain face significant risks arising from climate change. These countries have a relatively low population density and therefore competition for land is not as high as in other European countries.

Key sectors of the Portuguese and Spanish economy, such as agriculture, forestry, tourism, and transport, are closely dependent on the climate. As countries vulnerable to climate change, the Portuguese and Spanish policy framework for National Actions Plans for Adaptation to Climate Change emphasizes climate change adaptation and mitigation. Thus, massive afforestation and reforestation in the southern Mediterranean countries with species adapted to hot and dry climate (Annex 2, Figure 18E) can play an important role not only for these countries but also for the northern European countries, because these massive populations of trees can somehow be a vegetation barrier to the desertification in the north. This information can be corroborated with the SIF data presented (Figure 5c,f,I,l; Figure 11) where there is a positive correlation between the productive potential of the plants and the potential of CO_2 sequestration for LMTs and specific regions. Consequently, SIF also correlates with climatic variables, such as the LST/P ratio (Figure 12) and therefore can be used to analyse the effect of climate variations on plant comfortability and resilience.

3.2 SIF data as a link proxy measure for biomass and carbon uptake

Data earlier showed that TROPOMI SIF (Figure 5) and SENTINEL (Figure 6) are positively correlated with plant biomass potential (GPP) and consequently with carbon uptake. At same time climate observations such as LST (MSG) and Precipitation, were linked to SIF and to plant photosynthesis performance and thus, SIF is directly linked to the photosynthetic carbon uptake (Figure 5).

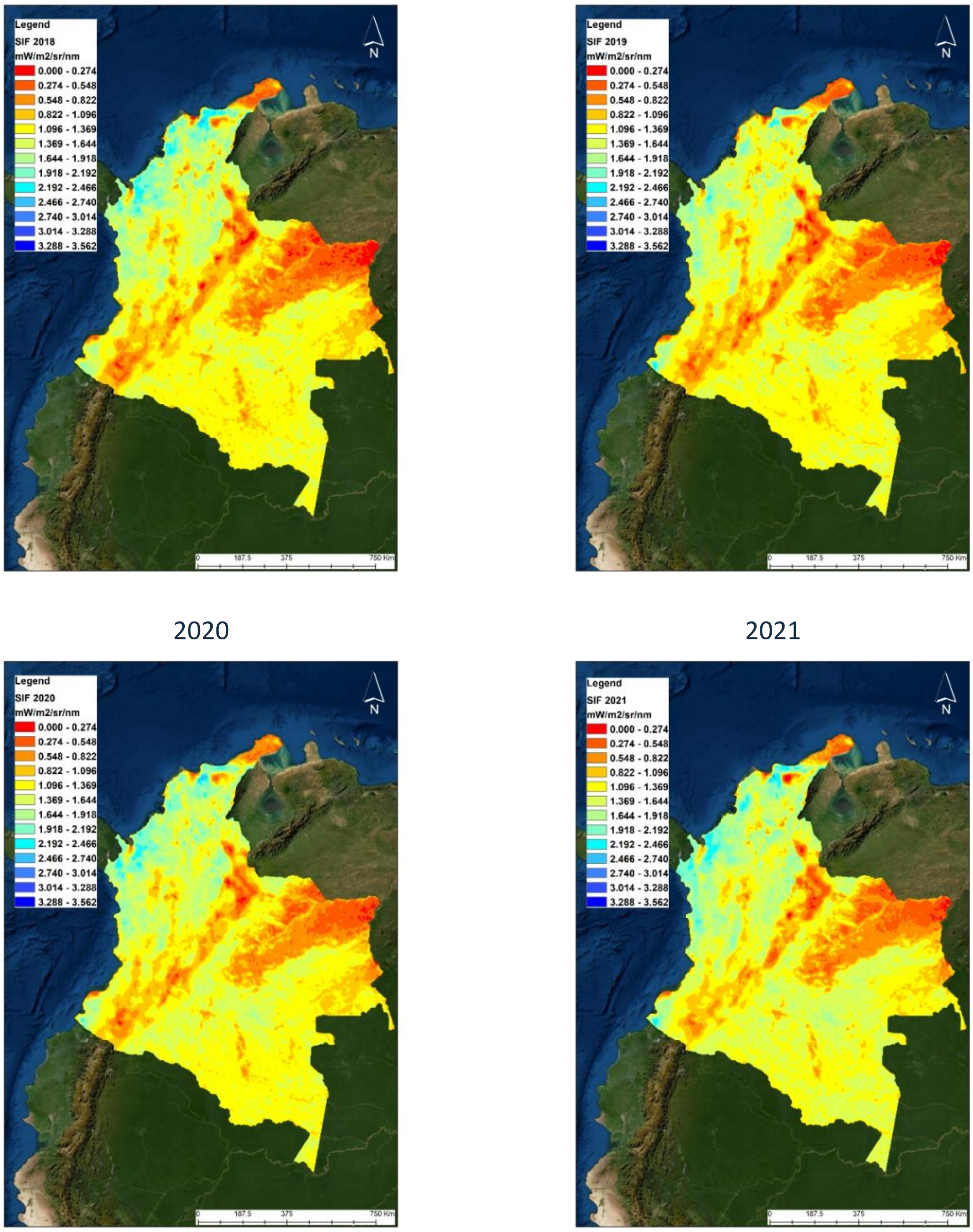
Low values of SIF usually indicate: i) low plant density; ii) low plant photosynthesis; iii) low mineral/organic inputs for plants best performance; and iv) unfit with the best edaphoclimatic conditions (e.g., temperature, radiation, nutrients and water availability) for plant growth, biomass production and carbon uptake. On the other hand, high values of SIF can normally indicate: i) high plant density; ii) high plant photosynthesis; iii) high mineral/organic inputs for plants best performance; and iv) fit with the best edaphoclimatic conditions (e.g., temperature, radiation, nutrients and water availability) for plant growth, biomass production and carbon uptake.

SIF can also be useful in defining bioindicators for specific regions to help better design specific policies in terms of the species that must be considered for future plantations and climate change adaptation. SIF values must take into account plants that are normally adapted to the edaphoclimatic factors that control SIF growth and vegetation performance (e.g., **deserts**, low values of SIF – species adapted to areas with low precipitation and high temperatures; **high mountains**, low values of SIF – vegetation adapted to areas with low temperature but rarely with snow; **boreal forest**, low values of SIF – species adapted to snow and ice in a major part of the year; **wet savanna**, low values of SIF – vegetation adapted to low flat land with problems of water drainage; **tropical forests**, high values of SIF – species adapted to high precipitation regimes and high temperatures; **agriculture**, high values of SIF – species that normally have all the ideal conditions to growth, such as, good genetics, soils, water, temperature and mineral/organic nutrients; etc.).

From the list of case studies (Figure 2), we selected the case study of Colombia to discuss the relationship of SIF data of 2018, 2019, 2020 and 2021 as a link proxy measure for biomass and carbon uptake (Figure 14). Over time, Colombia presents in general similar SIF trend each year. However, Colombia presents a very high annual SIF average spatial variation that varies between ~100 $mW\ m^2\ sr^{-1}\ nm^{-1}\ year^{-1}$ to ~1000 $mW\ m^2\ sr^{-1}\ nm^{-1}\ year^{-1}$. These annual average SIF variation in Colombia are normally associated with the wet or dry savanna (NE) and with the high cold mountains (Andes) for low SIF values and the tropical forest (W – NW - S) for high SIF values. Therefore, on Colombia or in other country in the world (Annex 3), biomass and carbon uptake potential usually are positively correlated with SIF, i.e., low and high values of SIF mean correspond to low and high values of biomass and carbon uptake.

In Annex 3, the SIF maps show countries of some of the case studies where LANDMARC LMTs are being studied and analysed (e.g., Germany, Burkina Faso, Canada, Spain, Netherlands, Indonesia, Kenya, Nepal, Portugal, South Africa, Switzerland, United Kingdom, Venezuela, and Vietnam). The analysis of these maps enables the identification of the places where the local vegetation presents a good/bad performance in terms of biomass and CO_2 sequestration, considering the available resources, i.e., temperature, water, radiation, nutrients, etc. For example, high SIF values are noticed over Indonesia (Annex 3, Figure 24), Venezuela (Annex 3, Figure 31), Vietnam (Annex 3, Figure 32), where climatic restrictions are limited, i.e., temperature and water, that are the two main variables for the best plants performance. On the other hand, hot and dry countries, such as, Burkina Faso (Annex 3, Figure 20), Kenya (Annex 3, Figure 25), and South Africa (Annex 3, Figure 28) have low SIF values due to vegetation climatic restrictions. In the case of cold countries, such as Canada (Annex 3, Figure 21) and parts of other countries where altitude plays an important role in limiting vegetation growth, have low SIF values. Germany (Annex 3, Figure 19), Spain (Annex 3, Figure 22), Netherlands (Annex 3, Figure 23), Nepal (Annex 3, Figure 26), Portugal (Annex 3, Figure 27), Switzerland (Annex 3, Figure 29) and United Kingdom (UK, Annex 3, Figure 30), compared with tropical, hot and dry, and cold countries, show intermediate SIF values. These results are in accordance with the study in climate risk for reforestation in north-central China (see point 3.3) where positive correlations between the increased forest cover and SIF observation over most of the afforested regions were observe and in which the inter-annual variation in SIF is, besides by land use change, impacted by climatic factors. Moreover, the Netherlands and the UK locally have some high SIF values, most of which are related to agricultural activities. In places with high agricultural activity/intensity, the SIF value will always be high due to the high availability of plant inputs (e.g., nutrients, water irrigation, etc.). In summary, despite poor growing conditions affecting plant growth and CO_2 sequestration from plants, some plants are more affected than others due to their genetic abilities. Thus, plant genetics and their resilience to climate change in plant dependent LMTs must be considered in future plantations.

In conclusion, this deliverable D4.2 highlights the use of SIF as a very powerful tool to study plants biomass and CO_2 sequestration potential and plants biomes for specific local interventions for climate change adaptation.



2018

2019

2020

2021

Figure 14: Colombia average annual SIF for 2018, 2019, 2020 and 2021.

3.3 Monitoring reforestation at climate risk in north-central China

The monitoring of vegetation dynamics over areas where LMTs are being implemented (here reforestation) enables insight in the resilience of LMTs to climate risks. In this section, we focus on the monitoring of vegetation dynamics and climate variations over large-scale reforested areas in north-central China. North-central China suffers from severe soil erosion and is seriously affected by multiple drought events over the last years. In response to the soil erosion and continuous desertification, the Chinese government implemented multiple large-scale restoration campaigns from the 1950’s. The combination of large-scale LMT implementation and the exposure to climate risks make this region particularly interesting monitoring the climate robustness after land management. A recent study by Ding et al. (2021) found that vegetation response to drought improved over forested areas as opposed to non-forested areas in north-central China.

Using KNMI-retrieved GOME-2A SIF data, we analysed the vegetation dynamics of areas that experienced significant reforestation between 2007 and 2012. We selected (0.5° x 0.5°) grid cells of which the forested area increased by >2%, or >49.5 km^2 over a 6-year timeframe (Figure 15b). Most reforestation took place over the grassland-dominated region of north Shaanxi, an area with a mixture of cropland and forest in south-east Gansu, and a forest-dominated area with patches of cropland in south-east Shaanxi (Figures 15a and 15b).

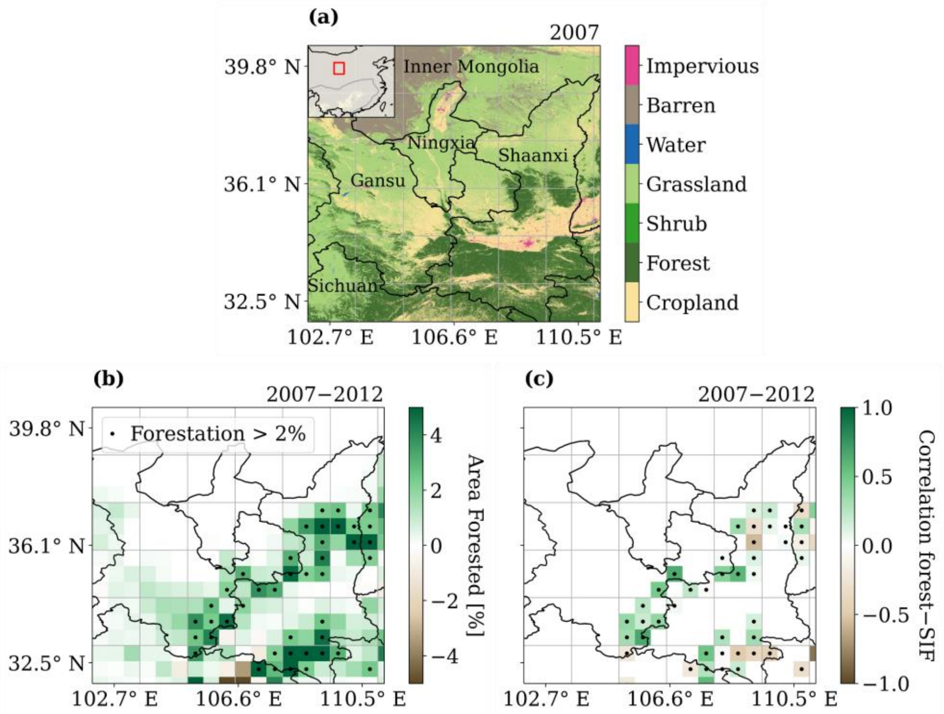


Figure 15: Land cover in 2007 (Yang and Huang, 2021) a), area forested between 2007 and 2012 in percentage of grid cell area with the bullets indicating the grid cells of which the cover increased by forest >2% b) and the Pearson correlation between forest cover and the observed SIF (June–July) c).

The reforested regions are dominated by semi-arid to semi-humid climates. Figure 15c shows the spatio-temporal correlation of SIF with forested area, and the generally positive numbers indicate that SIF increases as the forested area increases.

Figure 16a presents the averaged SIF in summer (June—August) observed over the forested regions on clear-sky days between 2007 and 2012. Figure 16a shows an increase in SIF between 2007 and 2009, whereafter SIF drops significantly in 2011. After the sharp reduction in 2011, SIF shows a strong increase over the forested regions in 2012. Not only reforestation but also climate variability influences the SIF increase (and decrease) over time.

To understand the roles of simultaneous net reforestation and climate variation in the vegetation dynamics pattern, we compare temporal SIF summer (June–August) patterns against annual forest cover and several climate variables. The net reforestation was obtained from Landsat-derived annual land cover data (Yang and Huang, 2021). As climate variables, we used the number of hot days (NHDs), temperature anomaly and precipitation anomaly, shown respectively in Figure 16b,c,d. The NHDs is defined as the number of days exceeding the 90th percentile threshold of collected maximum temperature data over 1979–2019 with a temporal window of 5 days

The maximum temperature between June and August over 2007—2012 was high in comparison to the average observed between 1979 and 2019. From Figure 16d, we see that the summer period, June to August, for the years 2008, 2009, 2011 and 2012 had a negative precipitation anomaly. The patterns in the temperature and the precipitation anomaly do not clearly synchronise with the inter-annual variation in SIF. However, the strong drop in SIF in 2011 coincides with the high number of hot days (average of ~15 days) in 2011 as seen in Figure 16a,c. Recent findings (not shown here) suggest even better correlation between soil moisture deficits and reductions in SIF.

We draw the preliminary qualitative conclusion that SIF measurements from space are valuable to monitor the effectiveness of reforestation over time, and at the same time the data suggest a substantial imprint of climate extremes (or climate risk), such as drought (indicators). Further ongoing research aims to disentangle the relative contributions of reforestation and climate variability on vegetation dynamics as diagnosed with SIF over north central China.

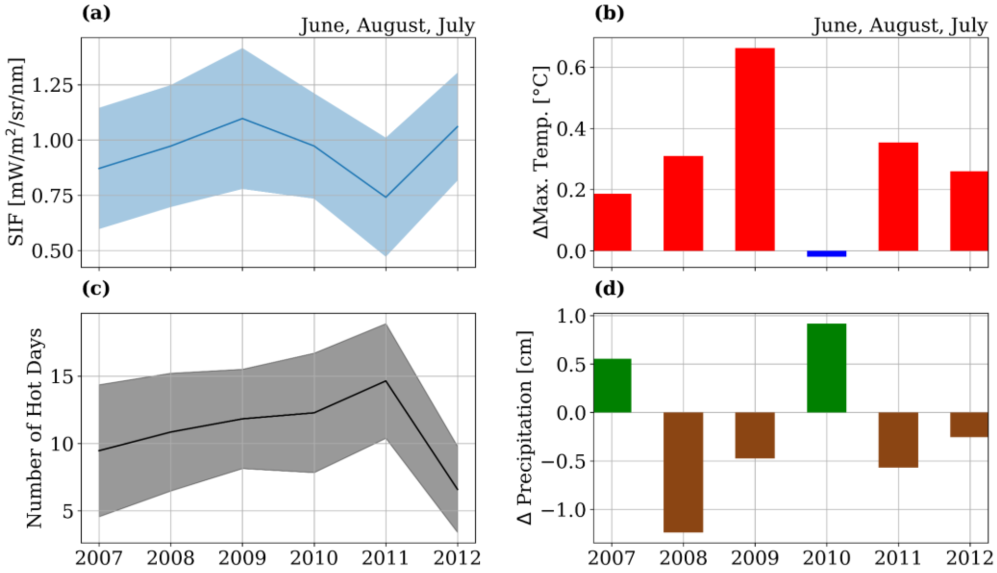


Figure 16: Time series GOME-2A SIF (a) and the climate variables: temperature anomaly (b), number of hot days (NHDs) (c), and the precipitation anomaly (d), averaged over the afforested regions. Both anomalies are calculated using ERA-5 data averaged over June–August between 1979 and 2019. The shaded area in (a) and (c) indicate the standard deviation of, respectively, SIF and the NHDs over the reforested region and the summer season.

4. Conclusions

The goal of Deliverable 4.2 is to better understand climate conditions that favour or compromise the different LMT solutions in their effectiveness as carbon storage in different contexts. From the analysis of the literature review, preliminary results of the stakeholders' climate-related sensitivity survey and EO data regarding climate-related sensitivities of LMTs for the climate (change) risk assessment, we may conclude that the assessment of vegetation climate resilience is difficult to study due to the interaction of multiple factors in vegetation behaviour to climate stress.

Nevertheless, some clear take-home messages emerge as both literature review (Section 1) *and* LANDMARC stakeholders (Section 2) indicate a future climate change in which hot and dry conditions are the major risk factors for LMTs. The impact of climate change on soils, nutrients, droughts, and ecosystem suitability for maintaining particular vegetation types is a major concern for the sustainability of plant growth and subsequent carbon storage. The literature review also pointed out that it is important to adapt LMTs (i.e., vegetation types) in step with climate change. Failing to do so poses the risk of increasingly ill-adapted ecosystems turning what is otherwise a sink of carbon into a net source via increasing respiration. Moreover, the preliminary results of stakeholders' survey identified the heavy rainfalls and heat/cold waves as the main climate risks for the LMTs.

On the other hand, specific analysis based on EO data (Section 3) showed that species location is associated with their resilience to climate conditions of water (precipitation) and thermal (heat/cold waves) stress. For instance, the rise in temperature in regions characterized by wet and cool winters and mild summers may stimulates photosynthetic activity, while in regions characterized by mild wet winters and warm to hot and dry summers the increased temperatures are associated with reduce biomass production because the precipitation is the limiting factor for biomass production. Also, the annual thermal accumulation of precipitation revealed to be a limiting factor for growth and carbon uptake, i.e., hot, and dry regions may have lower sequestration potential when compared to humid and hot regions.

In addition, we verify that SIF can also be useful in defining bioindicators for specific regions to help better design specific policies in terms of the species that must be considered for future plantations and climate change adaptation, i.e., to study the vegetation biome and the most adapted/resilient species to climate extremes sensitivity such as drought and heat/cold waves. The different studied countries showed that low and high values of SIF mean correspond to low and high values of biomass and carbon uptake. SIF can also be used as a link proxy measure to delineate potential biomass and carbon uptake regions.

These conclusions highlight the diversity of climatic resilience situations to which vegetation based LMTs is subject and also the importance of plant genetics and their resilience to climate change in LMTs that should be considered in future plantations.

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Annex 1

The photos presented in this section (Figure 17) were taken on the 4th day of an extreme heat event in Portugal with temperatures above 44°C in July 2022. These photos show the suffering of the trees due to high temperatures and lack of water. However, some trees are very green and appear not to be suffering any kind of stress. The trees react to this stress by reducing their canopy. In winter the trees will rejuvenate through the production of new leaves and new biomass production. Although the trees of this particular LMT (Montado/Dehesa) have a high climate resilience, these extreme weather events (positive or negative) will eventually affect their performance. Currently, the main climate resilience concern of the Montado/Dehesa is its age (e.g., lack of new young trees due to livestock intensification) and the overall pressure that man exerts on natural systems due to agricultural intensification.

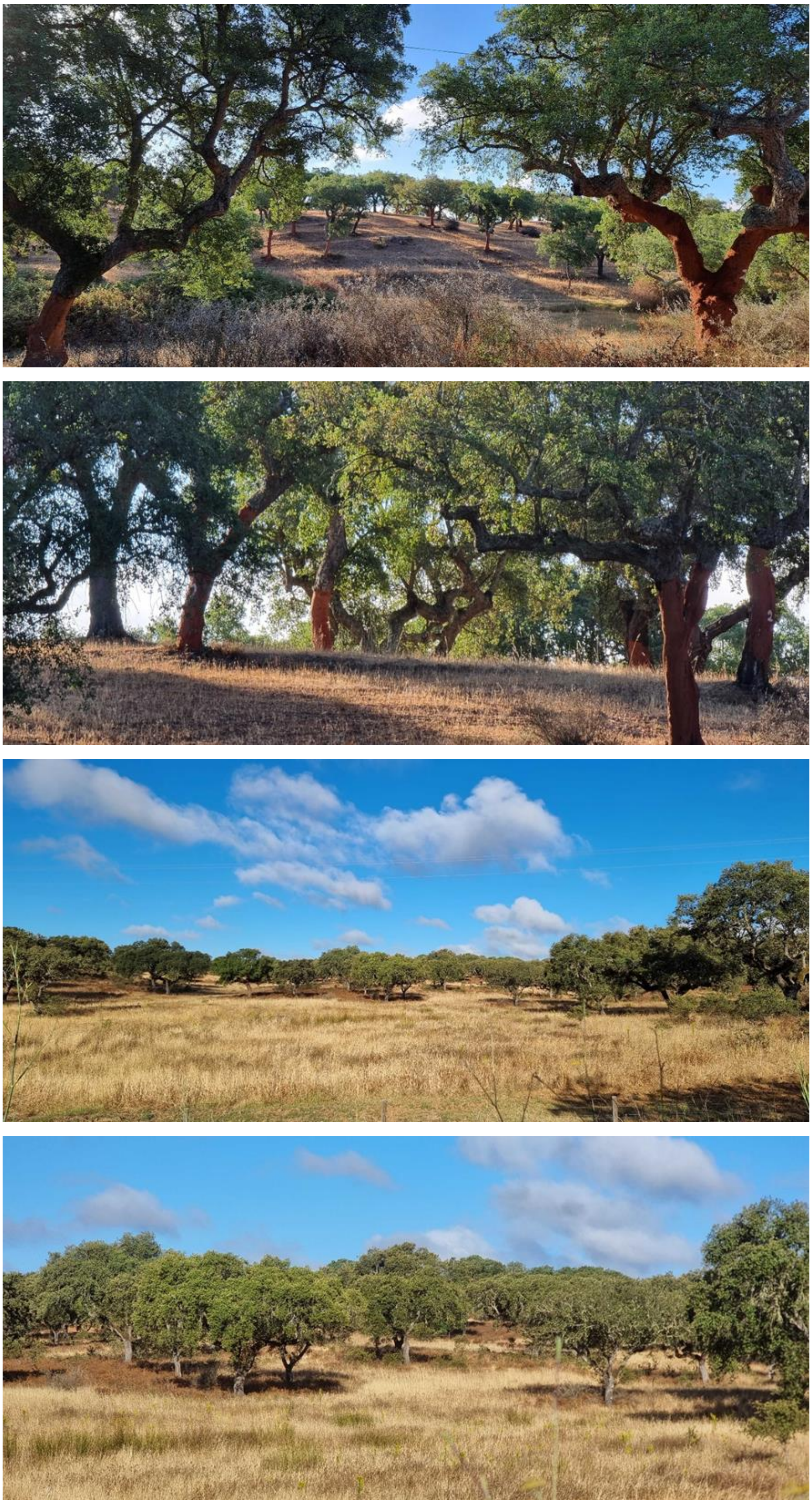


Figure 17. Photos of the trees suffering of Montado/Dehesa LMT taken on the 4th day of an extreme heat event in Portugal with temperatures above 44°C in July 2022.

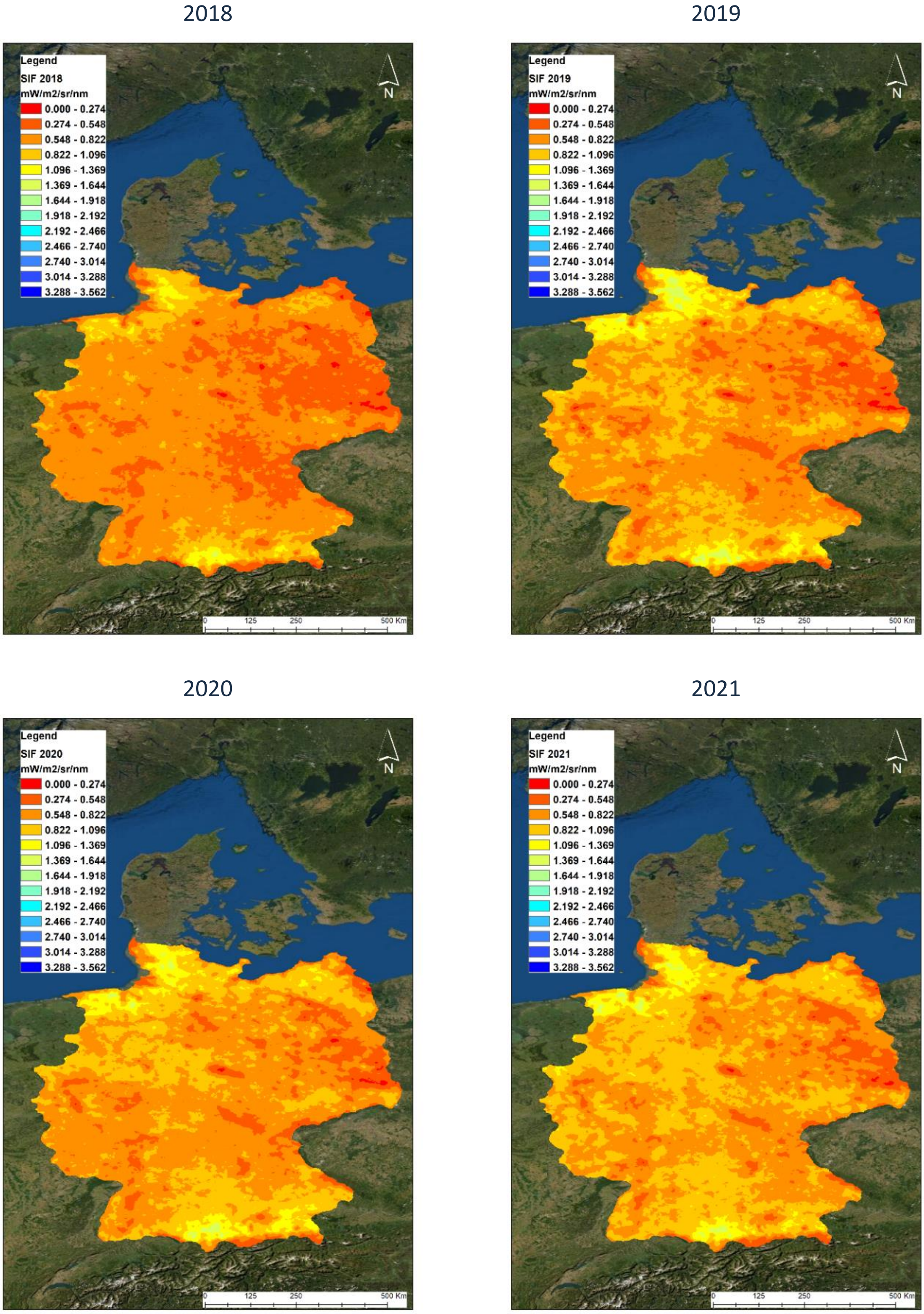
Annex 2

	**(A)** – Mild and humid (> 1000 mm) **Trees** – Quercus robur sbsp. Broteroana; Quercus pyrenaica; Quercus suber; Prunus lusitânica; Pyrus bourgaeana; Acer peudoplatanus; Arbutus unedo; Phillyrea latifólia; Ilex aquifolium; Pinus pinea **Shrubs** – Corylus avellana; Prunus spinosa; Crataegus monogyna; Cytisus striatus; Cytisus scoparius; Alnus glutinosa; Viburnum tinus; Taxus baccata; Rosa canina
	**(B)** – Dry and cold **Trees** – Quercus pyrenaica; Quercus robur sbsp. Broteroana; Quercus suber; Quercus rotundifólia; Pinus pinea; Arbutus unedo; Betula celtibérica; Sorbus aucuparia; Pyrus bourgaeana; Prunus avium; Ilex aquifolium **Shrubs** – Crataegus monogyna; Prunus spinosa; Taxus baccata; Cytisus scoparius; Alnus glutinosa; Vaccinium myrtillus; Rosa canina; Juniperus spp..
	**(C)** – Altitude (winter with T°C < -10°C) **Trees** – Betula celtibérica; Sorbus aucuparia; Quercus pyrenaica; Pinus sylvestris **Shrubs** – Juniperus spp.; Calluna spp.;Cytisus scoparius; Vaccinium myrtillus; Echinospartum ibericum; Amelanchier ovalis.
	**(D)** – Hot and humid (600 – 1000 mm) **Trees** – Quercus suber; Quercus pyrenaica; Quercus faginea subsp. Broteroi; Olea europea; Quercus coccifera; Quercus rotundifólia; Rhamnus alaternos; Arbutus unedo; Laurus nobillies; Rhamnus alaternus; Pyrus bourgaeana; Pinus pinea; Ceratonia siliqua **Shrubs** – Crataegus monogyna; Prunus spinosa; Ruscus aculeatus; Pistacia lentiscus; Myrtus communis; Erica arbórea; Erica scoparia subsp. Scoparia;

	Phillyrea angustifólia; Viburnum tinus; Rosa canina; Lonicera etrusca Santi
	**(E)** – Dry and hot (< 600 mm) **Trees** – Quercus rotundifolia; Quercus suber; Quercus faginea subsp. Broteroi; Quercus pyrenaica; Olea europea; Pyrus bourgaeana; Arbutus unedo; Acer monspessulanum; Pinus pinea; Quercus coccifera. **Shrubs** – Ruscus aculeatus; Asparagus acutifolius; Asparagus albus; Cytisus multiflorus; Retama sphaerocarpa; Pistacia terebinthus; Pistacia lentiscus; Jasminum fruticans; Lonicera etrusca Santi; Rhamnus alaternus; Nerium oleander; Thymus mastichina.
	
(F) – Vegetation series Due to topography and soil/water availability almost all previous regions (A, B, D, E) can be found all over the territory because in the top of the topography shown above one can found species more adapted and resilient to poor rocky soils and to low water availability and on the other extreme position one can have species adapted and resilient to deep fertile soils and excess of water.	

Figure 18. Vegetation potential regions and vegetation series inside of each potential Montado/Dehesa region (Adapted from Cabral & Telles, 2022).

Annex 3


2018

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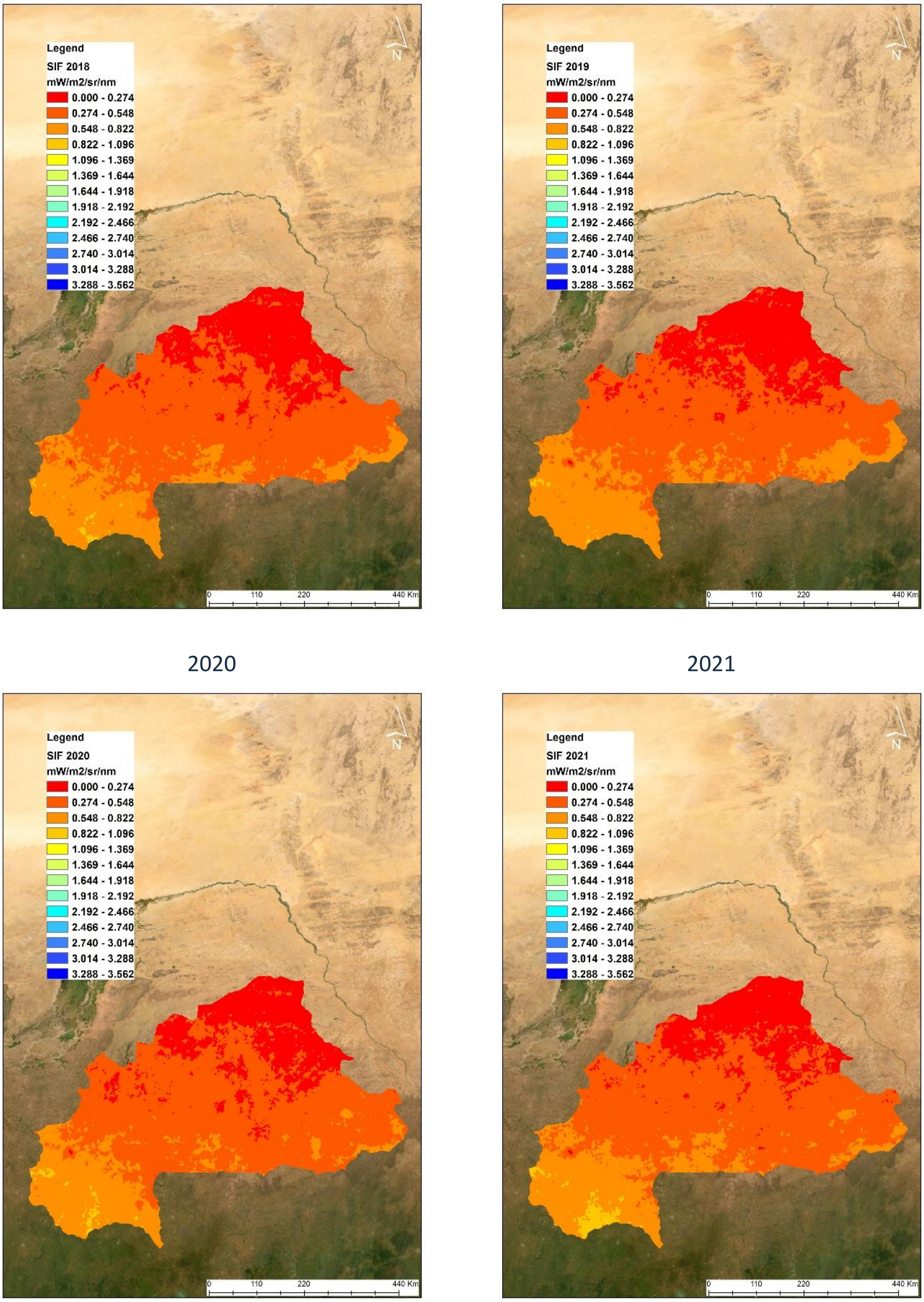
2020

2021

Figure 19. Germany average annual SIF for 2018, 2019, 2020 and 2021.

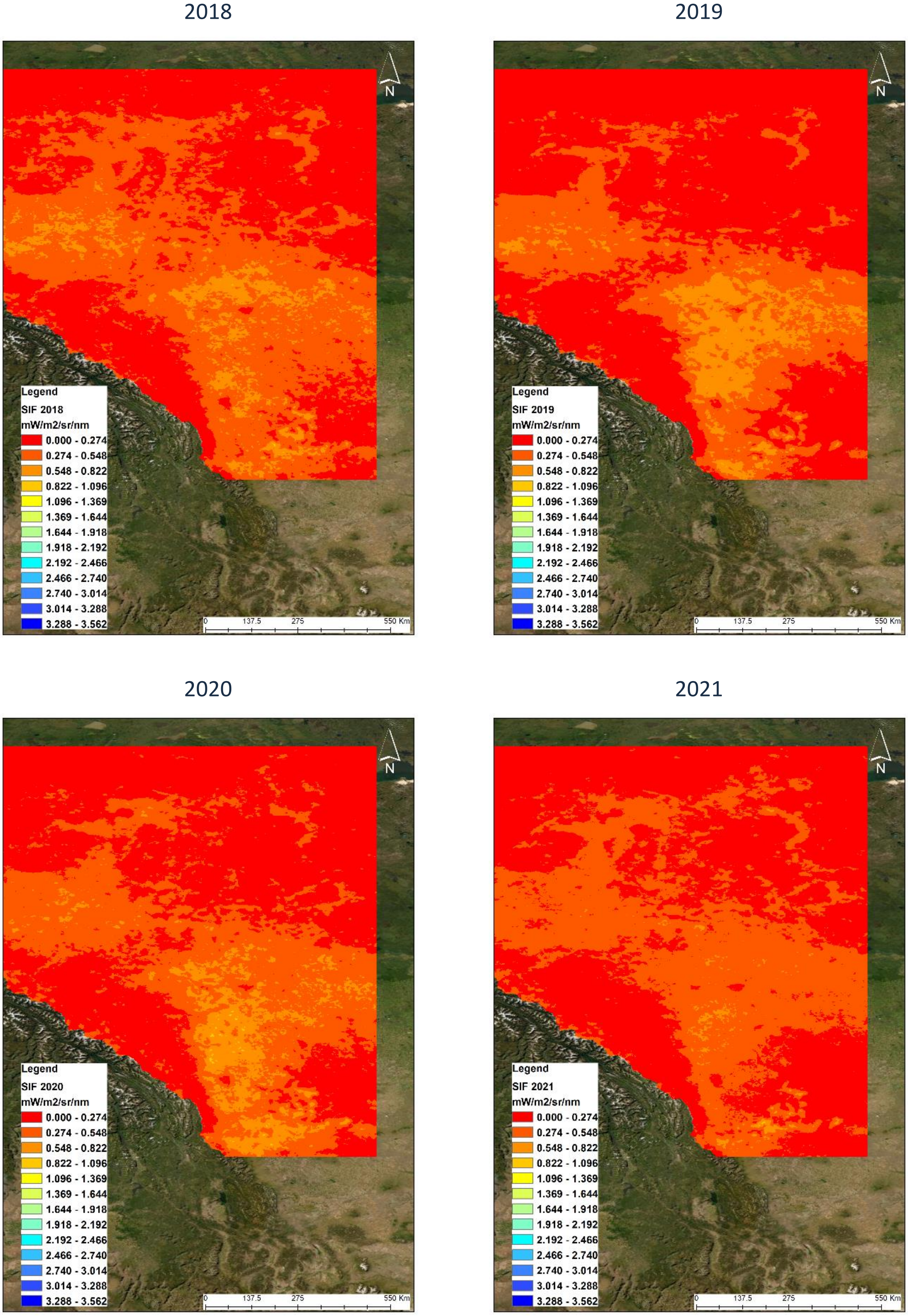

2018

2019

2020

2021

Figure 20. Burkina Fasso average annual SIF for 2018, 2019, 2020 and 2021.



2018

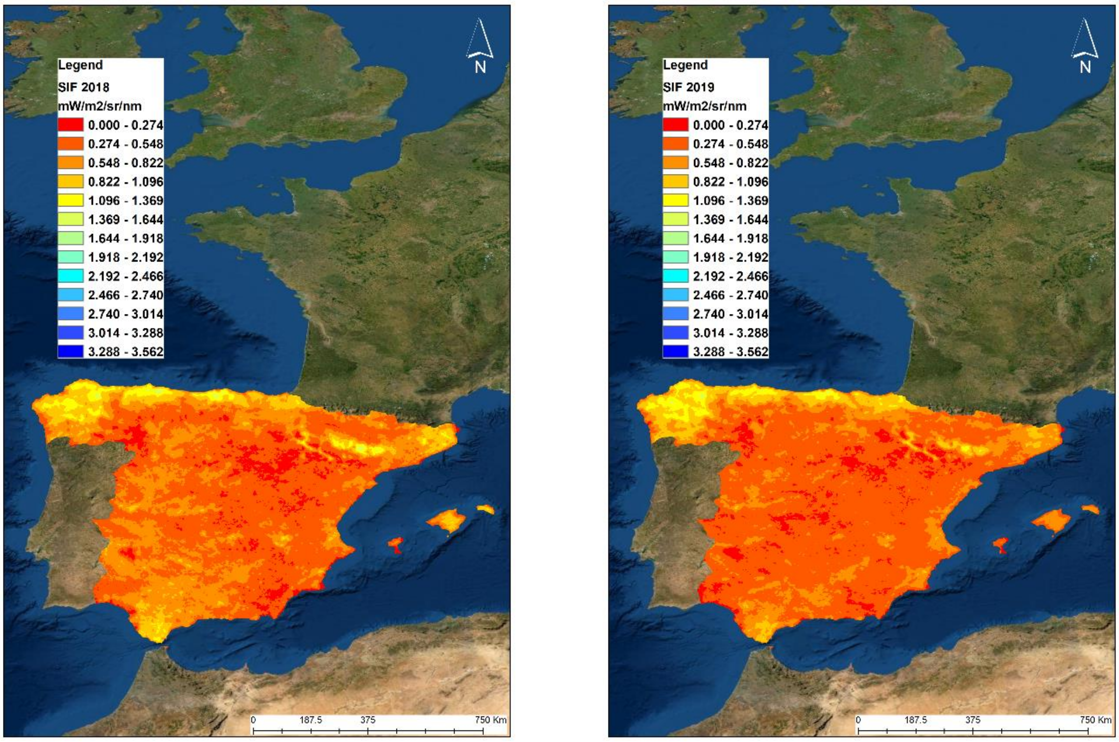
2019

2020

2021

Figure 21. Canada average annual SIF for 2018, 2019, 2020 and 2021.

2018 2019



2020 2021

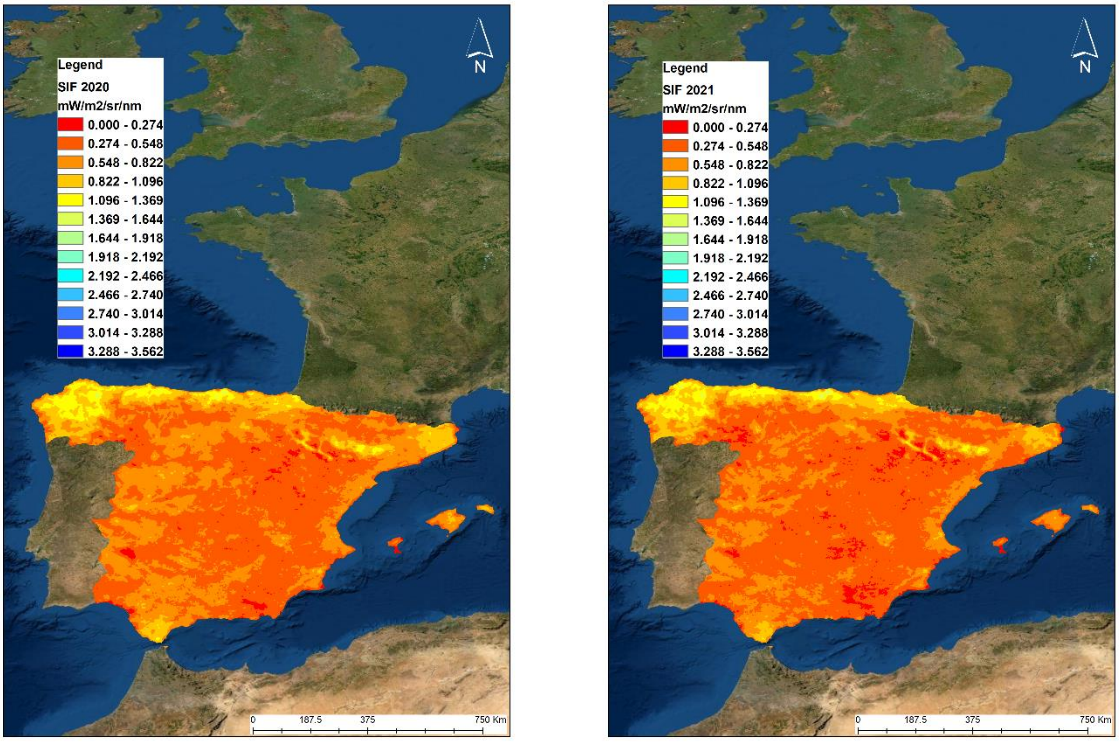


Figure 22. Spain average annual SIF for 2018, 2019, 2020 and 2021.

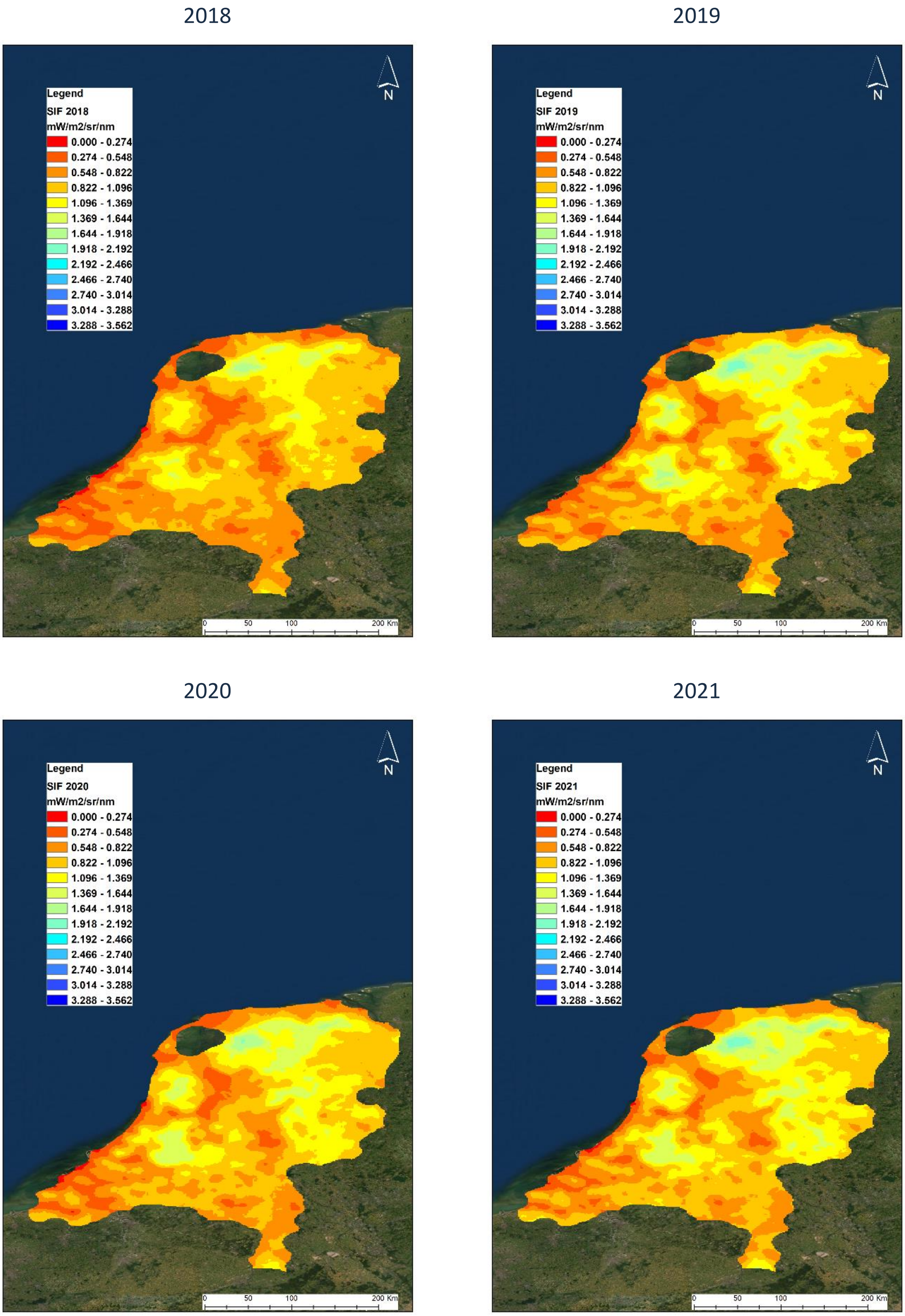

2018

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Figure 23. The Netherlands average annual SIF for 2018, 2019, 2020 and 2021.

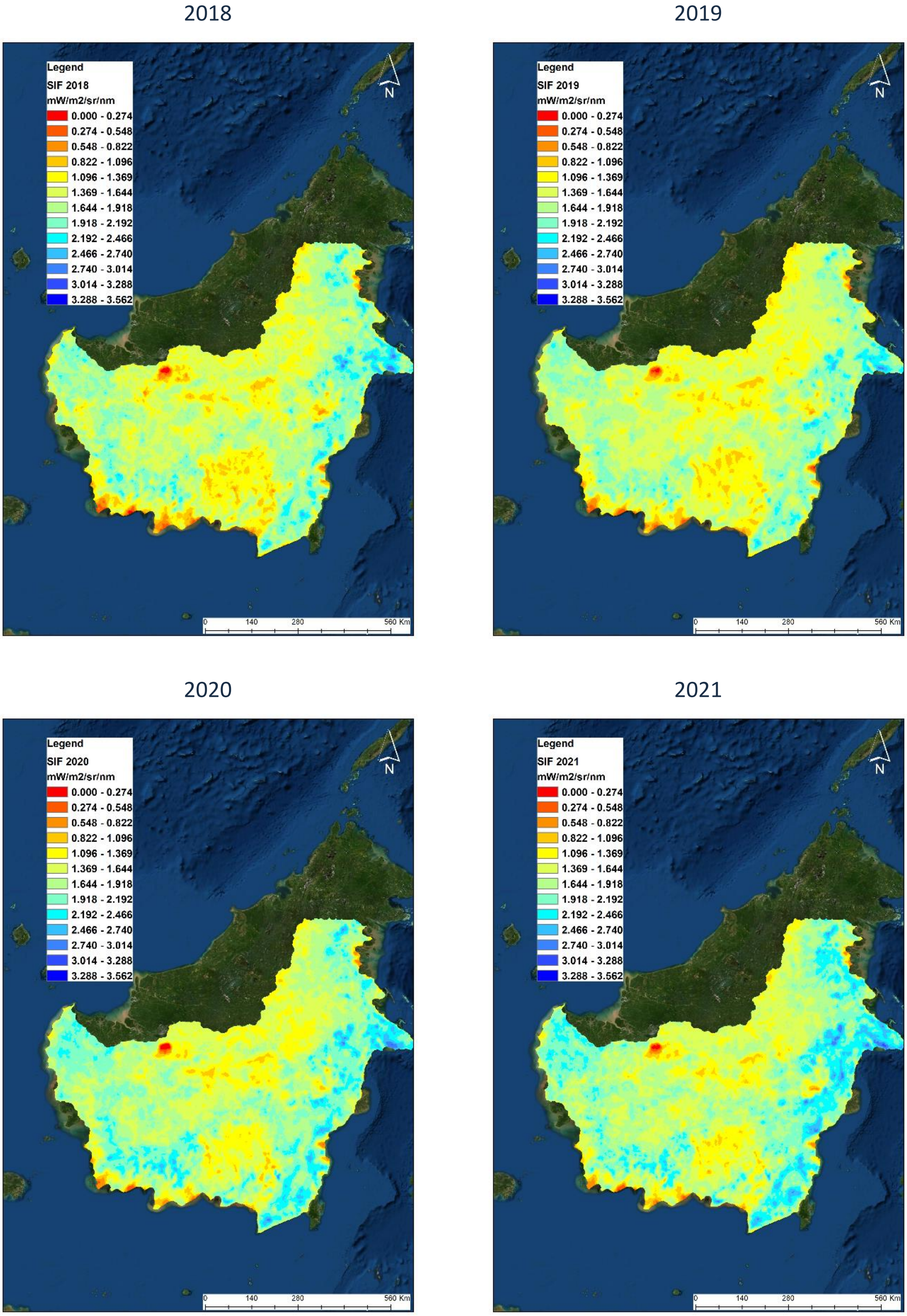
2018
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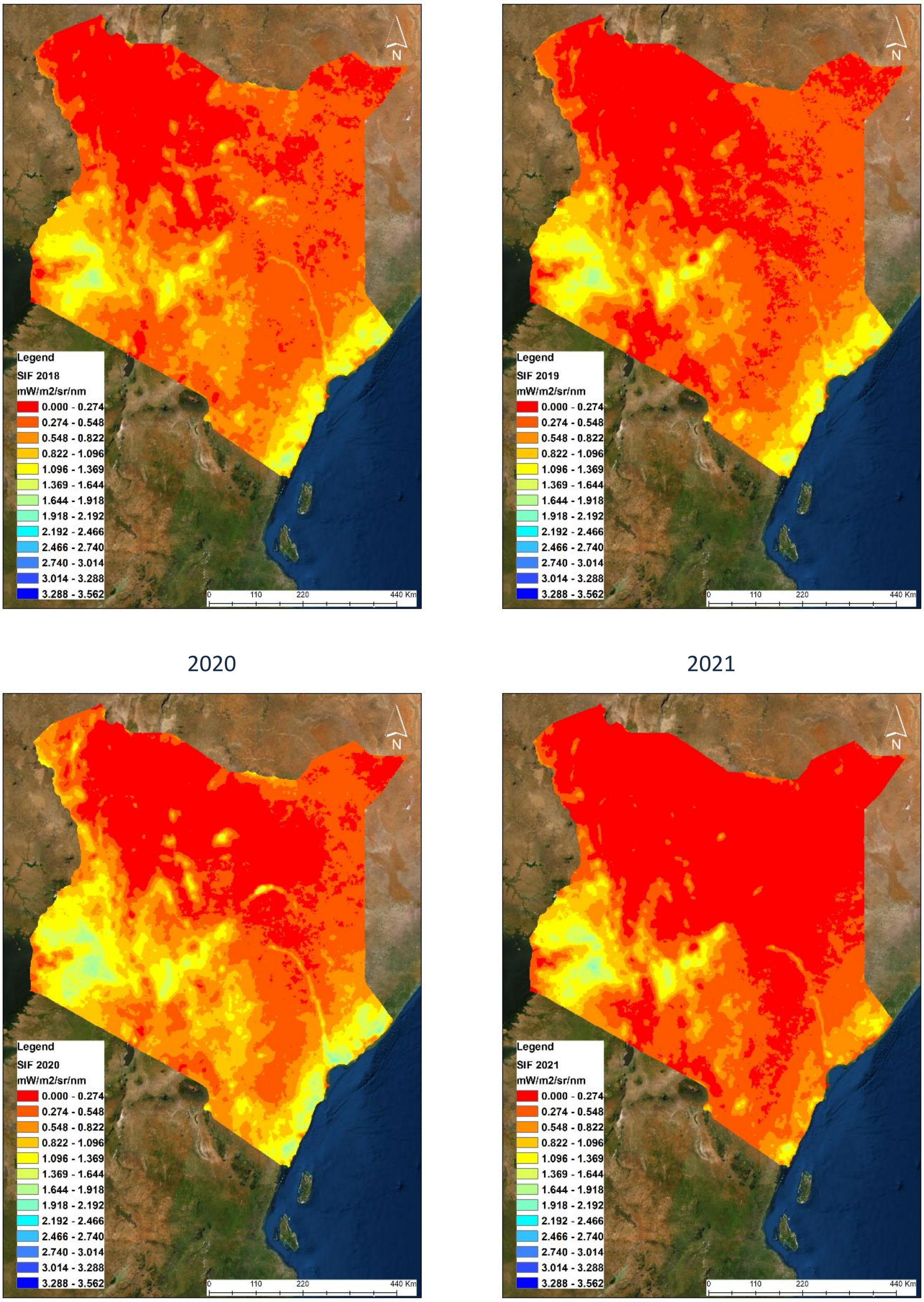
Figure 24. Indonesia average annual SIF for 2018, 2019, 2020 and 2021.

2018 2019



2020 2021

Figure 25. Kenia average annual SIF for 2018, 2019, 2020 and 2021.

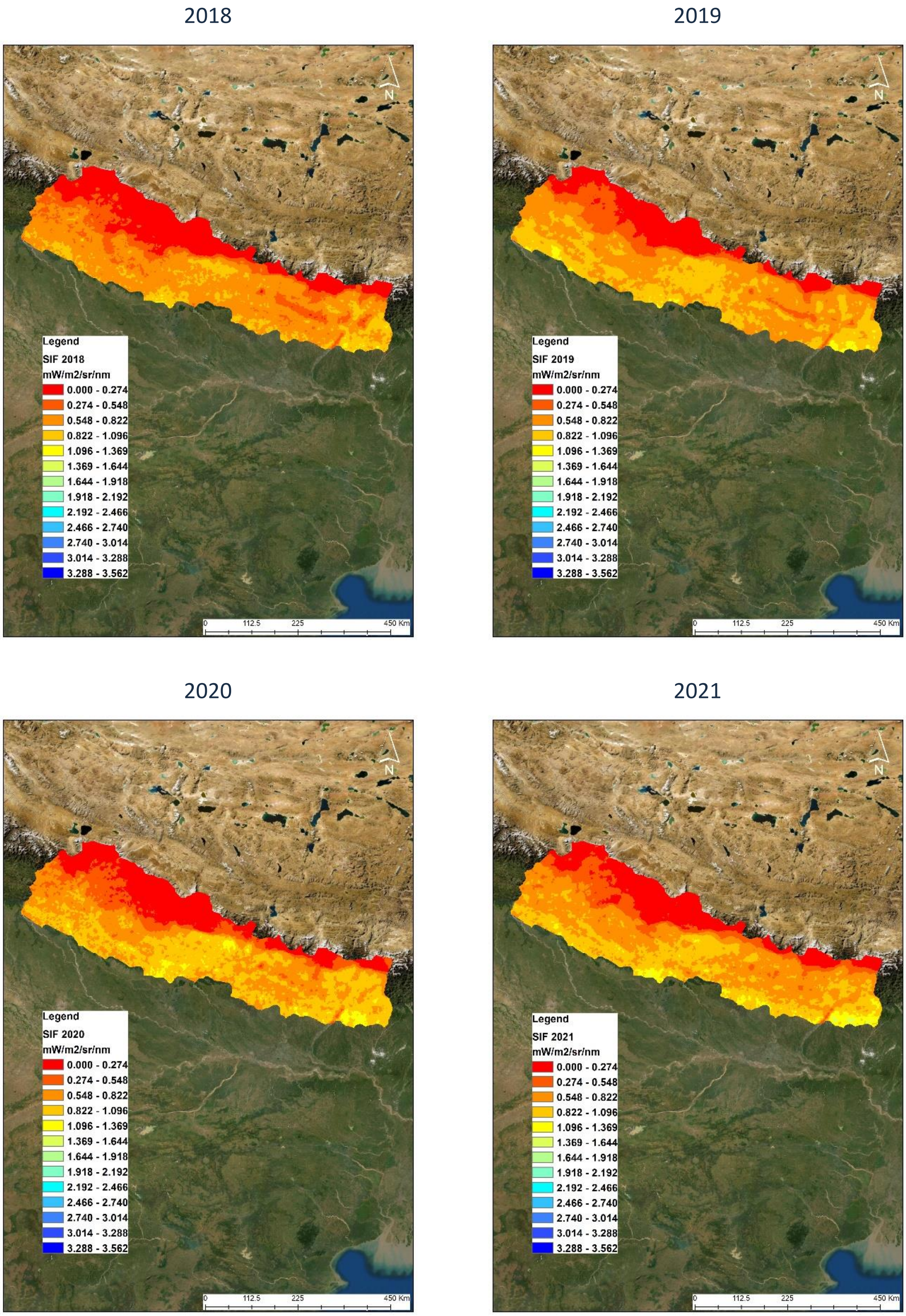


Figure 26. Nepal average annual SIF for 2018, 2019, 2020 and 2021.

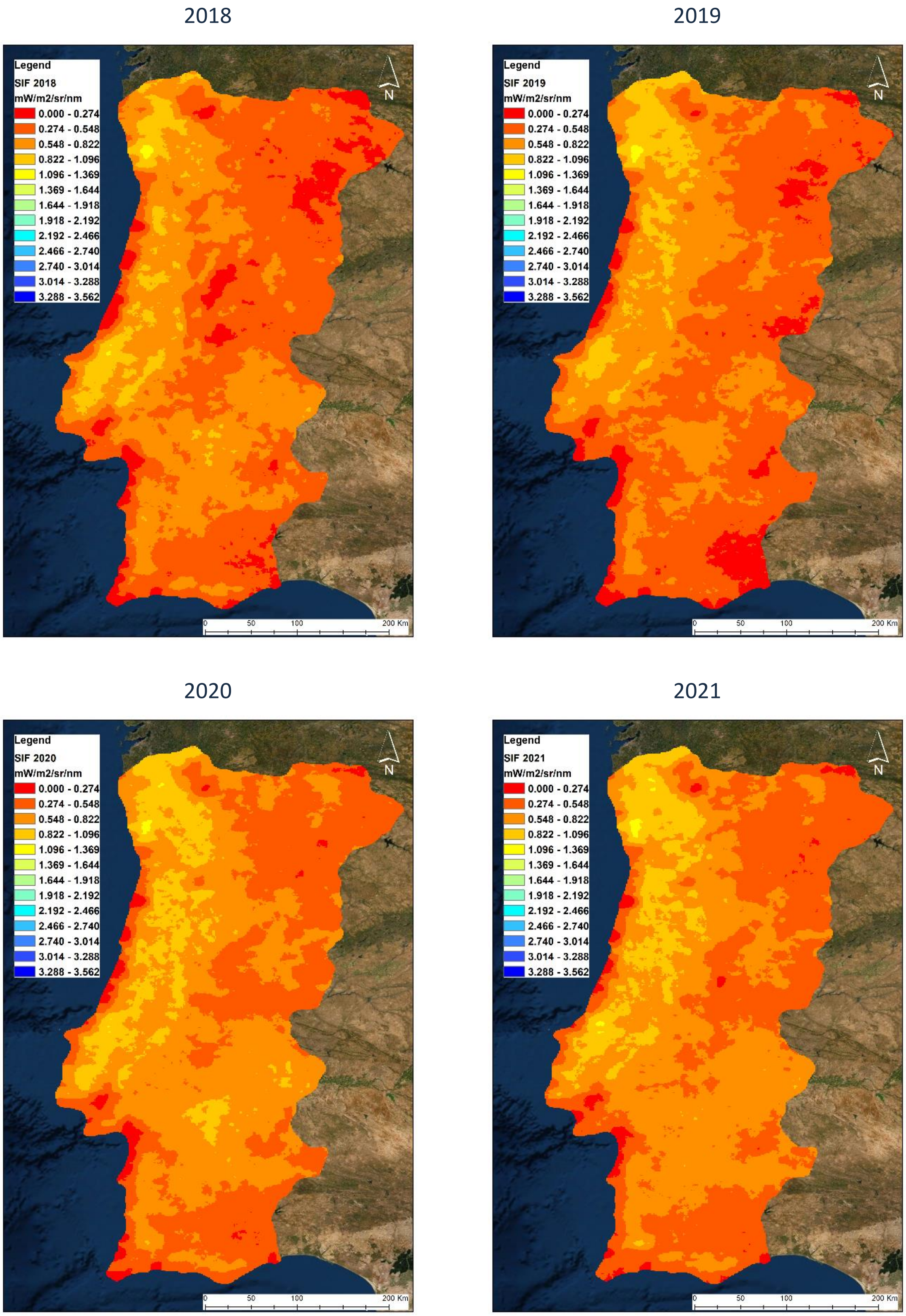
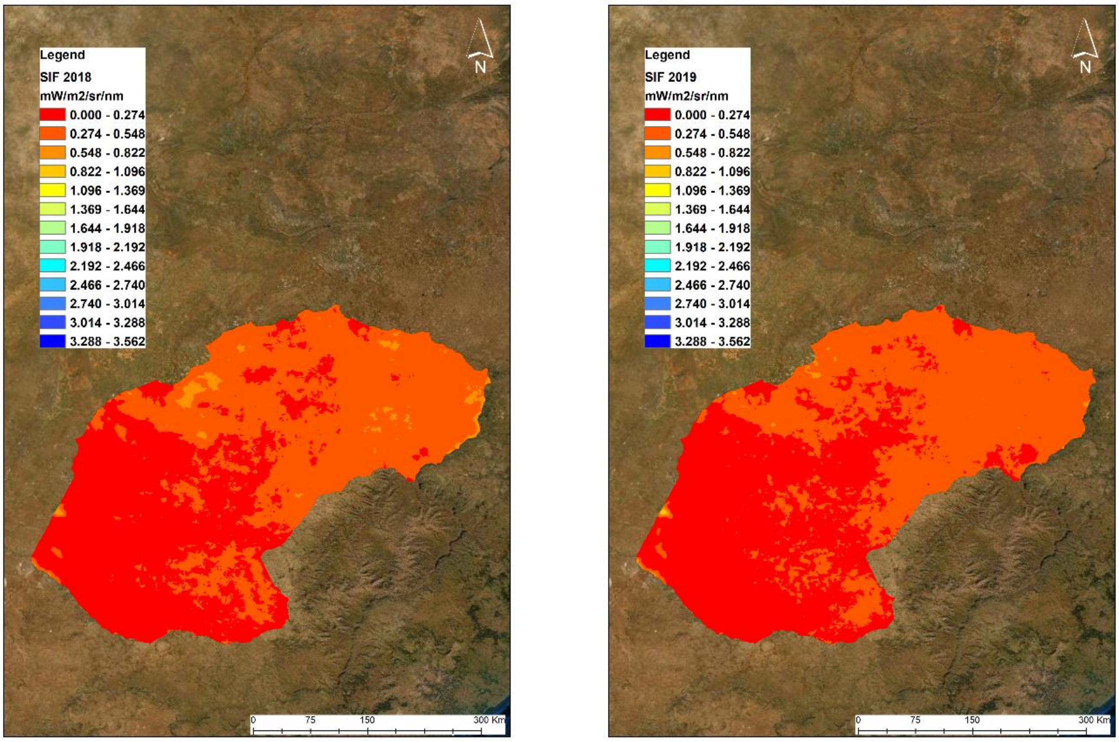


Figure 27. Portugal average annual SIF for 2018, 2019, 2020 and 2021. ANEXO

2018 2019



2020 2021

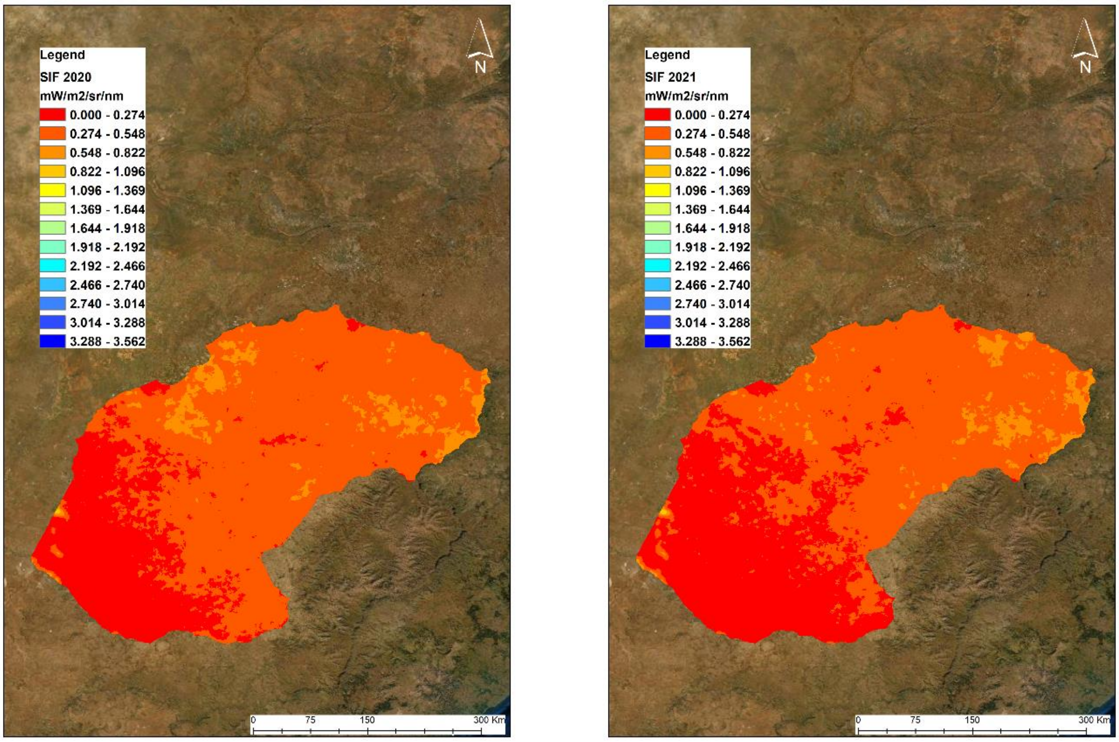
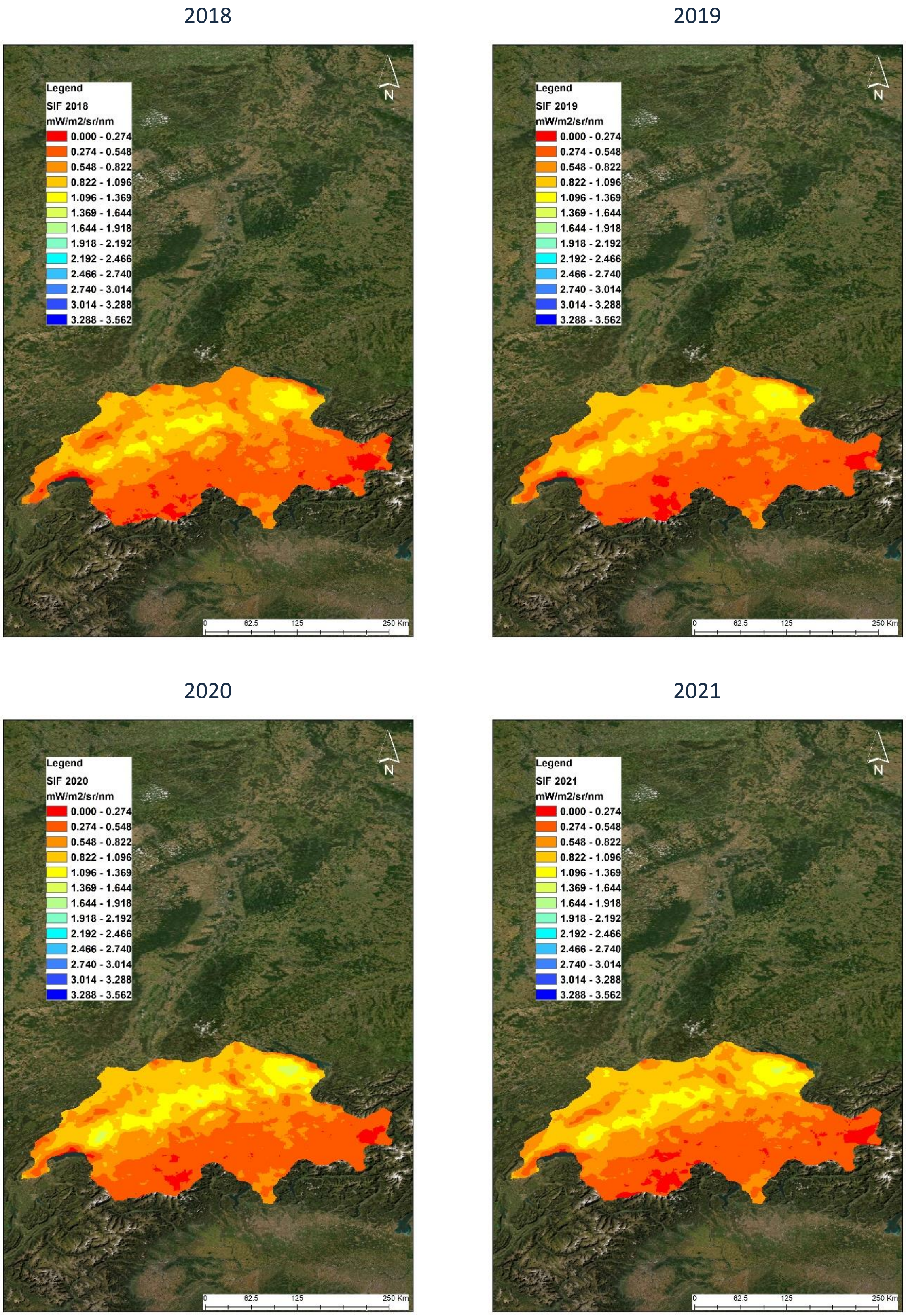


Figure 28. South Africa average annual SIF for 2018, 2019, 2020 and 2021.

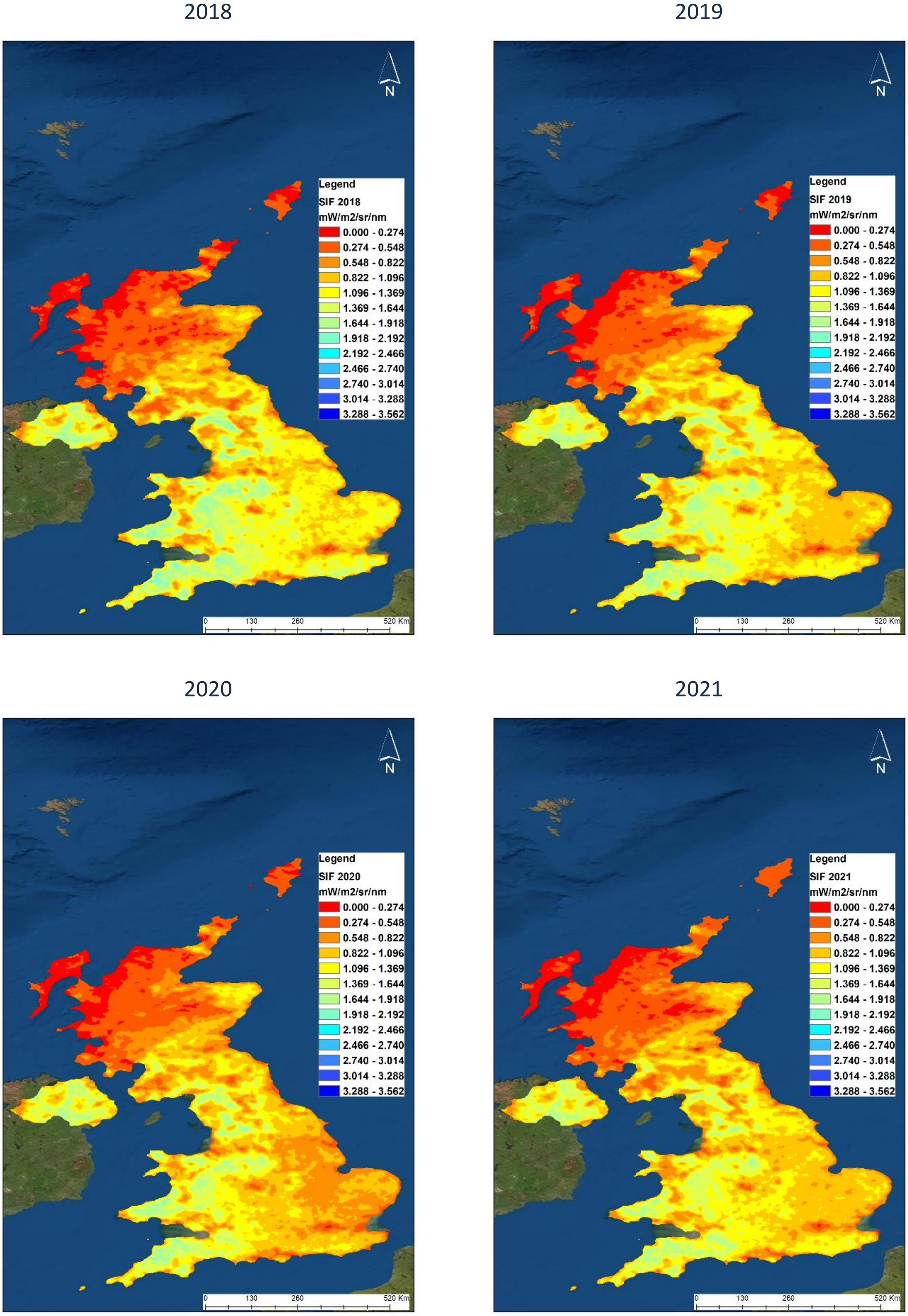

2018

2019

2020

2021

Figure 29. Switzerland average annual SIF for 2018, 2019, 2020 and 2021.


2018

2019

2020

2021

Figure 30. United Kingdom average annual SIF for 2018, 2019, 2020 and 2021.

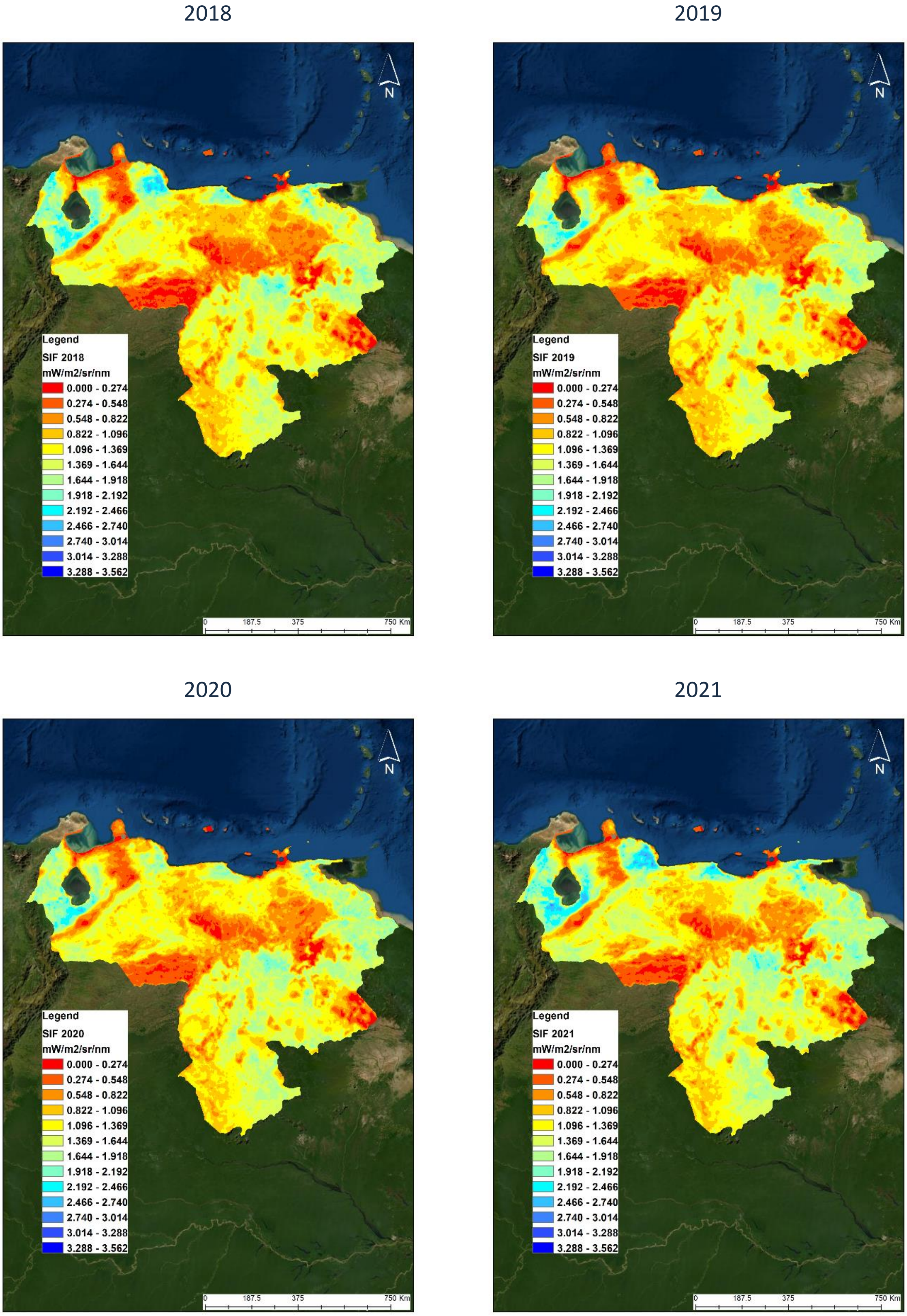


Figure 31. Venezuela average annual SIF for 2018, 2019, 2020 and 2021. ANEXO

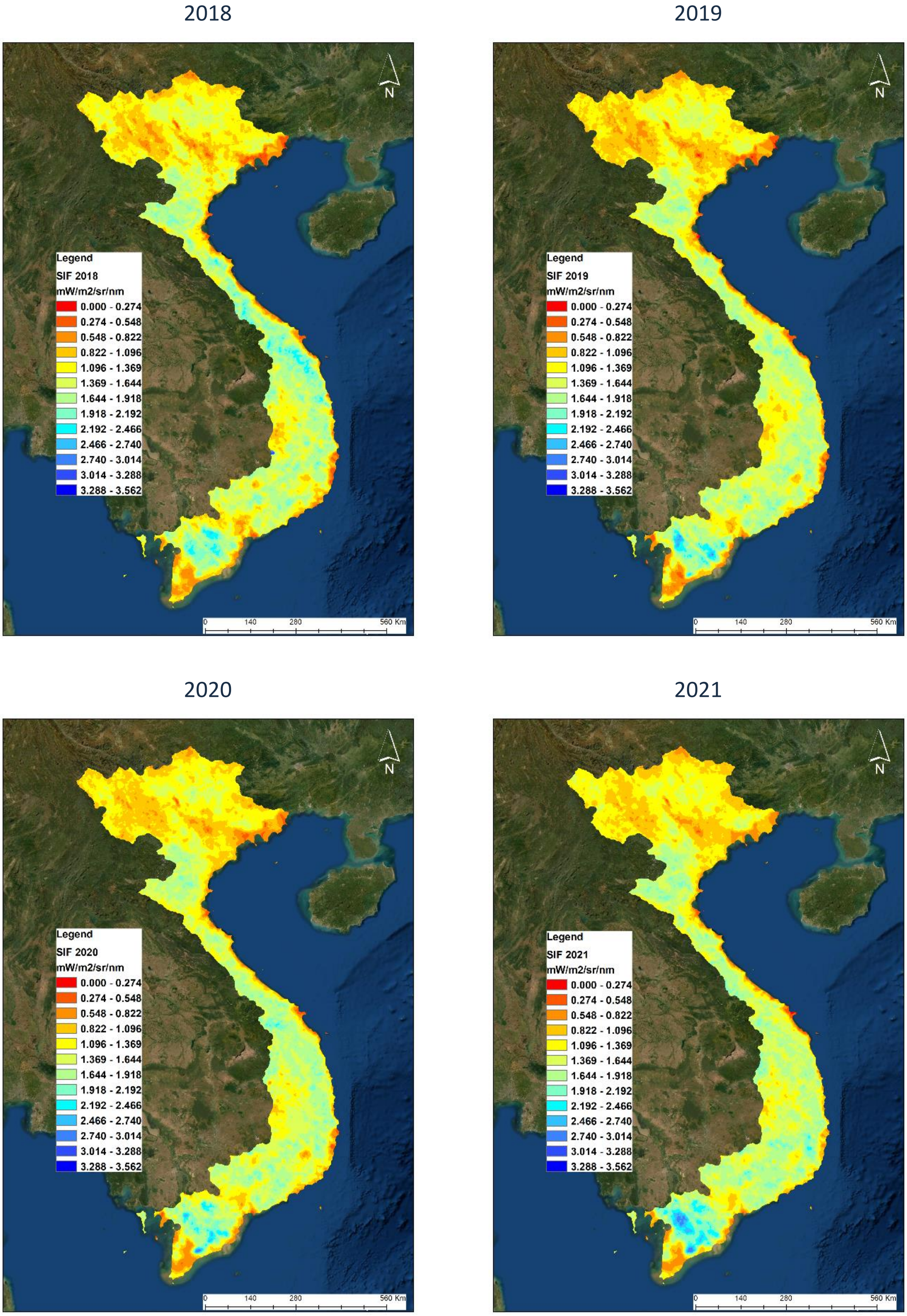


Figure 32. Vietnam average annual SIF for 2018, 2019, 2020 and 2021. ANEXO