Detecting changes in vegetation and climate that serve as early warning signal on land degradation using remote sensing: A review

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ABSTRACT:

Desertification and land degradation have severe negative effects on land-use, water resources, soil stability, agriculture and biodiversity. Especially, drylands cover 33.8% of northern Mediterranean countries: approximately 69% of Spain and 66% of Cyprus. The European Environment Agency (EEA) indicated that 8% of the territory of the European Union (mostly in Bulgaria, Cyprus, Greece, Italy, Spain and Portugal) experience a 'very high' or 'high sensitivity' to desertification. For Cyprus Island, 9.68% of the land area was found to be susceptible to land degradation.

The objective of this literature review is to provide a detailed synthesis of the main contributions of the global vegetation phenology research to the development of environmental knowledge, based on land degradation/ desertification and Earth observation (EO)-based science and technology. The study identifies the current fields of research and possible research gaps. To achieve this, more than 700 scientific papers were screened from which approximately 549 papers were reviewed, identifying and the state of land surfaces and vegetation phenology with remote sensing data.

Most of the studies have as a central research object direct human-induced land degradation or the degradation of anthropogenic-modified landscapes, without having considered long-term un-altered natural vegetation, in order to assess the impact and the level of climate change. Hence, a detailed EO-based time-series monitoring and analysis of un-altered natural vegetation could provide indicators that may serve as early warning signals for the scale and level of climate change induced effects on vegetation and ecosystems that might lead to land degradation and even to desertification.

Keywords: vegetation phenology, remote sensing, desertification, land degradation, early warning signals

1. INTRODUCTION

The frequency at which climate change is pressing an ecosystem and the living organisms constitutes a major threat to sustaining the natural resources that the human need to survive over the years. Human activities are a major driver that causes profound changes to ecosystems such as lakes, wetlands and forests. As the years pass gradual and predictable changes will be rare and may become abrupt, nonlinear and irreversible [1].

Through warming period, declining of vegetation and especially of forests may be accelerated in many regions due to the lack of water supplies. Hence, the water shortage and drought may reduce tree productivity and affects forests ecosystems [2]. Unfortunately, drought is a major key factor that influence the vegetation [3]. Equally, through drought processes pests and pathogens grow easily on weak trees and increase their mortality [4].

Studies found that land degradation, defined as a reduction of vegetation cover, significantly impacts soils. The increases and decreases of vegetation could therefore be used as indicator of soil fertility and erosion [5].

Desertification involves a complex set of factors, interacting in space and time leading to decrease in land productivity. It is closely related to many environmental factors such as climate, soil, vegetation cover, and morphology of which the character and intensity contribute to the evolution and characterization of different degradation levels. Moreover, is strongly linked to socio-economic factors, since man's behavior and his social and economic actions can greatly influence the evolution of numerous environmental characteristics.

As mentioned above, the lack of water reserves that occurs in an area may cause ecosystem to desert as the soils are depleted of humus and rather destroyed, and vegetation is done rare and sparse. Repeated and deep plowing in some cases can also lead to soil degradation [6]. Environmental sensitivity is related to various bio-natural and anthropogenic factors, the characteristics and intensity of which contribute to the development of different levels of degradation.

To be more precise, land degradation occurs mainly, but not exclusively in dryland regions and in 2013 was affecting 1,9 billion hectares of land worldwide and 250 million people [7], where at the same time it is come to be as the most pressing environmental issue [8]. It is a fact that, in the last decade 1.5 billion people depend on land that degraded, 75 billion tons of fertile soil and 12 million hectares of land are lost every year to desertification and drought alone [7].

1.1 The objective of the literature review

The objective of this review is to provide a detailed synthesis of the main contributions of the Earth Observation (EO)-based global vegetation phenology research to the development of environmental knowledge of land degradation and desertification. The study investigates the links of human activity and climate change leading to desertification and identifies the current fields of research and possible research gaps. The study is structured in three research sections:

1. approaches adopted to prevent from, and mitigate and adapt to desertification and the factors increasing the risk of desertification.
2. EO contributions to desertification studies, from real-time desertification management to adaptation planning and abrupt transition predictions.
3. suggestions for future studies and research gaps to combat abrupt desertification processes.

1.2 Monitoring Land degradation

Productivity metrics could provide information about mapping and assessing aspects of land degradation at the growing season of plants. Thus, governments have the opportunity to adopt and develop environmental actions plans to tackle the land degradation [9].

The NDVI also provides information for the photosynthetic activity and the primary production from vegetation biomass related with vegetation health. Similarly, with NDVI, EVI is less sensitive to noise from background soil and atmospheric particles and less saturated in high-biomass areas. Another relevant indicator assessing land degradation is NDWI measuring canopy leaf water content and monitoring vegetation moisture stress [10]. With regards to vegetation trends and changes, Landsat monitoring have better possibilities to detect often-subtle trends in vegetation productivity at any area within 8km pixel [11]. On the other hand, MODIS GIMMS3gis is able to detect anomalies of low NDVI of vegetation during drought events within 8km pixel [4].

Another main indicator on mapping prone areas of land degradation is the leaf area index (LAI) that is directly related to the loss of biomass which is affected by climate and human activities. Furthermore, albedo and evapotranspiration (ET) are responding partially to biomass changes, comprehending part of the land degradation cycle. Comparing albedo and LAI, LAI respond as a better indicator for assessing land degradation due to a wider range of variation, showing also high relationship with ET. However, the major driver of ET is precipitation [12].

Additionally, to detect susceptible areas to land degradation, one of the best choices that several studies use is the calculation of the Environmentally Sensitive Areas Index (ESAI). Calculation the ESAI index provides information for environmental sensitive areas and susceptible to land degradation. The ESAI index consists of the grouping of some indicators such us, the Climate Quality Index (CQI), Demographic Index (DI), Soil Quality Index (SQI) and Vegetation Quality Index (VQI). To be more precise:

- the parameters used to calculate the CQI are the precipitation, aspect and Normalized Difference Water Index (NDWI) that are categorized with constant characteristics and numbers.
- the parameters used to calculate the DI are the population density (number of people per km2) and population growth rate (%) that are categorized with constant numbers
- the parameters used to calculate the SQI are the soil moisture, slope, average surface temperature (K) and Bare Soil Index (BSI) that are categorized with constant numbers.
- the parameters used to calculate the VQI are the land use/ land cover, fire risk, drought resistance and Normalized Difference Vegetation Index (NDVI) that are categorized with constant characteristics and numbers [13].

Equally important is to emphasize to stressors parameters that may trigger land degradation such as extreme droughts. SPEI indicator, is a conventional meteorological index that is the most suitable drought index [14]. Measuring the drought with spatial similarity and different timescale without climatology, highlights the usefulness of the indicator [15, 16]. The creation of SPEI index was an update version of SPI index that measured only the precipitation factor but on the other hand SPEI index includes the influence of meteorological variables such as temperature, humidity, wind etc. In view of this, various studies [14,17-20] have shown that these meteorological variables play a major role to understand and analyze the drought events. Eventually, SPEI index depict the climate water balance (D) which is calculated as a difference between precipitation and potential evapotranspiration (PET). According to Horion et al. (2019), the SPIE index responses ranging between 0 and -1 in abnormally dry conditions, moderately dry between -1 and -2 and severely dry for below -2 [21].

1.3 Monitoring phenology using remote sensing

Vegetation cover changes may represent direct the response of vegetation under climate change impact and human pressure [22]. The main stages of phenophases are: (a) the start of the season (SOS), (b) the start of vegetation maturation, (c) the time of maximum NDVI, (d) start of the browning (senescence) of NDVI and (e) end of the season (EOS) [23].

Global warming influences the vegetation phenology and may alter the duration of the season and the phenophases. As critical characteristics, vegetation phenology and its productivity influenced the regional and climatic patterns as well as on the biogeochemical cycles [3]. In view of this, the relationship between vegetation phenology and climatic drivers such as temperature, precipitation or CO2 concentration it would be a knowledge gap in the recent years [24].

To be more precise, the analysis of the impact of extreme climatic condition on vegetation phenology and productivity is complexed and the knowledge on the subject is still insufficient. Hence, is essential to evaluate the vegetation phenology and productivity through the pressure of climate change, especially from land degradation [3]. The phenological changes become apparent through, (a) shifting the timing of the lifecycle events, (b) shifting range boundaries led to extirpation and colonization, (c) changing morphology, reproduction or (d) extinction [23].

1.4 Remotely-sensed early warning signals of a critical transition

Analysis and characterization correctly of ecosystems dynamics across multiple scales in space and time, can be achieved integrating it with remote sensing technology with statistical approaches estimating early warning signals of critical transitions in complex ecosystems. Early warning signal is the need to avoid and predict abrupt transitions between alternative states, typified by the collapse of ecological systems which then exhibit hysteresis [25]. Robust early warning signals for upcoming critical transitions could be developed through mechanistic links to ecosystem dynamics of remotely sensed based metrics [1].

The natural or human-induced physical event that causes damage and the critical and abrupt transitions will be more frequently in the near future for several ecosystems. Before critical transitions, according to the theory, there are variables that warn the state and the ecosystem for an upcoming change. These state variables warnings are called “early warning signals” of the upcoming critical transitions. Prior of a critical transition the dynamic phenomenon called ’critical slowing down’ occurs. To be more precise, a low-resilience ecosystem recovers at a reduced rate and therefore the ecosystem with state variables leading to a transition have reduced equilibrium return rates following perturbations [1].

2. THE 2010-2021 LITERATURE REVIEW

2.1 Methodology

For the literature review, I used the following combination of keywords: Topic = “desertification” OR Topic= “degradation” or "drought" as a word in all text AND Topic = “remote sensing” as a subject term AND Topic = “research gap” or “future studies” as a word in all text. The first topic defined the environmental issue of interest, while the second topic re-strained further to only show papers while link desertification through remote sensing.

The second step was complementary to the first, which added journal articles about desertification through remote sensing in various regions have been established since 2010.

The third step was to search in Google Scholar (with the searching keywords of ‘desertification’ and ‘remote sensing’), up to 2021 to pick up any important publications that were missed from the first two steps. As the quality of the selected literature was important to draw the conclusions of this review paper, any result that was not a journal article (e.g., conference proceeding, book chapter, lecture notes) was not selected.

To begin with, 725 papers were detected by the search, of which 549 were chosen for analysis. Studies which are included, are focusing on vegetation changes, recent future studies and extreme climatic phenomena. The rest of papers did not study vegetation, and some articles even belonged to other branches of science. The 549 papers analyzed were published in the period 2010 to 2021 (July) (Fig. 1). Most of the published papers of this study topic were published in 2020 and shown an increasing trend. Nonetheless, the fluctuation that followed the trend was remarkable reaching 126 articles by 2020. This steep increase trend suggests the need to fill gaps that they appear in order to combat extreme disasters.

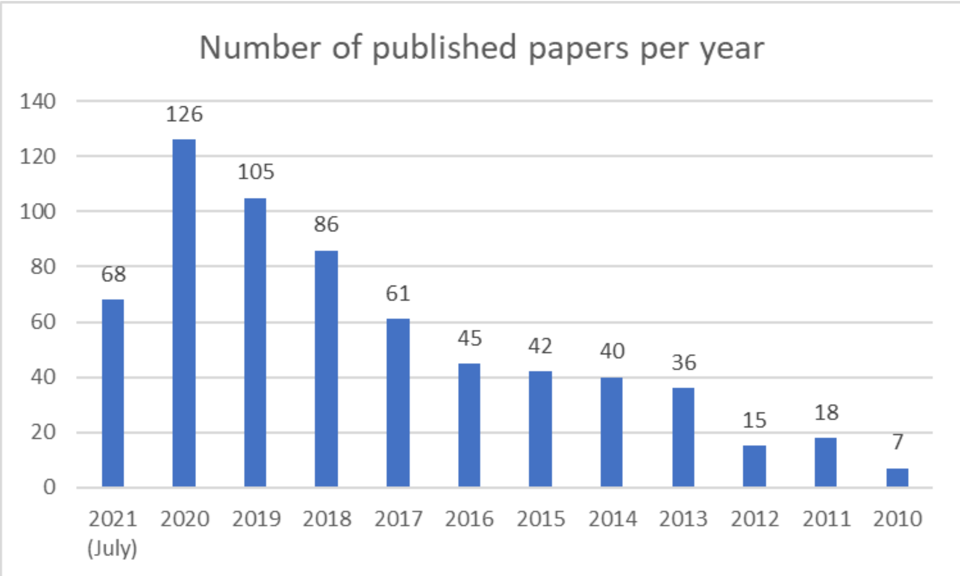

Fig. 1. Number of papers/studies grouped by year that suggest future studies and research gap in vegetation monitoring and desertification.

2.2 Spatial distribution of studies

About the journal articles, 725 pieces of published literature were found (up to 2021) from the first step. After checking articles manually, 547 (i.e., conference materials, magazines) and 2 (not written in English) were further accepted for analysis.

The second step resulted in 549 articles, which were selected for the review, articles which adopt modern and newest techniques, satellites images and software.

From the third step, a further 30 articles were added to the list, which makes up an important and representative part of the reference list. The selected papers are listed in a table below.

The purpose of the combination is to cover all the possible articles that recommend any future studies and research gaps related with desertification with remote sensing. Specifically, 109 reviewed publications focused on China. In North America, California gained the most attention (10), more than triple as much as the second most investigated areas Texas, Illinois and Florida (3). Apart from U.S.A, Mediterranean countries are the other hot spots which are consists in sum 30 articles. The region of Spain has published 12 articles and Italy 3 articles while the other territory of the Mediterranean together number 10 articles (Fig. 3). Optical sensors (Landsat, SPOT, Sentinel and MODIS) are the most commonly applied. Generally, Asia has total 234 published articles with almost half of these were published by China followed by India (16) and Iran (12). It should be noted that the main ecosystem studied worldwide are forests (Fig. 2).

The published papers were mainly distributed among of 180 journals, where the lowest impact factor was 0.44 for the "Walailak journal of science & technology", and the highest was 11,78 for the journal "Science of Bulletin". In addition, there were journals that were prominent in terms of quantity of publications (Fig. 4). Journals with specialization of remote sensing were shown more frequently.

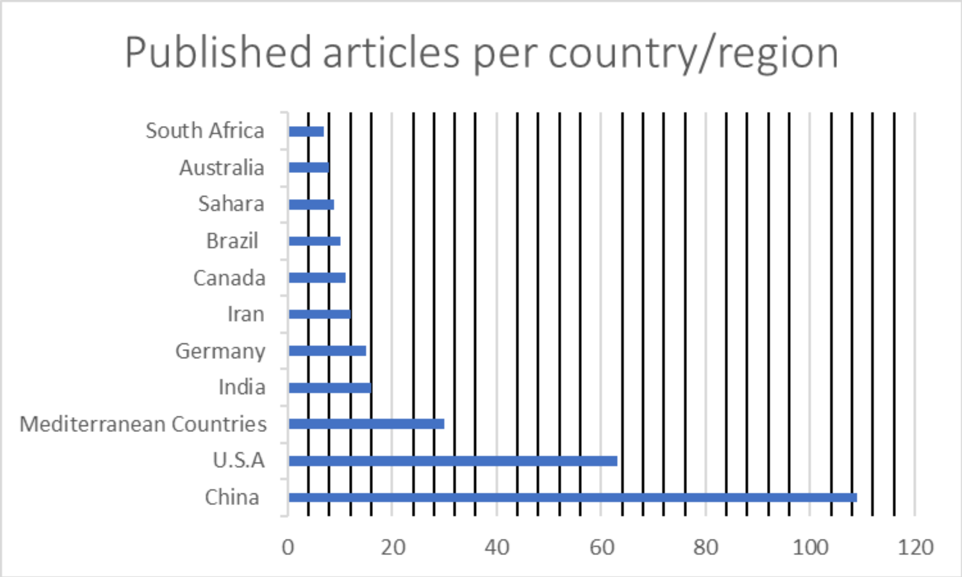

Fig. 3. The 11 countries/regions with the most articles on remote sensing and desertification.

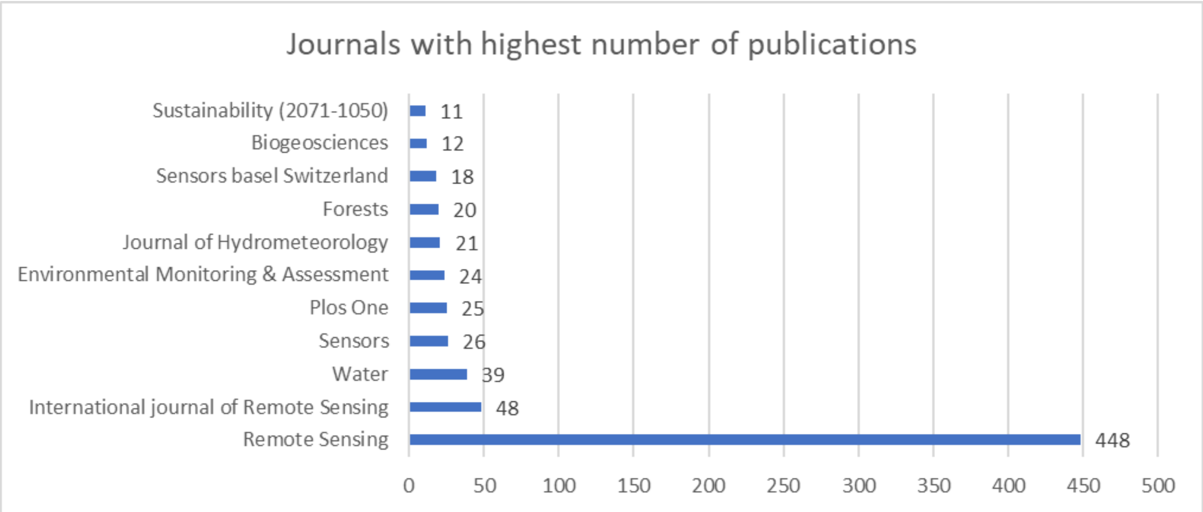

Fig. 4. Journals with highest number of publications on remote sensing, desertification or drought.

The main methodologies found are based on monitoring of vegetation under extreme pressures and monitoring of phenological states. Most of these methods use the vegetation index NDVI as the main element. Studies focusing on trends and review articles are also popular. Moreover, leaf area index (LAI), evapotranspiration (ET) and land surface temperature (LST) are also used to analyze and characterized the response of vegetation changes. An interesting aspect found was that the research mostly utilized climatic information and metric based indicators, as ancillary data. In Fig. 5, methodology is summarized. The NDVI, LST, LAI, EVI is the most popular algorithms in the literature.

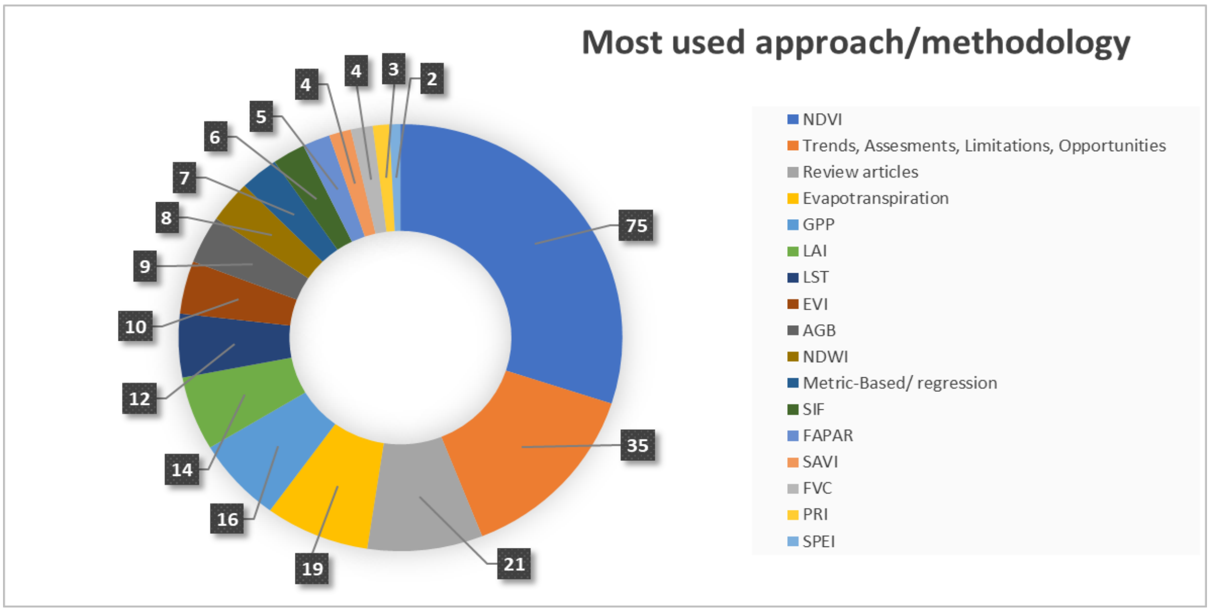

Fig. 5. Main algorithms/indexes and approaches for vegetation monitoring using time series data.

3. RESULTS

3.1 Global and regional correlation between remotely sensed analysis and phenological metrics

Previous studies compared the efficiency of NDVI and EVI for the assessment of vegetation phenology. Apart from this, studies suggest that EVI is more efficient than NDVI because it enhanced the vegetation response in high biomass regions. The application of EVI time series presents more responsive results on canopy variations, types, architecture and plant physiognomy and hence is more associated with stress and changes related to drought than NDVI [3]. Nonetheless, NDVI time series show the better performance to estimate the SOS and EOS. The period of SOS (start of the season) starts of the green vegetation and EOS (end of the season) end the green vegetation [26].

It is an undeniable fact that, most of the studies use these vegetation indices (VIs), the normalized difference vegetation index (NDVI) and enhanced vegetation index (EVI). Otherwise, there are areas such as forest with evergreen species were not able to detect SOS and EOS, easily, with these indices. At this point, the variability of the land surface temperature (LST) with a combination of the canopy greenness is a helpful way to detect and analyze the phenology of evergreen forests. It is important to note that, the variability of LST shows better performance than any other VI indicator at this type of forests. Similarly, the variability of LST, is more useful than LST itself in detecting changes according to recent studies [27].

The large amount of the studies is based on two groups of phenological studies: a) extracting the trends and information from VIs graphs, b) analysis and deriving the phenophase time and status in order to detect changes in phenological patterns over space and time. Smoothed data from VIs data, overcomes noises caused by cloud cover, mixed pixel effects and sensor anomalies which can be calculated, i) statistical, ii) curve fitting and iii) data transformation techniques [28]. As opposed to estimation changes of phenological parameters or phenophases detection, are often using, i) threshold, ii) curve derived and iii) functional model fitting methods [29].

3.2 Drought drive to land degradation as the major impact on terrestrial ecosystem processes

As mentioned, some studies support that the major factor that leads to land degradation is the drought. Drought events is explaining of the occurrence of major degradation is some region [30]. Especially, Prince et al. (1998) investigate to the rain-use efficiency in Sahel and refers that the reduction of vegetation canopy and coverage is correlated of the decreasing of the rain use efficiency [31, 32]. Long-term analysis of biomass and environmental based data could provide an assessment on land degradation. To be more precise, Vicente-Serrano (2007) analyze the precipitation anomalies and the response of vegetation in order to assess the drought impact on the land in the Mediterranean semiarid region [33, 34]. Anomalies of regional precipitation is affected also from other external drivers, especially of sea surface temperature in low latitudes [35].

As one of the controlling factors of vegetation, temperature with the impact of drought is the primary climate characteristics associated with tree mortality [4]. As a response of the global climate change could be consider the drought processes and high temperatures triggered tree mortality, enhance the chances of weakened forest occurrences in some locations [36]. A study, observed that several European beeches suffered from dehydration during an extreme drought and high temperature events resulting massive canopy dieback [37]. This event of mortality appears often when drought is prolonged or repeated [38-41]. Southern parts of Europe, especially in the Mediterranean, experienced often tree die-offs examples (Fig. 6). North America temperate and boreal forests in recent decades depict steep increase on tree mortality rates and thus in 1997 and over 10 million ha have been affected as a result of all these extreme conditions that led to tree mortality. In summary, it is recognized that the common denominator of these examples is the considerable increase of temperature and / or water stress, becoming the world's forests warming and drying. Water limitations response on specific forest types that grouped into four biome types: (1) savannas, (2) conifer forests and Mediterranean woodlands, (3) temperate evergreen and deciduous forests, and (4) evergreen broadleaved tropical forests [36]. Eventually, a severe drought may lead vegetation species to mortality [4d]**.** Before the event of mortality and during the extreme drought process severely delayed or even undetectable phenological cycles are pointed out in dryland ecosystems [42].

Fig 6. Satellite map of Europe, with documented drought-induced mortality areas indicated with numbers. R photo: *Quercus alnifolia Poech* mortality, Machairas Forest, Cyprus by Filippos Eliades M photo: *Pinus sylvestris* mortality, Valais, Switzerland; 1999, by Beat Wermelinger. L photo: *Pinus sylvestris* die-off, Sierra de los Filabres, Spain; 2006, by Rafael Navarro-Cerrillo [36].

To sum up, climate induced pressure led the ecosystem to several changes, as we mentioned above such as land degradation, delayed of phenological cycle, increasing of tree mortality etc. All these changes are also called as abrupt shifts, regime shifts or critical transitions. These phenomena appear when an ecosystem have low resilience and cannot tackle the external pressure. Then, when an ecosystem is under of the intensive climate pressure, its recovery would be slower on small disturbances until is so close to a critical threshold that is also called a 'tipping point' [1]. Generally, tipping points behave such as the game "Jenga" where every block that is removing from the wooden structure are stacked on the top of each other and players in every round remove a block and place it on the top of the tower. The probability to collapse the block tower is low at the beginning of the game due to its strong structure, but the probability increases with each turn. The removal of the blocks operates such as gradual changes making the structure unstable (low resilience) until the wooden block collapse (irreversible state). Similarly, tipping points theory behave in the same way, with each day of accumulated environmental stress pushing the ecosystem closer to irreversible state such as desertification [43].

3.3 Application of early-warning signals on vegetation changes

As it mentioned before, the low resilience of an ecosystem faced critical transitions before is close to a tipping point due to the low trend of its recovery. The three metrics that depict an upcoming critical transition in any dynamic system such as an ecosystem are the spatial variance / standard deviation, skewness and autocorrelation [43]. The estimation trend of the above metric-based indicators implemented through Kendall's τ. Prior of a critical transition when the ecosystem lost its resilience, autocorrelation and standard deviation always depict an increasing rate [44]. In this case, the ecosystem is asymmetric near the tipping points resulting an increasing of skewness time series [1].

Equally remarkable is the method of linear regression that is well-suited to detect early warning signals especially on tree mortality. Theil-Sen method is qualitatively identical with simple linear regression but with decreasing influence on Landsat and MODIS data. Emphasizing to the vegetation changes, especially on tree mortality, several studies illustrate that linear regression application responds better on negative jumps and increasingly steep slopes of time series NDVI. Non-normal residual distributions and autocorrelation is evidenced, especially when mortality events are close [4].

Smoothing of the data is the primary step before applying the metric-based models that it mentioned above in order to eliminate the effect of nonstationary conditions on the leading indicators. Popular smoothing and detrending approaches are Gaussian, Linear and Loess filters and first-differencing.

4. DISCUSSION

Overall, monitoring the vegetation phenology of biomass in different period of the season under the extreme temperature, precipitation and severe drought could provide information to predict the responses of ecosystems in the future. These kinds of studies will permit more accurate results [45]. On the contrary, the process of desertification influenced on local climate provide information for upcoming changes. The impact of desertification on local climate can alter the carbon cycle resulting the increasing level of atmospheric CO2 which is related with the global climate change. Equally, surface energy exchange and water budgets are directly related with local climate [46].

Hence, the assessment report of the IPCC depicts that the soil moisture in Mediterranean, southwest USA and southern Africa region is decreasing. For this reason, Miao et al. analyzes the trends of desertification for the upcoming years under the RCP scenario 8.5 of IPCC has pointed out that the desertification will accelerate [47]. Using NDVI and other indicators to monitor land uses and types of ecosystems, in some instances would give false positive data, especially in the relationship between biomass and productivity [48]. For instance, the combination of intensive monocropping and fertilizer application give satellite data as increased productivity though these could be considered as land degradation. In view of this, there are regions undergoing desertification and drylands that are greening on average.

Undoubtedly, phenological changes could operate as an indicator to analyze and assess climate change and vegetation responses which can improve the correlation between land and atmosphere such as the quality of carbon, water and energy exchanges [49]. Land degradation is a complex phenomenon and quantifying and detecting degradation from space remains limited because to identify land degradation by reduction of canopy cover and/or biomass is difficult [43].

To resume, the natural driving forces that mentioned in the article, are vital factors on the variations of phenophases of individual species. The sensitivity of the organisms under of the stressor conditions indicate changes of the sequence, frequency and duration of phenophases. To be more specific, Buitenwerf et al. (2016) investigate, from 1981 to 2012, the vegetation phenology and argue that the global land surface suffered from severe changes [50]. As for example, herbaceous phenophases in the eastern Tibetan Plateau faced delaying growing season (SOS) and end of the growing season (EOS) and thus, expand length of the growing season (LOS). This study shows that some areas of Tibet evident moisture stress. Various studies marked that phenology changes under climate change pressure can be perceived several months before [51, 52].

Clearly, the estimation of critical transitions of real complex ecosystems under climate change pressure is difficult. Establishing early warning signals with the integration of remote sensing to detect upcoming critical transitions can bridging the gap between abstract theory and ecosystem dynamics. Using early warning signals preventing changes such as desertification can allow Governments and policy makers to develop effective plans and strategies.

5. NEW TRENDS, LIMITATIONS AND FUTURE STUDIES

Recent land degradation trends and the detection of abrupt transitions that apply early warning signals using climate-induced stressors are constrained by a number of research gaps and scientific uncertainties.

The results from the presented literature review showed a considerable correlation on how climatic stressors parameters such as lack of precipitation and extremely high temperature constitute the major drivers to drought. Various of studies experienced the association between drought and land degradation focusing to the vegetation changes, reduce of productivity and tree mortality, due to the extreme conditions. Focusing to this approach various limitations are located that may guide to future studies in order to understand the response of an ecosystem and the operation of land degradation / desertification.

In view of this, studies demonstrate the necessity to investigate early warning signals in order to predict abrupt and irreversible transitions. Kéfi et al. (2007) emphasizes the need to fill the research gap of respond analysis of consistent deviations from power of laws that is absolute correlated with desertification. These deviations may be operating as early warning signals for desertification of several arid ecosystems [53]. A remarkable approach of these transitions is also the determination of tipping (flipping) points that warn for upcoming alternative (degraded) state, particularly in this case of desertification / land degradation, while passing these points the ecosystem restoration becoming irreversible [54]. At this point, Boisvenue and Running (2006) and Bonan (2008) also mention the importance to predict the consequences on ecosystems in order to avoid these transitions, especially to forecast the irreparable loss in forests, under of climatic stressors considering them as grand challenges [55, 56].

An example of critical transition that many researchers investigate is manifested in forest trees increasing their mortality that led to a completed dying. Comparing semiarid regions, especially in Mediterranean, using vegetation indicators such as NDVI, EVI etc., climatic conditions and other hydrological states could provide a holistic view, improving the mortality prediction incorporating also with long lead times and at fine spatial scales [57]. Additionally, monitoring various semiarid regions that face unpredicted vegetation changes leading to tree mortality during extreme drought periods, may shrinkage an area resulting in degradation and even to desertification. These types of changes in vegetation phenology that is closely linked to the variability of climate patterns may operate as an early warning signal. Therefore, tree phenology may respond differently to climate warming as for example an increase winter temperature that is correlated with depletion of carbohydrate reserves relevant to carbon starvation thresholds [36]. At this point, focusing on the relationship between vegetation phenology and climatic drivers such as temperature, precipitation or CO_2 concentration is also a promising research gap.

6. CONCLUSION

Since 2010, most of the articles were published reflecting the major changes of land under stressor parameters. Asia and the Mediterranean region are the regions with the highest number of vegetation monitoring publications since 2010 due to their sensitivity to desertification. The main ecosystems studied are forests and agricultural land, although various studies monitor vegetation on a global scale.

Monitoring vegetation functions is a very demanding field and therefore the proper choice of satellite data plays a major role. The SPOT satellite has been used more to monitor vegetation changes and more widely in this field. Nevertheless, the Sentinel satellite would become one of the most popular in the future according to studies due to its high resolution, periodicity and availability of its data. It is worth noting that due to its large temporal resolution, the Sentinel-2 satellite offers enormous potential for many scientific studies. However, the combination between data and metric-based indicators could improve the quality of the results.

Our findings in this literature review have as a central research object the long-term un-altered natural vegetation monitoring under of climatic stressors that affect vegetation phenology leading them to mortality. A major research gap that needs to be filled in future research is the monitoring of areas and vegetation, which have not been affected by human activities but only by climatic parameters such as changing temperatures and a decline of precipitation.

In this study, we summarized (1) established methods of monitoring vegetation changes and degraded land using satellite data, (2) the utility and importance to use metric-based methods of autocorrelation, skewness and standard deviation related with VIs indicators in order to present suitable early warning signals, (3) the current understanding of land changes that leading to reduce of vegetation productivity and (4) future challenges and research needs of detecting early warning signals in order to avoid abrupt transitions such as tree mortality due to the extreme droughts.

Overall, reviewed studies about tree mortality are limited and the need to predict critical transitions under extreme droughts leading to land degradation and therefore desertification. Fluctuations on timeseries data of various indicators as derived from the literature review as the most popular such as NDVI, LAI, EVI, ET and LST could operate as early warning signals before critical transitions. Recent studies correlate the variations of different vegetation indicators with various statistical approaches of metric-based indicators such as autocorrelation, standard deviation and skewness where they are quantifying changes in time series by increase and decrease, resulting in better approximations and display early warning signals in different ecosystems [1].

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REFERENCES

[1] Alibakhshi, S., Groen, T., Rautiainen, M. and Naimi, B., "Remotely-Sensed Early Warning Signals of a Critical Transition in a Wetland Ecosystem, " Remote Sensing, 9(4), 352 (2017).

[2] Park Williams, A., Allen, C., Macalady, A., Griffin, D., Woodhouse, C., Meko, D., Swetnam, T., Rauscher, S., Seager, R., Grissino-Mayer, H., Dean, J., Cook, E., Gangodagamage, C., Cai, M. and McDowell, N., "Temperature as a potent driver of regional forest drought stress and tree mortality," Nature Climate Change, 3(3), 292-297 (2012).

[3] Javed, T., Li, Y., Feng, K., Ayantobo, O., Ahmad, S., Chen, X., Rashid, S. and Suon, S., 2020. "Monitoring responses of vegetation phenology and productivity to extreme climatic conditions using remote sensing across different sub-regions of China," Environmental Science and Pollution Research, 28(3), 3644-3659 (2020).

[4] Rogers, B., Solvik, K., Hogg, E., Ju, J., Masek, J., Michaelian, M., Berner, L. and Goetz, S., "Detecting early warning signals of tree mortality in boreal North America using multiscale satellite data," Global Change Biology, 24(6), 2284-2304 (2018).

[5] Mansour, K., Mutanga, O., Adam, E. and Abdel-Rahman, E., "Multispectral remote sensing for mapping grassland degradation using the key indicators of grass species and edaphic factors," Geocarto International, 31(5), 477-491 (2015).

[6] Bedoui, C., "Study of desertification sensitivity in Talh region (Central Tunisia) using remote sensing, G.I.S. and the M.E.D.A.L.U.S. approach, " Geoenvironmental Disasters, 7(1) (2020).

[7] Unccd.int., “The United Nations Decade for Deserts (2010-2020) and the fight against Desertification | UNCCD”, n.d., <https://www.unccd.int/actions/united-nations-decade-deserts-2010-2020-and-fight-against-desertification> (13 June 2021).

[8] Wessels, K., van den Bergh, F., and Scholes, R., "Limits to detectability of land degradation by trend analysis of vegetation index data", Remote Sensing of Environment 125, 10-22 (2012).

[9] Copernicus., “High Resolution Vegetation Phenology and Productivity”, n.d., <https://land.copernicus.eu/pan-european/biophysical-parameters/high-resolution-vegetation-phenology-and-productivity> (13 June 2021).

[10] Byer, S., and Jin, Y., "Detecting Drought-Induced Tree Mortality in Sierra Nevada Forests with Time Series of Satellite Data", Remote Sensing 9(9), 929 (2017).

[11] Ju, J., & Masek, J. G., "The vegetation greenness trend in Canada and US Alaska from 1984-2012 Landsat data," Remote Sensing of Environment, 176, 1–16 (2016).

[12] Mariano, D., Santos, C., Wardlow, B., Anderson, M., Schiltmeyer, A., Tadesse, T., and Svoboda, M., "Use of remote sensing indicators to assess effects of drought and human-induced land degradation on ecosystem health in Northeastern Brazil", Remote Sensing of Environment 213, 129-143 (2018).

[13] Chen, H., Ye, S., Zhang, D., Areshkina, L. and Ablameyko, S., "Change detection based on difference image and energy moments in remote sensing image monitoring, " Pattern Recogn. and Image Analysis, 28(2), pp. 273-281 (2018).

[14] E. Ujeneza, B.J., "Drought regimes in Southern Africa and how well GCMs simulate them?, " Climate Dynamics 44 (5), 1595-1609 (2014).

[15] S.M. Vicente-Serrano, C. Gouveia, J.J. Camarero, S. Beguería, R. Trigo, J.I. López-Moreno, C. Azorín-Molina, E. Pasho, J. Lorenzo-Lacruz, J. R., "Response of vegetation to drought time-scales across global land biomes," PNAS 110, 52-57 (2013).

[16] Gazol, A., Camarero, J., Vicente-Serrano, S., Sánchez-Salguero, R., Gutiérrez, E., de Luis, M., Sangüesa-Barreda, G., Novak, K., and Rozas, V. et al., "Forest resilience to drought varies across biomes", Global Change Biology 24(5), 2143-2158 (2018).

[17] E.L., "Ujeneza Simulating the Characteristics of Droughts in Southern Africa," M.Sc. Thesis 1295 University of Cape Town, South Africa (2014)

[18] Vicente-Serrano, S., Tomas-Burguera, M., Beguería, S., Reig, F., Latorre, B., Peña-Gallardo, M., Luna, M., Morata, A., and González-Hidalgo, J., "A High Resolution Dataset of Drought Indices for Spain", Data 2(3), 22 (2017).

[19] Lawal, S., Lennard, C., Jack, C., Wolski, P., Hewitson, B., and Abiodun, B., "The observed and model-simulated response of southern African vegetation to drought", Agricultural and Forest Meteorology 279, 107698 (2019).

[20] Lawal, S., Lennard, C., and Hewitson, B., "Response of southern African vegetation to climate change at 1.5 and 2.0° global warming above the pre-industrial level", Climate Services 16, 100134 (2019).

[21] Horion, S., Ivits, E., De Keersmaecker, W., Tagesson, T., Vogt, J., and Fensholt, R., "Mapping European ecosystem change types in response to land-use change, extreme climate events, and land degradation", Land Degradation & Development 30(8), 951-963 (2019).

[22] Gong, Z., Kawamura, K., Ishikawa, N., Goto, M., Wulan, T., Alateng, D., Yin, T., and Ito, Y., "MODIS normalized difference vegetation index (NDVI) and vegetation phenology dynamics in the Inner Mongolia grassland", Solid Earth 6(4), 1185-1194 (2015).

[23] Workie, T., and Debella, H., "Climate change and its effects on vegetation phenology across ecoregions of Ethiopia", Global Ecology and Conservation 13, e00366 (2018).

[24] Bisigato, A., Campanella, M., and Pazos, G., "Plant phenology as affected by land degradation in the arid Patagonian Monte, Argentina: A multivariate approach", Journal of Arid Environments 91, 79-87 (2013).

[25] Clements, C., McCarthy, M., and Blanchard, J., "Early warning signals of recovery in complex systems", Nature Communications 10(1), (2019).

[26] Zhou, J., Cai, W., Qin, Y., Lai, L., Guan, T., Zhang, X., Jiang, L., Du, H., and Yang, D. et al., "Alpine vegetation phenology dynamic over 16 years and its covariation with climate in a semi-arid region of China", Science of The Total Environment 572, 119-128 (2016).

[27] Liu, Y., Wu, C., Peng, D., Xu, S., Gonsamo, A., Jassal, R., Altaf Arain, M., Lu, L., and Fang, B. et al., "Improved modeling of land surface phenology using MODIS land surface reflectance and temperature at evergreen needleleaf forests of central North America", Remote Sensing of Environment 176, 152-162 (2016).

[28] Atkinson, P., Jeganathan, C., Dash, J., and Atzberger, C., "Inter-comparison of four models for smoothing satellite sensor time-series data to estimate vegetation phenology", Remote Sensing of Environment 123, 400-417 (2012).

[29] Hudson, I., and Keatley, M., [Phenological Research], Methods for Environmental and Climate Change Analysis, 177-208 (2010).

[30] Vicente-Serrano, S., Cabello, D., Tomás-Burguera, M., Martín-Hernández, N., Beguería, S., Azorin-Molina, C., and Kenawy, A., "Drought Variability and Land Degradation in Semiarid Regions: Assessment Using Remote Sensing Data and Drought Indices (1982–2011)", Remote Sensing 7(4), 4391-4423 (2015).

[31] Prince, S., De Colstoun, E., and Kravitz, L., "Evidence from rain-use efficiencies does not indicate extensive Sahelian desertification", Global Change Biology 4(4), 359-374 (1998).

[32] Chen, H., Liu, X., Ding, C., and Huang, F., "Phenology-Based Residual Trend Analysis of MODIS-NDVI Time Series for Assessing Human-Induced Land Degradation", Sensors 18(11), 3676 (2018).

[33] Vicente-Serrano, S., "Evaluating the Impact of Drought Using Remote Sensing in a Mediterranean, Semi-arid Region", Natural Hazards 40(1), 173-208 (2006).

[34] Symeonakis, E., Karathanasis, N., Koukoulas, S., and Panagopoulos, G., "Monitoring Sensitivity to Land Degradation and Desertification with the Environmentally Sensitive Area Index: The Case of Lesvos Island", Land Degradation & Development 27(6), 1562-1573 (2014).

[35] Higginbottom, T., and Symeonakis, E., "Assessing Land Degradation and Desertification Using Vegetation Index Data: Current Frameworks and Future Directions", Remote Sensing 6(10), 9552-9575 (2014).

[36] Allen, C., Macalady, A., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., Kitzberger, T., Rigling, A., and Breshears, D. et al., "A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests", Forest Ecology and Management 259(4), 660-684 (2010).

[37] Schuldt, B., Buras, A., Arend, M., Vitasse, Y., Beierkuhnlein, C., Damm, A., Gharun, M., Grams, T., and Hauck, M. et al., "A first assessment of the impact of the extreme 2018 summer drought on Central European forests", Basic and Applied Ecology 45, 86-103 (2020).

[38] Bigler, C., Bräker, O., Bugmann, H., Dobbertin, M., and Rigling, A., "Drought as an Inciting Mortality Factor in Scots Pine Stands of the Valais, Switzerland", Ecosystems 9(3), 330-343 (2006).

[39] Gustafson, E., and Sturtevant, B., "Modeling Forest Mortality Caused by Drought Stress: Implications for Climate Change", Ecosystems 16(1), 60-74 (2012).

[40] Jump, A., Ruiz-Benito, P., Greenwood, S., Allen, C., Kitzberger, T., Fensham, R., Martínez-Vilalta, J., and Lloret, F., "Structural overshoot of tree growth with climate variability and the global spectrum of drought-induced forest dieback", Global Change Biology 23(9), 3742-3757 (2017).

[41] Mitchell, P., O'Grady, A., Tissue, D., White, D., Ottenschlaeger, M., and Pinkard, E., "Drought response strategies define the relative contributions of hydraulic dysfunction and carbohydrate depletion during tree mortality", New Phytologist 197(3), 862-872 (2012).

[42] Ma, X., Huete, A., Moran, S., Ponce-Campos, G., and Eamus, D., "Abrupt shifts in phenology and vegetation productivity under climate extremes", Journal of Geophysical Research: Biogeosciences 120(10), 2036-2052 (2015).

[43] Ahrends, A., Bulling, M., Platts, P., Swetnam, R., Ryan, C., Doggart, N., Hollingsworth, P., Marchant, R., and Balmford, A. et al., "Detecting and predicting forest degradation: A comparison of ground surveys and remote sensing in Tanzanian forests", PLANTS, PEOPLE, PLANET 3(3), 268-281 (2021).

[44] Dakos, V., van Nes, E., D'Odorico, P., and Scheffer, M., "Robustness of variance and autocorrelation as indicators of critical slowing down", Ecology 93(2), 264-271 (2012).

[45] He, Z., Du, J., Chen, L., Zhu, X., Lin, P., Zhao, M., and Fang, S., "Impacts of recent climate extremes on spring phenology in arid-mountain ecosystems in China", Agricultural and Forest Meteorology 260-261, 31-40 (2018).

[46] IPCC, “Desertification”, <https://www.ipcc.ch/site/assets/uploads/sites/4/2019/11/06_Chapter-3.pdf> (13 June 2021).

[47] Miao, L., Ye, P., He, B., Chen, L., and Cui, X., "Future Climate Impact on the Desertification in the Dry Land Asia Using AVHRR GIMMS NDVI3g Data", Remote Sensing 7(4), 3863-3877 (2015).

[48] Pattison, R., Jorgenson, J., Raynolds, M., and Welker, J., "Trends in NDVI and Tundra Community Composition in the Arctic of NE Alaska Between 1984 and 2009", Ecosystems 18(4), 707-719 (2015).

[49] Ma, X., Zhao, C., Tao, H., Zhu, J., and Kundzewicz, Z., "Projections of actual evapotranspiration under the 1.5 °C and 2.0 °C global warming scenarios in sandy areas in northern China", Science of The Total Environment 645, 1496-1508 (2018).

[50] Buitenwerf, R., Rose, L., and Higgins, S., "Three decades of multi-dimensional change in global leaf phenology", Nature Climate Change 5(4), 364-368 (2015).

[51] Estrella, N., and Menzel, A., "Responses of leaf colouring in four deciduous tree species to climate and weather in Germany", Climate Research 32, 253-267 (2006).

[52] Miller-Rushing, A., and Primack, R., "GLOBAL WARMING AND FLOWERING TIMES IN THOREAU'S CONCORD: A COMMUNITY PERSPECTIVE", Ecology 89(2), 332-341 (2008).

[53] Kéfi, S., Rietkerk, M., Alados, C., Pueyo, Y., Papanastasis, V., ElAich, A., and de Ruiter, P., "Spatial vegetation patterns and imminent desertification in Mediterranean arid ecosystems", Nature 449(7159), 213-217 (2007).

[54] Vågen, and Winowiecki, "Predicting the Spatial Distribution and Severity of Soil Erosion in the Global Tropics using Satellite Remote Sensing", Remote Sensing 11(15), 1800 (2019).

[55] BOISVENUE, C., and RUNNING, S., "Impacts of climate change on natural forest productivity - evidence since the middle of the 20th century", Global Change Biology 12(5), 862-882 (2006).

[56] Bonan, G., "Forests and Climate Change: Forcings, Feedbacks, and the Climate Benefits of Forests", Science 320(5882), 1444-1449 (2008).

[57] Liu, Y., Kumar, M., Katul, G., and Porporato, A., "Reduced resilience as an early warning signal of forest mortality", Nature Climate Change 9(11), 880-885 (2019).