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Review

Impact of El Niño–Southern Oscillation on Global Vegetation

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Abstract: El Niño–Southern Oscillation (ENSO), as the strongest source of interannual variability in the tropics, has far-reaching impacts on global climate through teleconnections. As a key factor modulating the vegetation changes, the impact of ENSO has been studied over the past two decades using satellite observations. The paper aims to review results from the past 10–20 years and put together into a consistent picture of ENSO global impacts on vegetation. While ENSO affects vegetation worldwide, its impact varies regionally. Different ENSO flavors, Central Pacific and Eastern Pacific events, can have distinct impacts in the same regions. The underlying mechanisms involve ENSO-driven changes in precipitation and temperature, modulated by the background climate states, with varying response from vegetations of different types. However, the interactions between vegetation and ENSO remain largely unexplored, highlighting a critical gap for future research.

Keywords: vegetation changes; ENSO; CP/EP ENSO; climate variability (NAO; IOD; AO)

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1. Introduction

El Niño–Southern Oscillation (ENSO) is the strongest signal of interannual climate variability in the Pacific Ocean, exerting significant influence on the global climate. ENSO consists of two phases: El Niño (the warm phase) and La Niña (the cold phase) [1]. An El Niño (La Niña) event is typically defined by a three-month sliding mean of the Niño 3.4 index (5° N–5° S, 170° W–120° W) reaching or exceeding 0.5 °C (or dropping to −0.5 °C or lower) and persisting for at least five months [2,3]. During ENSO, sea surface temperature (SST) anomalies drive atmospheric convection that influences the climate of both tropical and extratropical regions, mainly through modulating the Walker and Hadley Circulations [4]. With a cycle of 2 to 7 years, ENSO serves as a crucial predictor of interannual climate variability in the tropics [5], closely associated with extreme climate events such as floods and droughts [6].

The interactions between climate and vegetation are a core focus of global change research [7]. Reports from the Intergovernmental Panel on Climate Change (IPCC) and the International Plant Protection Convention (IPPC) address various issues related to vegetation and climate change [8,9]. Climate is generally considered an external driver of vegetation change, influencing vegetation cover directly or indirectly through factors such as temperature, precipitation, air humidity, and light [10]. Vegetation is significantly affected by climate change, contributing approximately 55% to the global greening trend in drylands [11]. Temperature and precipitation are key determinants of vegetation growth, and ENSO plays a crucial role in shaping global temperature and precipitation patterns, thereby impacting vegetation. Understanding how vegetation adapts to the ENSO, based on vegetation type and ENSO periodicity, can provide valuable insights for predicting

future vegetation variability. Moreover, vegetation phenology serves as an indicator of regional climate conditions. Monitoring and modeling vegetation cover can help track regional climate change trends. Therefore, studying the impact of ENSO on vegetation is of great scientific significance.

Over the past two decades, advancements in satellite observation technology have provided extensive vegetation data, enabling research on the relationship between ENSO and vegetation. This paper reviews 41 research articles published over the past two decades, offering a comprehensive analysis of ENSO's global influence on vegetation (see Figure 1). It summarizes recent research progress, with a particular focus on the impacts of El Niño and La Niña events on vegetation dynamics, highlighting the differential responses of various vegetation types within the study area. Additionally, the paper provides a brief overview of ENSO's influence on vegetation in conjunction with other climate variability patterns, including the North Atlantic Oscillation (NAO), Indian Ocean Dipole (IOD), and Arctic Oscillation (AO).

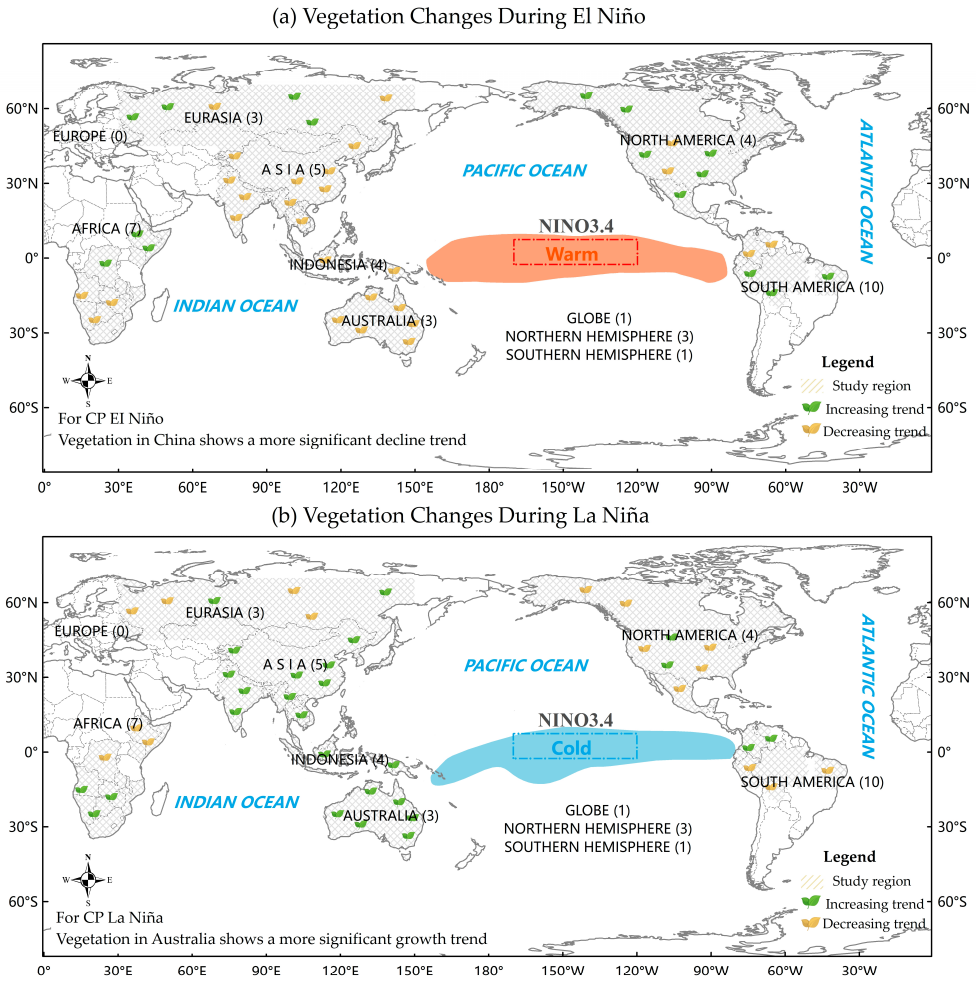


Figure 1. Comparison of vegetation trends under (**a**) El Niño and (**b**) La Niña conditions, based on anomalies in the normalized difference vegetation index (NDVI) for most global regions, leaf area index (LAI) anomalies specifically for Australia, and fraction of photosynthetically active radiation (FPAR) anomalies for North America. Gray-shaded areas indicate the study regions analyzed in the reviewed articles, with numbers in parentheses representing the corresponding publication counts. Green grass denotes favorable conditions for vegetation growth, while yellow grass signifies unfavorable conditions.

2. Impact of ENSO on Vegetation

2.1. El Niño and La Niña

2.1.1. Asia

Northeast Asia is in the mid- to high-latitude region and includes northeastern China, Japan, South Korea, and the Russian Far East. The region is primarily covered by coniferous and deciduous forests. ENSO influences the lower atmospheric circulation of the Northwest Pacific, which in turn alters the East Asian monsoon and subsequently affects the climate of the region [12]. Li et al. [13] investigated the response of summer (June–July–August) vegetation to preceding ENSO in Northeast Aisa. Their findings indicated that atmospheric circulation responds asymmetrically to the two ENSO phases. During EI Niño, the atmospheric circulation in Northeast Asia exhibits a meridional teleconnection pattern characterized by an anticyclone–cyclone–anticyclone structure. The study area (45–55° N, 110–145° E) lay at the boundary between high-latitude anticyclonic and mid-latitude cyclonic anomalies, resulting in strong northeasterly winds that transport dry, cold air from eastern Siberia. Consequently, vegetation growth was significantly suppressed, leading to negative anomalies in the normalized difference vegetation index (NDVI). NDVI, derived from the reflectance properties of vegetation in the red and near-infrared bands, is widely used to quantify vegetation cover [14]. In contrast, during La Niña, the teleconnection effects on local climate were relatively weak, leading to a slight increase in vegetation growth. Overall, Northeast Asian vegetation exhibited opposite response signals to El Niño and La Niña, with a stronger response to EI Niño.

Mainland China vegetation is influenced by ENSO, with climate variability in most regions closely linked to ENSO [15]. During ENSO, the varying position of SST anomaly peaks influences the east–west movement of the Walker Circulation, leading to changes in sea level pressure that in turn cause anomalies in the South Asian monsoon, affecting precipitation and temperature in China. During El Niño, South Asian monsoon rainfall tends to decrease, whereas during La Niña, the summer monsoon usually strengthens, leading to increased rainfall in the region [4]. EI Niño generally has negative effects on vegetation growth in China due to reduced precipitation, particularly in southern China (e.g., mixed forests). In contrast, La Niña tends to have positive effects, benefiting vegetation in central China (e.g., cultivated land), northern Inner Mongolia (e.g., grasslands), and the northern Tibetan Plateau [15,16]. Wang et al. [17] analyzed the relationship between ENSO and vegetation in the Western Pacific region from 1982 to 2017 and found that approximately 34% of leaf area index (LAI) variations were correlated with the ENSO index. LAI, defined as the ratio of total leaf surface area to the ground area it covers, effectively represents the vertical structure of plant communities [18]. The highest proportion of the vegetation affected by ENSO is found in highland climates, where more than 50% of vegetation changes are linked to ENSO, particularly in mountainous regions in southwestern China (e.g., high-altitude areas of Guizhou and Yunnan Provinces). Overall, the area of vegetation influenced by La Niña is slightly larger than that affected by El Niño in China [16]. Additionally, La Niña exerts a stronger impact on vegetation, with even weak La Niña events promoting vegetation growth, whereas strong El Niño events suppress it. Furthermore, coastal vegetation is less affected by ENSO than that in the inland region [15].

2.1.2. The Maritime Continent

The Maritime Continent lies at the center of the Walker Circulation and is directly affected by ENSO. During El Niño, Indonesia falls under the subsiding branch of the circulation, leading to below-average rainfall. In contrast, during La Niña, the Walker Circulation intensifies, promoting large-scale ascending convection and resulting in above-average precipitation in Indonesia [4]. ENSO influences long-term vegetation trends in tropical

regions. Most extreme rainfall events in Indonesia and the Philippine archipelago are associated with ENSO, posing serious threats to vegetation growth [19]. An analysis of the time series of NDVI anomalies and the ENSO index in tropical rainforests of Indonesia from 1981 to 2000 revealed distinct patterns, showing a decreasing NDVI trend during El Niño and an increasing trend during La Niña [20]. Among all tropical vegetation communities, savannas are the most affected by ENSO, with nearly 53% of their variability linked to ENSO fluctuations [21]. Vegetation resilience to climate variability is also influenced by the degree of land use and human activity, with core areas impacted by ENSO typically characterized by intensive land use [22]. Generally, El Niño events lead to significant and unusual vegetation degradation. A study examining the impact of El Niño events on vegetation changes in Indonesia from 1982 to 2006 focused on two El Niño episodes: the late-starting EI Niño of 1982/1983 and the early-starting EI Niño of 1997/1998. The results indicated that the extent of vegetation response in Indonesia was closely related to El Niño intensity. In contrast, moderate EI Niño events did not result in significant vegetation changes [22]. Yan et al. developed an ENSO–vegetation response index to investigate variations in tropical vegetation responses to ENSO events. Their results demonstrated that ENSO significantly affected at least 10% of tropical vegetation, with particularly strong impacts on observed in East Africa and Indonesia. Furthermore, since 2000, the positive effects of La Niña on tropical vegetation have weakened, while its inhibitory effects have become more pronounced [23].

2.1.3. Australia

The climate of Australia is strongly influenced by ENSO. During El Niño events, the eastward shift of the Walker Circulation places Australia under its subsiding branch, resulting in higher temperatures, reduced precipitation, and an increased risks of droughts and heatwaves. In contrast, La Niña enhances convective activity, leading to lower temperatures and increased rainfall. Notably, La Niña intensity shows a strong correlation with precipitation variability, whereas the relationship between El Niño and precipitation is comparatively weaker [4]. Australia, the driest continent in the world, is primarily characterized by savanna and desert climates [24]. Its vegetation is highly sensitive to fluctuations in temperature and precipitation. Vegetation communities sensitive to ENSO are mainly found in the savannas of northern and eastern Australia. Tropical desert climate zones cover approximately 70% of the Australian landmass and are dominated by monocultural vegetation with weak resistance to climate change variability, making them particularly susceptible to ENSO impacts [25]. When El Niño and La Niña events are of equal intensity, vegetation is generally more affected by La Niña [16]. Vegetation changes are typically negatively correlated with the ENSO index, with growth increasing during La Niña and declining during El Niño. For instance, in 2011, an intense La Niña event brought heavy precipitation, leading to rapid vegetation growth in Australian arid and semiarid regions [26]. In contrast, drought events in Australia are strongly linked to El Niño, with long-term soil moisture and vegetation observations indicating that eastern Australia is more sensitive to El Niño than other regions [27].

2.1.4. North America

In North America, climate is primarily influenced by ENSO through two key mechanisms. First, during ENSO events, anomalies in atmospheric circulation driven by changes in Pacific SST directly affect regional climate conditions. Second, ENSO indirectly shapes Atlantic climate patterns, such as the Atlantic Meridional Mode and the Pacific South Atlantic Mode, further influencing the North American climate [4].

Vegetation dynamics across many regions of North America are significantly influenced by ENSO. For instance, the 2002/2003 El Niño event altered precipitation and temperatures patterns in ways that were favorable for vegetation growth, except in the western United States [28,29]. ENSO neutrality, the absence of ENSO events, provides the optimal conditions for vegetation growth in the southeastern United States. Elevated SSTs associated with El Niño in the eastern Pacific Ocean contribute to summer droughts in this region and increase the likelihood of extreme weather events in both winter and summer, negatively impacting vegetation growth. Agricultural and forest vegetation are particularly affected by ENSO [30]. Mennis [31] applied the sliding average and baseline methods to analyze the interactions between vegetation cover and ENSO across agricultural lands, deciduous forests, and evergreen forests in the southeastern United States. The results indicated a weak but persistent negative correlation between El Niño and vegetation growth, though this relationship varied across different regions.

2.1.5. The Amazon Region of South America

In South America, ENSO is the primary driver of interannual variability in temperature, rainfall, and cloud cover [32]. During El Niño events, tropical regions of South America fall within the subsiding branch of the Walker Circulation and are affected by variations in the tropical Atlantic zonal mode, leading to reduced precipitation. In contrast, extratropical regions experience increased rainfall due to the influence of the Pacific–South America mode. During La Niña, a southward shift of the Intertropical Convergence Zone results in enhanced precipitation in the tropical areas, while extratropical regions are more prone to drought conditions [4,33]. Thus, in the northern part of the continent, vegetation in different regions exhibits opposing responses to the same ENSO event. During El Niño, vegetation tends to decline north of the equator while increasing south of it. Conversely, during La Niña, this pattern reverses because of ENSO-driven changes in precipitation.

The Amazon rainforest, spanning over 6 million square kilometers, extends across northern South America, encompassing parts of Brazil, Peru, Colombia, Ecuador, and other countries [34]. It covers more than 60% of Brazil's land area and is widely regarded as a critical component of the Earth's ecosystem [35]. Lagged impact analysis indicated that vegetation responses were generally stronger and more prolonged during El Niño than La Niña. Under extended El Niño conditions, vegetation in the Amazon region may undergo significant changes. While the region is typically wet and resilient to short-term droughts, prolonged dry periods can lead to vegetation decline. Studies have indicated that between 2000 and 2012, the Amazon experienced significant vegetation changes, with the most severe degradation occurring during El Niño events [36]. Both average temperature and the evapotranspiration index (a key indicter of drought intensity) showed a positive correlation with the El Niño index, highlighting the event's negative impact on vegetation growth. As a result, El Niño has a significant negative impact on vegetation growth. Notably, substantial vegetation degradation was observed in the Amazon during the 2015 El Niño event [34]. In the Andean watershed basins, vegetation growth is strongly correlated with ENSO, with notable increases observed during El Niño events [37]. ENSO is linked to drought events in northeastern Brazil, where El Niño is closely associated with vegetation decline. However, because of the influence of other climate factors, not all El Niño events lead to negative vegetation NDVI anomalies [33,38]. Within the region, the Caatinga, a dry forest ecosystem, is highly sensitive to climatic variations and exhibits a stronger response to ENSO than other vegetation communities [39]. Additionally, greater attention should be given to seasonal droughts in northern South America, where vegetation is particularly vulnerable to ENSO fluctuations [40]. Periodic El Niño-driven precipitation can also have beneficial

ecological effects on arid zones along the Pacific coast, including the Andes Mountains and Peru, by promoting seed germination, plant growth, and seed bank development [41].

2.1.6. Africa

Africa, situated between the Atlantic and Indian Oceans, experiences a climate influenced by both oceanic systems. Disentangling the effects of the El Niño–Southern Oscillation (ENSO) from other climatic drivers, such as the Indian Ocean Dipole (IOD), remains a challenge [4]. ENSO significantly influences the climate of Eastern and Southern Africa, contributing to extreme dry and heat events across the continent [42]. Because Africa is far away from the core area of ENSO, vegetation in Southern and Eastern Africa responds to ENSO with a noticeable lag [43–45]. An analysis of vegetation and ENSO in Southern Africa during the austral summer (1982 to 2015) revealed a vegetation response lag of approximately one to three months, with a predominantly negative correlation between NDVI anomalies and the ENSO index across most of the region [44]. The 1997/98 El Niño event resulted in significant vegetation changes in Southern Africa, with negative NDVI anomalies in the western half and positive NDVI anomalies in the eastern half. These patterns were driven by the combined effects of warming SST anomalies in the coastal Indian Ocean and the lagged impact of EI Niño [43]. Shikwambana et al. [46] examined the impact of two strong ENSO events (2010/11 La Niña, 2015/16 El Niño) on vegetation and climate in Southern Africa. Their findings indicated that vegetation was more strongly affected by precipitation changes, particularly during La Niña, while temperature played a comparatively weaker role. ENSO is significantly correlated with vegetation conditions in both Southern and Eastern Africa. For instance, during La Niña events, African crop yields exhibit notable regional differences, with increased yields in Southern Africa and decreased yields in Eastern Africa [45].

2.1.7. Global Vegetation

For global vegetation, ENSO exerts a stronger and more direct influence in low-latitude regions, where its impacts on precipitation and temperature are most pronounced. In contrast, its effects in mid- and high-latitude regions tend to be weaker and more variable, as they are often modulated by additional climatic and environmental factors [47]. The vegetation response to ENSO from a hemispheric perspective has been investigated, revealing contrasting patterns in semiarid regions of the Northern and Southern hemispheres. The findings indicate that vegetation in these regions exhibits opposite responses to ENSO, largely because of differences in ENSO-driven precipitation anomalies between the two hemispheres. In the Southern Hemisphere, vegetation in semiarid regions responds rapidly to ENSO events, showing a consistent negative correlation with El Niño and noticeable greening during La Niña events [48]. El Niño typically increases precipitation in semiarid regions of the Northern Hemisphere, such as the southwestern United States and parts of Central Asia, while reducing rainfall in semiarid areas of the Southern Hemisphere, including northern and eastern Australia, southern Africa, and eastern South America. In contrast, La Niña generally produces the opposite pattern [6]. Overall, vegetation in the Southern Hemisphere responds more strongly and more rapidly to ENSO [16,48].

This section investigates the impacts of El Niño and La Niña on global vegetation trends. Figure 2 illustrates the relationship between vegetation NDVI anomalies and the Niño 3.4 index, which represents ENSO intensity, based on existing studies. To ensure data reliability, only data from the 1982–2010 period were included. An examination of the scatter plots along the X-axis revealed that El Niño events as a group tend to be stronger than La Niña events, which was consistent with previous research [49]. The fitted line represents the NDVI anomaly in response to varying intensities of ENSO across different

regions. The red fitted line indicates a negative correlation between global vegetation and El Niño events. Moreover, when the Niño 3.4 index exceeded approximately 0.82, stronger El Niño events led to more severe declines in vegetation growth. In contrast, the influence of La Niña on global vegetation was relatively weak and did not reach statistical significance. Additionally, there were notable changes in the NDVI anomaly and the Niño 3.4 index over the time series.

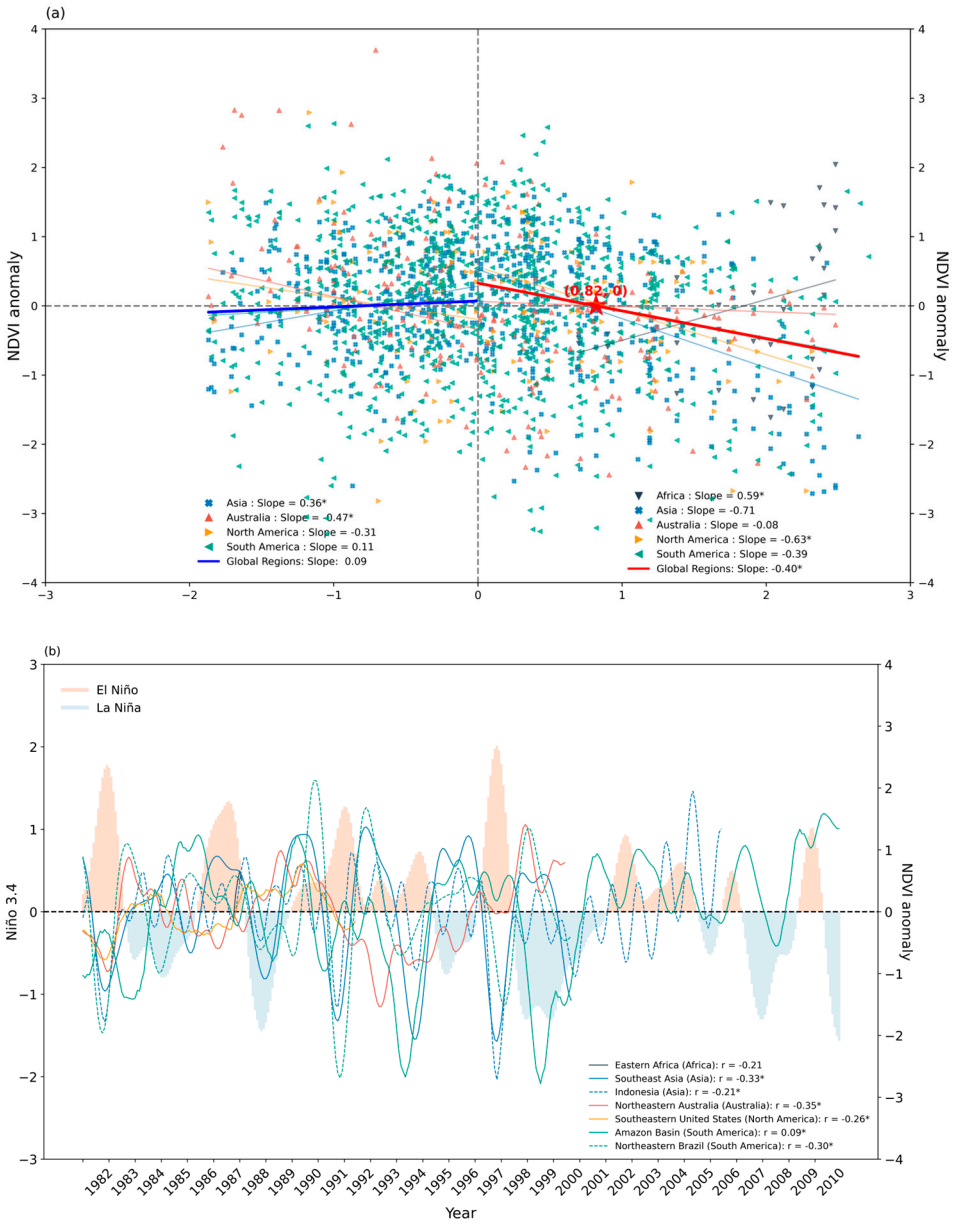


Figure 2. (**a**) Normalized NDVI anomalies plotted against the Niño 3.4 index. The bold red and blue lines represent the fitted trends of vegetation change under El Niño and La Niña, respectively. The red star marks the x-intercept of the fitted line during El Niño, indicating the Nino3.4 index at which the global vegetation decline trend starts. Slope statistics for each region are provided, with values marked with an asterisk indicating statistical significance at the 90% confidence level. (**b**) Intermonth variability of normalized NDVI anomalies across seven regions from 1982 to 2010. The red and blue shading indicates the different phases of ENSO. Correlation coefficients between the Niño 3.4 index and normalized NDVI anomalies for each region are displayed in the legend.

2.2. CP ENSO and EP ENSO

Based on the spatial pattern of SST anomalies, ENSO can be broadly classified into Eastern Pacific (EP) ENSO and Central Pacific (CP) ENSO. Since 1999/2000, ENSO events have undergone notable changes, including increased frequency, a relative decline in the occurrence of strong events, and reduced predictability [50]. These shifts are closely associated with a transition from the dominance of EP ENSO to a greater prevalence of CP ENSO [51]. In the context of global warming, the observational data indicate a shift toward the central equatorial Pacific, favoring the development of CP ENSO events [52]. EP ENSO often leads to extreme precipitation events and significant increases in global temperatures. In contrast, CP ENSO has a more moderate influence on global precipitation and induces a broader but relatively weaker effect on global temperatures [53,54]. In terms of temperature, EP and CP types of El Niño events exhibit significant differences in their effects on eastern North America, northern Eurasia, and northern Africa. With respect to precipitation, notable contrasts have been observed in eastern Australia, southern Africa, southern South America, and India [55].

The climate of the Western Pacific region exhibits distinct temperature and precipitation patterns under the two types of ENSO, which in turn leads to different directions of vegetation change. In this region, vegetation anomalies in response to CP ENSO tend to be greater than those associated with EP ENSO under similar conditions, and vegetation is more sensitive to La Niña than El Niño [17]. Focusing on Australia, vegetation changes are more strongly influenced by La Niña, particularly in semiarid ecosystems in the eastern and northern regions. LAI anomalies exhibit an inverse variation between the two types of La Niña events. CP La Niña has a stronger influence, bringing increased precipitation and lower temperatures, which promote vegetation growth across about 92% of the region. In contrast, EP La Niña suppresses vegetation growth in about 80% of the region. During El Niño, changes in Australian LAI anomalies are more pronounced for EP El Niño than for CP El Niño. EP El Niño may result in either an increase or a decrease in vegetation, whereas CP El Niño consistently leads to vegetation decline. EP El Niño is associated with increased precipitation in southern China, while CP El Niño is linked to reduced precipitation [56]. As a result, CP El Niño generally causes negative vegetation changes, whereas EP El Niño can lead to either positive or negative vegetation changes. Comparing ENSO-induced vegetation changes in China and Australia, the magnitude of vegetation response is positively correlated with ENSO intensity. El Niño has a stronger impact on vegetation in China than in Australia, whereas La Niña, particularly CP La Niña, exerts a greater influence on Australian vegetation than on China [16].

Table 1 summarizes Sections 2.1 and 2.2, outlining the various mechanisms through which ENSO impacts vegetation. It highlights the distinct effects across different regions, illustrating how variations in temperature and precipitation conditions are linked to ENSO influence on vegetation.

Table 1. Impacts of ENSO (El Niño and La Niña) on vegetation across different regions.

Region	ENSO	ENSO	
		El Niño	La Niña
Eurasia	The asymmetric response of atmospheric circulation to ENSO leads to asymmetric inverse phase changes in vegetation cover [13,57]	NDVI anomalies exhibit a negative–positive–negative pattern, reflecting the spatial variation in El Niño's impacts Spring vegetation changes in the East Russian region are closely related to ENSO, with EP types inhibiting vegetation growth Significant negative NDVI anomalies occur in summer vegetation across Northeast Asia	Summer vegetation NDVI anomalies in Northeast Asia increased only slightly
China	ENSO disrupts the Asian monsoon, altering temperature and precipitation patterns, which in turn affect vegetation The distribution of ENSO sensitive vegetation in China exhibits notable regional variations [5,15]	Vegetation in the southern region (e.g., mixed forests) responds negatively to reduced precipitation Compared with EP El Niño, CP El Niño exerts a more pronounced inhibitory effect on vegetation	Positive response in central cultivated land, grassland in northern Inner Mongolia, and the northern basin of the Tibetan plateau
Central South Peninsula	ENSO influences the South Asian monsoon, and a strong correlation exits between vegetation and ENSO [58]	Inhibition of vegetation growth due to reduced precipitation	Favorable vegetation growth with increased cloudiness and precipitation
Maritime Continent	Situated at the core of the Walker Circulation, the region's climate is strongly influenced by ENSO. Extreme rainfall events, closely related to ENSO, have a significant impact on local vegetation [21,22]	Significant decline in vegetation due to large-scale drought events, such as in 1982/1983 and 1997/1998	Increased vegetation cover
Australia	The climate is influenced by various alterations in convective activity associated with ENSO La Niña events exert a more pronounced impact on vegetation, particularly in the northern and eastern regions Under comparable conditions, CP ENSO has a greater effect than EP ENSO	EP El Niño can either increase or decrease vegetation, while CP El Niño generally leads to vegetation decline	Compared with EP La Niña events, CP La Niña events significantly enhance vegetation growth
North America	ENSO negatively impacts on vegetation [28–31]	Promotes vegetation growth across most of North America, except in the eastern United States	Suppress vegetation growth
Amazon region	The combined influence of ENSO-driven modifications to the Walker Circulation and variations in the tropical Atlantic climate pattern plays a critical role in shaping regional climate dynamics ENSO alters precipitation patterns, with El Niño impacts greater than La Niña impacts [33,36,40,41]	Vegetation decreases in tropical regions but increases in extratropical zones Forest degradation in the Amazon region	Increased vegetation north of the equator and decreased vegetation south of the equator

Table 1. *Cont.*

Region	ENSO	ENSO	
		El Niño	**La Niña**
Africa	Eastern and Southern vegetation is significantly influenced by precipitation pattern changes induced by ENSO, with a lagged response [43,45,46,59]	Enhanced vegetation cover in Eastern Africa (e.g., Ethiopian region) Decline in vegetation cover in Southern Africa	Crop yields increase in Southern Africa and decrease in Eastern Africa

2.3. ENSO Interactions with Other Climate Modes

In some regions, such as Africa and North America, the impacts of ENSO on vegetation often interact with other climate variability, altering both the intensity and direction of its effects [60,61].

The IOD plays a significant role in the Indian Ocean and is defined by the difference in SST between two regions, exhibiting a quasi-periodicity of 3 to 5 years. A positive IOD occurs when the SSTs in the western Indian Ocean are warmer than those in the eastern Indian Ocean, whereas a negative IOD occurs when the eastern Indian Ocean is warmer than the western Indian Ocean. The IOD influences the climate of coastal regions around the Indian Ocean and serves as a primary driver of precipitation in these areas [62]. ENSO and IOD often interact synergistically to influence precipitation patterns [63,64]. In the Northern Hemisphere, El Niño (La Niña) events have historically coincided with positive (negative) IOD events, however, this relationship weakened following the emergence of CP ENSOs [65]. In India, both ENSO and IOD contribute to vegetation changes. A study on vegetation in the Bhima Basin, central India, found that El Niño adversely affected vegetation, whereas La Niña had no significant impact. When considering the effects of IOD alone, positive and negative IOD events regulate precipitation in the Bhima basin, thereby influencing regional vegetation. During autumn and winter, vegetation cover is greater during negative IOD events than during positive IOD events, which tend to have a suppressive effect on vegetation growth [63]. In Africa, during the 1997/98 period, a positive IOD coincided with El Niño. In southeastern Africa, the positive IOD had a stronger impact than El Niño, shifting El Niño's usual suppressive effect on vegetation photosynthesis into an enhancing one [66].

NAO is the dominant atmospheric pattern in the North Atlantic region, characterized by the persistent north–south fluctuations in the sea level pressure field. It is primarily associated with the interannual variability of the Icelandic low-pressure system at high-latitudes and the Azores high-pressure system at mid-latitudes. ENSO and NAO do not typically occur in isolation, and the ENSO signal can be detected in North Atlantic atmospheric circulation. With the projected increase in the variability of ENSO events in the future, the relationship between ENSO and NAO is becoming more complex and uncertain [67]. The Eurasian steppe (EAS) is a vast vegetation belt spanning the northern regions of the Asian and European continents, influenced by both ENSO and NAO. In the southern grasslands of the EAS, vegetation growth in desert climates responds most strongly to ENSO events during the spring and summer. In contrast, vegetation changes in the northern grasslands are more sensitive to NAO events, particularly in spring. The combined effects of El Niño and positive NAO events lead to warming and significant grassland expansion. Conversely, La Niña or negative NAO events contribute to cooling and reduced precipitation, intensifying grassland degradation [68].The AO also plays a crucial role in shaping temperature patterns across the Northern Hemisphere [69]. Changes in Northern Hemisphere vegetation, particularly in regions such as in North America and

East Asia, are significantly correlated with temperature variations driven by ENSO and the AO. However, the underlying mechanisms remain poorly understood.

3. Discussion

3.1. Current State of Research

3.1.1. Limitations of Existing Studies

Current research on ENSO and vegetation changes remains limited, primarily focusing on the analyzing vegetation indices in response to El Niño and La Niña events. While such studies provide insights into ENSO's impact on vegetation, they offer only a limited understanding of the specific mechanisms driving these effects. Additionally, most research has focused on the past 10 to 20 years, largely constrained by the availability of remote sensing vegetation data. Vegetation trend monitoring primarily relies on two types of datasets: NDVI and LAI, both provide valuable insights into vegetation dynamics and changes. However, these datasets have limitations, such as the inability to distinguish specific vegetation types affected by ENSO events.

The geographic distribution of studied regions is uneven (see Figure 1), and global terrestrial research lacks comprehensive coverage. Although existing studies indicate that ENSO affects vegetation in regions such as southern North America and Alaska [70], detailed investigations across these and other areas are still scarce. Furthermore, the current literature predominantly concentrates on coastal regions, resulting in a fragmented and regionally biased understanding of ENSO's influence on global vegetation dynamics.

3.1.2. Uncertainty in the Impact of ENSO on Vegetation

Several studies have examined the delayed response of vegetation to ENSO, which is reflected in two key aspects: first, the delayed impact of ENSO on local climate, as observed in regions like Eastern Africa [71]; second, the lagged response of vegetation to ENSO-induced climate variations, such as in the Amazon rainforest [41]. In the absence of ENSO events, vegetation changes are influenced by other factors such as climate fluctuations and human activities, which increase the uncertainty in isolating ENSO's specific impact on vegetation dynamics. These factors pose significant challenges to accurately assessing the effects of ENSO on vegetation.

3.1.3. Impacts of ENSO Diversity on Vegetation

Recent research on ENSO has indicated that the intensity of ENSO events, particularly extreme ones, has been increasing. Projections suggest that extreme El Niño and La Niña events will occur more frequently, with their recurrence rates rising from approximately once every 20 and 23 years to once every 10 and 13 years, respectively. In terms of ENSO types, observational data have shown a shift in the warming center toward the central equatorial Pacific, corresponding with an increased frequency of CP ENSO events. In contrast, model simulations tend to place the intensity center in the eastern equatorial Pacific, exhibiting features characteristic of EP ENSO. These discrepancies between observations and model simulations are largely attributed to differences in background climate states [52,72,73]. Although CP ENSO and traditional EP ENSO exhibit distinct impacts on vegetation [55], research differentiating between the two remains limited. Most existing studies do not explicitly distinguish the effects of CP and EP ENSO events, despite evidence of their differing influences on global vegetation dynamics. This distinction warrants greater attention, particularly in light of the shift in the ENSO regime observed since approximately 1999/2000 [50].

Additionally, ENSO interacts with other climate variability factors, influencing vegetation in regions beyond its core areas. However, studies in these regions are scarce, primarily

focusing on the effects of ENSO and other climatic factors on vegetation change rather than investigating the specific mechanisms driving these impacts.

3.2. Future Research Focus

3.2.1. Numerical Models Used to Investigate ENSO's Influence on Vegetation Under Global Warming

Against the backdrop of rising greenhouse gas concentrations and global warming, the influence of ENSO on the global climate is expected to undergo significant changes. Elevated temperatures increase atmospheric water vapor content, which may amplify ENSO-related global precipitation anomalies even if the intrinsic characteristics of ENSO remain unchanged. Additionally, anthropogenic warming is projected to affect the internal variability of ENSO, potentially increasing the amplitude of ENSO-related sea surface temperature anomalies. As a result, the atmospheric teleconnection patterns associated with ENSO are likely to intensify [74,75]. Among the climate models from Phase 5 of the Coupled Model Intercomparison Project (CMIP5) that can distinguish between EP ENSO and CP ENSO types, simulation results have indicated a widespread increase in SST variability associated with EP ENSO under global warming [76]. Under a low-greenhouse-gas-concentration scenario, CMIP5 simulations also project an increase in the frequency of extreme ENSO events, following a linear trend with rising global mean temperatures [77]. These extreme events are closely associated with droughts and floods in tropical regions, leading to significant impacts on vegetation. Further projections from CMIP6 models, under various future greenhouse gas emission scenarios, suggest that the spatial distribution of vegetation affected by ENSO will shift. Notably, under a medium-emission scenario, a larger area of vegetation is influenced by ENSO than under a high-emission scenario [16,50,71,75,77]. These findings underscore the urgent need for a deeper understanding of ENSO's ecological impacts in the context of ongoing climate change.

Climate models can be used to study the impact of ENSO on vegetation. Le [70] applied Earth system models to simulate future ENSO impacts on vegetation under a warming scenario and conducted a comparative analysis using historical data. Many studies have also used models to investigate the independent effects of different climate drivers on vegetation [11,78]. However, current models struggle to accurately simulate ENSO-induced vegetation changes, and model parameters need to be optimized in future research.

3.2.2. Impacts of Multiyear La Niña Events on Vegetation

Multiyear La Niña refers to La Niña events that persist for two to three years, a phenomenon that has become increasingly prominent since the 1970s. Between 1970 and 2020, 8 out of 11 recorded La Niña events were classified as multiyear [79]. The abnormal climatic conditions associated with La Niña pose significant threats to vegetation growth, with particularly severe impacts in arid and semiarid regions. During La Niña phases, precipitation typically decreases in extratropical areas of North and South America, as well as in eastern Africa. While short-term droughts may have limited effects on vegetation in humid regions, prolonged La Niña events can lead to substantial degradation of plant communities, even in ecosystems that are generally more resilient. Therefore, it is essential to investigate the ecological consequences of multiyear La Niña events on vegetation dynamics.

3.2.3. The Influence of ENSO on Other Aspects of Vegetation

In addition to influencing long-term vegetation change trends, ENSO has been shown to significantly affect vegetation phenology, plant encroachment, and biological succession. However, research in these specific areas remains limited. To advance understanding of

ENSO's complex effects on plant ecosystems, future studies should place greater emphasis on these underexplored dimensions.

In the western United States, both phases of ENSO exert notable impacts on vegetation phenology. During El Niño years, the southwestern United States typically experiences abnormally wet conditions [80], resulting in an earlier onset of the growing season than during La Niña years, while the end of the season remains relatively unchanged. As a result, the overall growing season tends to be extended in most regions during El Niño years [81].

ENSO-induced warm events in North America have played a key role in facilitating the spread of the invasive plant *Purple loosestrife*. Observational data have indicated that, compared with the baseline year of 1997, the 1998 El Niño event resulted in significantly earlier flowering phenology and increased biomass accumulation during the early growing season, creating favorable conditions for the species's successful invasion [82].

ENSO events exert a profound influence on the secondary succession of dry forests, often steering successional trajectories toward more drought-tolerant plant lineages. During the intense 2005 El Niño, severe drought conditions resulted in extensive plant mortality and species loss in Mexico's dry forests, with impacts persisting into the subsequent rainy season. While the initial drought caused widespread die-off due to acute water scarcity, the following rains triggered a surge in plant recruitment. However, this rapid influx of new growth intensified competition for limited resources, leading to a second wave of mortality. A similar pattern was observed during the 2015/2016 El Niño event, where drought conditions caused a sharp decline in biomass, which began to recover only in the following year. If El Niño events become more frequent, large-scale vegetation mortality could destabilize ecosystem functioning, potentially shifting dry forests from carbon sinks to carbon sources. In this context, leguminous species play a pivotal role in post-disturbance recovery by enriching soil nitrogen and facilitating the establishment of other plant species. Therefore, ENSO-related disturbances affecting these key functional groups may severely hinder natural regeneration processes and threaten the long-term resilience of dry forest ecosystems [83].

4. Conclusions

ENSO can influence global climate through atmospheric teleconnections, which in turn affect vegetation growth. This paper reviews the impacts of ENSO on vegetation changes. Vegetation in the Western Pacific region, particularly in Southeast Asia and Australia, shows a strong response to ENSO. In China, diverse vegetation types result in distinct regional responses. Overall, El Niño events tend to have negative effects on vegetation, while La Niña events generally promote vegetation growth. EP and CP ENSO have varying effects on vegetation in Australia, with studies highlighting contrasting impacts between the two types. In the Eastern Pacific region, ENSO-driven changes in global precipitation patterns strongly influence vegetation in South America. In Africa, ENSO-induced shifts in precipitation lead to vegetation changes. Additionally, ENSO interacts with other climate variability factors, affecting vegetation in noncore regions, for example, with NAO in Eurasia, IOD in India, and AO across the Northern Hemisphere.

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