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To cite this article: Shenshen Gao *et al* 2023 *Environ. Res. Lett.* **18** 104014

ENVIRONMENTAL RESEARCH
LETTERS

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RECEIVED
10 May 2023

REVISED
7 September 2023

ACCEPTED FOR PUBLICATION
12 September 2023

PUBLISHED
25 September 2023

LETTER

Community forestry dominates the recent land greening amid climate change in Nepal

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Keywords: land greening, leaf area index, community forest, soil moisture, climate change, Nepal

Supplementary material for this article is available online

Abstract

The Himalaya Plateau including Nepal is 'greening up' that has important implications to ecosystem services such as water supply, carbon sequestration, and local livelihoods. Understanding the combined causes behind greening is critical for effective policy makings in forest management and climate change adaptation towards achieving sustainable development goals. This national scale study comprehensively examined the natural and anthropogenic drivers of the long-term trend of vegetation dynamics across Nepal by correlation analysis and multiple linear regression analysis. We integrated multiple sources of data including global satellite-based leaf area index (LAI), climate data, landcover data, and forest land management information. Our study reveals a remarkable annual mean LAI increase of 22% (0.009 m^2 m^{-2} yr^{-1}) ($p < 0.05$) from 1982 to 2020, with an acceleration in the rate of increase to 0.016 m^2 m^{-2} yr^{-1} ($p < 0.05$) after 2004. The community forestry (CF) program, forest area changes, and soil moisture availability accounted for 40%, 12%, and 10% of LAI temporal variability, respectively. Our analysis found soil moisture and forest area changes to be the primary drivers of the greening trend before 2004, while CF and forest expansion were the dominant factors thereafter. Additionally, interannual vegetation dynamics were significantly influenced by winter precipitation, incoming solar radiation, and pre-monsoon soil moisture. The projections based on four Earth System Models from Coupled Model Intercomparison Project Phase 6 suggest that Nepal's greening trend is expected to continue at a rate of 0.009 m^2 m^{-2} yr^{-1} ($p < 0.05$) throughout the 21st century. We conclude that forest management program (CF) amid climate change that alters water and energy conditions have enhanced land greening, posing both opportunities and risks to ecosystem services in Nepal. This study provides much needed national-level information for developing forest management policies and designing Nature-based Solutions to respond to climate change and increasing demands for ecosystem services in Nepal.

1. Introduction

Vegetation dynamics are important to understand ecosystem processes such as land evapotranspiration (ET), water yield, primary productivity, energy balances that characterizes land-atmospheric interactions [1–5] and assess ecosystem services (e.g. water supply, flood control, carbon sequestration,

biodiversity conservation) that are critical to achieving national sustainable development goals. Vegetation dynamics reflect the long term cumulative and combined effects of natural and anthropogenic forces on the ecosystems, thus can serve as indictors of climate change and environmental change.

In the past decades, satellite observations have indicated global greening in many parts of the Earth, such as in Europe, Sahel, North America [6, 7], sub-Saharan Africa [8], China and India [7, 9] and northern Alaska and Canada [10] and other regions [11–13]. With providing the direct information of vegetation canopy structure and density, leaf area index (LAI) is a frequently used and highly relevant indicator to assess vegetation dynamics. For example, LAI showed a significant global greening trend of 0.068 m^2 m^{-2} yr^{-1} from 1982 to 2009 [6], while the normalized difference vegetation index (NDVI) showed consistent greening trend of 0.0005 yr^{-1} from 1982 to 2013 [12]. Some regions also showed browning hotspots to a different extent, such as the northwest and central United States [6], mid-low latitudes of the Northern Hemisphere [13], midwestern and eastern Africa [7, 14], and Central Asia [15]. This suggests significant spatiotemporal variations in global vegetation change pattern, highlighting the need to assess local greening (browning) stages and drivers.

Understanding the causes of land greening is critical to identifying areas that are sensitive to climate change and human-environment interactions, with the aim of providing information for land management decisions that promote environmental sustainability. Previous studies have examined global drivers of vegetation change, including anthropogenic, climatic, and biogeochemical factors [10]. For example, anthropogenic factors have dominated vegetation greenness in the northern temperate region since the 1980s. Remarkably, two prominent areas of increased vegetation, China and India, have been strongly influenced by reforestation programs and agricultural intensification, respectively [9]. However, warmer temperatures on the Qinghai-Tibet Plateau cause snow melting, increasing soil moisture and vegetation growing seasons, resulting in vegetation greening [16]. Soil moisture increase in dry areas is the primary reason for widespread greening in South Asia from 1982 to 2014 [17]. Precipitation can stimulate vegetation growth in water-limited areas and can also hinder vegetation growth by reducing radiation and triggering floods, erosion, and landslides [18–20]. Existing studies on biophysical controls on vegetation dynamics [21–28] rarely quantify the impacts of individual drivers due to spatiotemporal inhomogeneity, nonlinear impacts, and interactions among these factors.

Nepal is located on the southern slope of the Himalayas in South Asia. It has world's highest mountains and the 'Water Tower' for ten large Asian river systems [16] with a number of biodiversity 'hot spots'. Studies in Asia, including Nepal, illustrated an overall greening trend and local greenness amid melting glaciers in high elevation regions [16, 17, 29, 30]. For example, Nepal's national greening with NDVI increased at 0.0018 yr^{-1} from 2000 to 2017 [31].

In recent decades, Nepal has undergone profound changes in land cover and land use, significantly reshaping its vegetation patterns. These changes results from a complex interplay of factors, including agricultural expansion, deforestation, urbanization, overgrazing, and the persistent bushfires threat. Notably, innovative forest management, such as community forestry (CF) programs, has also played a pivotal role in these changes. Furthermore, Nepal having experienced rapid warming [32] and precipitation changes with wetter conditions in the east and drier conditions in the west since 1980 [33]. These changes could have significant on vegetation condition in Nepal, which, however, still remains unclear. Despite its ecological importance, Nepal is often overlooked as a distinct entity, with its unique vegetation characteristics and dynamics insufficiently recognized globally. Nepal is world known for its CF, a forest management program developed in the 1970s aimed at forest conservation and poverty reduction [34]. Managed by the community foresty user groups (CFUGs), CF provides ecological goods and services, socio-economic benefits to communities, and contributes to climate change adaptation and disaster risk reduction as a Nature-based Solution for sustainable development [35–42]. Today, 40% of the national forests are assigned in the CF regime and 50% of the total households are involved [35–38]. However, previous studies focusing on vegetation changes in Asia [16, 17, 29–31] relying on remote sensing observations lacked access to comprehensive ground policy data such as CF to Nepal's land greening. Meanwhile, existing studies [34–42] focusing on Nepal's CF have provided valuable case studies on these anthropogenic impacts, but rarely included national scale assessment. Thus, the drivers of Nepal's vegetation change over the past decades remains imprecise.

This study aims to understand the vegetation trend over the long-term in Nepal, considering its high regional variations as the southern slope of the third pole. This study firstly attempts to integrate remote sensing observational data with ground land management data to quantify both natural and anthropogenic drivers of vegetation change in Nepal. We hypothesized that land greening is influenced by climate, forest management, and land cover change. The study has employed a comprehensive multifaceted approach, utilizing datasets of vegetation LAI, climate variables, soil moisture, land cover, CF data, and agriculture data, to provide a thorough quantitative assessment of vegetation condition and its changes in Nepal. The findings from this study brings the

much-needed focus to Nepal's vegetation conditions and serve as a valuable reference for future studies and sustainable land management policies amidst environmental change and increasing resource demands.

2. Materials and methods

2.1. Study area

Nepal includes three topographical-ecological belts, controlled by interactions of the South Asia summer monsoon system and the Himalayas (figure 1(a)). The northern mountain belt is dominated by snow and barren lands, while the Middle Hilly Belt is the mountainous region with most of the Nepal's forests and the southern Terai Belt is an alluvial plain dominated by croplands (figure 1(b)). Forest (45.2%) and cropland (20.9%) are two dominant land cover types in 2020. Hill districts have the highest LAI in 2020, followed by Terai districts, and snow-covered mountains (figure 1(d)). In addition, Nepal has established 20 protected areas since 1973 at various altitudes with minimal human disturbances and strict restrictions and regulations on hunting, logging and forest harvesting (figure 1(b)).

In 2020, the greatest concentration of CFUGs was in the Middle Hilly Belt (around 82°E–87°E) (figure 1(c)). The number of CFUGs indicates the institutional robustness of CF in terms of size, capacity, and maturity.

2.2. Databases

In this study, LAI was adopted as the primary vegetation index for vegetation detection in Nepal due to its status as a widely used and reliable indicator of vegetation condition. Additionally, LAI allows for consistent comparison with future Coupled Model Intercomparison Project Phase 6 (CMIP6) Biogeochemical model outputs. The study period covered the historical period from 1982 to 2020 (39 years) and the future from 2015 to 2100 (86 years). The LAI datasets are derived from the 3rd generation of Global Inventory Modeling and Mapping Studies (GIMMS) [43], the Moderate Resolution Imaging Spectroradiometer (MODIS) (version 6) [44], and Global LAI Map of Chinese Academy of Sciences (GLOBMAP-CAS) [45] (table 1). GIMMS was chosen as the primary dataset due to its long-term records and consistency with the other two datasets.

Four earth system models (ESMs) were selected from the list of CMIP6 for projecting LAI from 2015 to 2100 (table 1). These chosen models from r1i1p1f1 list needed to include Biogeochemical processes and LAI output. Their historical LAI simulation in Nepal was evaluated using correlation, relative bias, and root mean square error. The top-performing four models were selected. These models were used to project LAI changes in Nepal under the SSP2-4.5 (4.5 W m^{-2} radiative forcing by 2100, middle-of-the-road economy).

Annual land cover data is obtained from European Space Agency with 26 types of land cover (table 1), which is classified into 7 categories in this study. Land cover transfer matrix from 1992 to 2020 can be found in table S2. The CF area and CFUG data were obtained from the Centre Bureau of Statistic of Nepal, Department of Forest and Soil Conservation of Nepal, and meta-analysis results (table S4) [46]. Only data from publications citing government reports were used to ensure data quality.

Five hydroclimate variables were selected from the ERA5-Land dataset developed by the European Centre for Medium-Range Weather Forecasts. The dataset has showed good agreements with in-situ measurements [47]. The five hydroclimatic variables are 2 m air temperature, precipitation, volumetric soil moisture at top 1 m, downward solar radiation and atmospheric water deficit (table 1, figure S2).

2.3. Statistical methods

We used trend analysis (Mann–Kendall test and Sen's slope) [48–50] and the Mann–Whitney–Pettit test for change points detection [51]. Seasonal and interannual variability were studied after detrending. To distinguish anthropogenic and natural drivers, we established baseline LAI trends in national parks for natural impacts, followed by nationwide LAI trend assessment that considered both human and natural influences. This comparison underscores human's impact on vegetation and categorizes drivers. Residual trend analysis was then applied to pinpoint human impacts' locations [52, 53]. LAI maps were simulated using natural factors, and residuals and trends were derived by subtracting observed LAI. The trend of residuals effectively highlighted anthropogenic influence at each grid point.

To quantify individual contributions of key factors on vegetation change, we conducted correlation analysis and multiple linear regression (MLR) analysis at the national level. MLR model fit quality was evaluated using the coefficient of determination (R^2), and the importance of each independent variable in predicting the dependent variable was assessed using standardized coefficients. The percentage of variability explained by each key factor in MLR was calculated using the ratio of regression sum of squares (SSR) to total sum of squares (SST). We confirmed low multicollinearity in MLR (the variance inflation factor, VIF < 5 for all variables). Geodetector was also used to identify driving factors considering LAI spatial heterogeneity (Higher Geodectector q implies larger attribution) [54]. Geodetector was conducted for three years (1993, 1996, and 2016) due to data integrity concerns for each factor (figure 8).

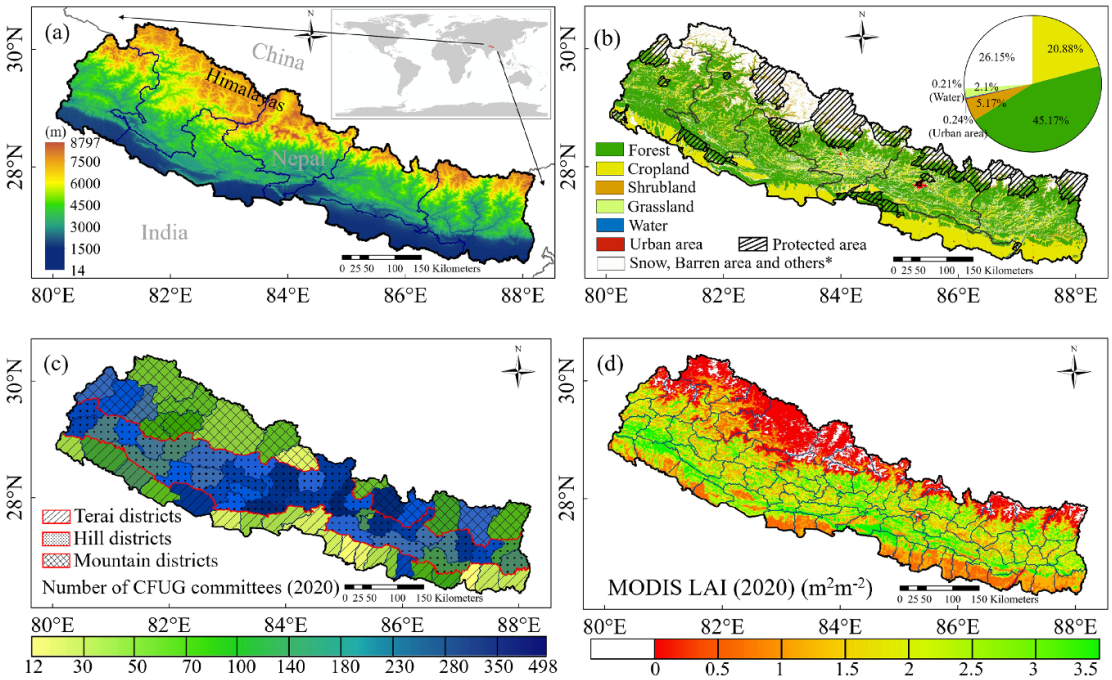

Figure 1. (a) Spatial pattern of the elevation and the location of Nepal; (b) the land use and land cover map of Nepal in 2020 with the proportion of each type (* others includes the mosaic natural vegetation such as tree, shrub, herbaceous cover, and cropland); (c) spatial distribution of the numbers of community forestry user groups (CFUGs) at the district level in 2020 (https://dofsc.gov.np/) (CFUGs are the community forestry local management institutions); (d) spatial pattern of LAI in 2020 Nepal based on Moderate Resolution Imaging Spectroradiometer (MODIS) (version 6) product of LAI dataset. The averaged LAI of three LAI datasets (GIMMS LAI, GLOBMP-CAS LAI and MODIS LAI) during 1982–2016 is in figure S1.

Table 1. A summary of datasets for leaf area index (LAI), landcover, climate at multiple temporal and spatial scales.

Variables	Source	Spatial and temporal resolution	Temporal coverage
LAI	GIMMS[1] GLOBMAP-CAS[2] MODIS[3]	1/12 degree; 15 d 8 km;15 and 8 d[a] 500 m; 8 d	1982–2016 1982–2019 2001–2020
LAI (projected)	CESM2-WACCM[4] MPI-ESM1-2-LR[4] GFDL-ESM4[4] CMCC-ESM2[4]	0.25° × 0.25°; monthly	2015–2100
Landcover	European Space Agency[5]	300 m; 1 year	1992–2020
Crops yield	ICIMOD[6], MoALD[7]	National; 1 year	1980–2013
Community forestry	CBS[8], DOFSC[9] and Meta-analysis results (table S4)	Districts; 1.7 year[b]	1986–2020
Precipitation Temperature (2 m air) Soil moisture (top 1 m) Solar radiation downward Atmospheric water deficit	ERA-Land[10]	0.1° × 0.1°, monthly	1982–2020

[a] 15 d before 2000, and 8 d from 2000.

[b] The CF data is not continuous from 1986 to 2020. We obtained 20 years of data from 1986 to 2020 with the average temporal resolution at 1.7 years. Please find the specific data in table S4.

Data are available at: (1 www.mdpi.com/2072-4292/5/2/927 2 www.resdc.cn/data.aspx?DATAID=336 3 https://modis.gsfc.nasa.gov 4 https://esgf-node.llnl.gov/search/cmip6 5 http://maps.elie.ucl.ac.be/CCI/viewer/ 6 http://rds.icimod.org/Home/Data?any=agriculture%20District%20level&Category=datasets&&themekey=Nepal&&page=1 7 http://nepal.spatialapps.net/agricultureatlas/index.html 8 https://cbs.gov.np/ 9 https://dofsc.gov.np/ 10 https://essd.copernicus.org/articles/13/4349/2021/).

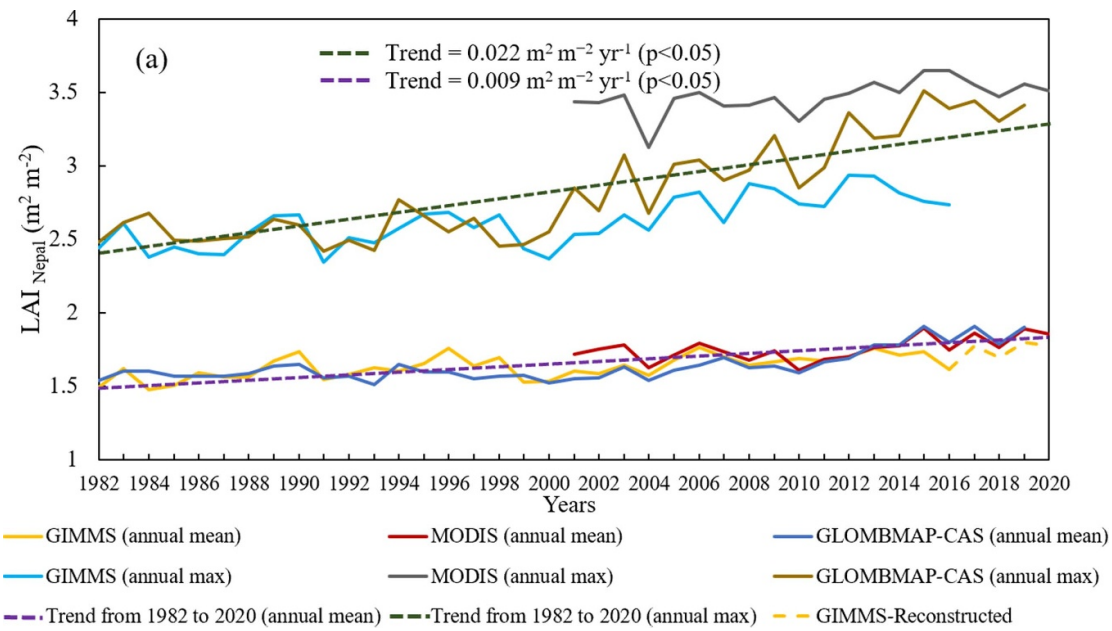

Figure 2. Time series and trends of annual mean and annual maximum leaf area index (LAI) at national scale, based on GIMMS, MODIS, GLOBMAP-CAS datasets.

3. Results

3.1. Historic temporal and spatial dynamics of vegetation

National-scale greening showed upward trend 1982–2020 with all three annual averaged LAI datasets (figure 2(a)). The LAI rate of increase from 1982 to 2020 is 0.009 m^2 m^{-2} yr^{-1} ($p < 0.05$), with an even higher rate for the maximum LAI value at 0.022 m^2 m^{-2} yr^{-1} ($p < 0.05$). The overall trend was separated into two stages by a change point in 2004. The first stage, from 1982 to 2003, showed a gentle increasing slope of 0.008 m^2 m^{-2} yr^{-1} ($p < 0.05$), with LAI increasing by 11.1%. The second stage, from 2004 to 2020, showed a steeper slope of 0.016 m^2 m^{-2} yr^{-1} ($p < 0.05$), with LAI increasing by 17.1% (table S3, figure 2(a)).

3.2. Dynamics of anthropogenic and climatic drivers

CF area has significantly increased ($p < 0.05$) since 1986 (figure 4(a), table S4). Initially, CF growth was limited to a small coverage area (up to 10 000 km^2, 6.8% of the nation), but during the second stage, CF areas increased by more than two-fold (figure 4(a)). Forest and cropland areas both underwent significant changes since 1992 ($p < 0.05$) (figure 5(a)). Forest land initially had a slight increase from 1992 to 1997, followed by a sharp decrease from 1998 to 2001, and a long-term gradual increase until 2020. Cropland experienced a long-term increase, with a short rise from 1998 to 2001, which corresponds to the drop in forest area during that period. The LAI values also reflect these changes, with a decrease during the forest area drop from 1998 to 2001 and an increase during the periods of forest area increase before 1998 and after 2001.

There were increasing trends in 2 m air temperature ($p < 0.05$) and precipitation ($p < 0.05$), and decreasing trends in atmospheric water deficit ($p < 0.05$) and downward solar radiation ($p < 0.05$) in Nepal (figures S5(a)–(c)). At the national scale, there was a slight but not significant increasing trend in soil moisture content ($p = 0.53$).

3.3. Drivers of temporal and spatial pattern of the long-term LAI trend

MLR analyses were performed to determine the possible drivers of the LAI increase. The R^2 of MLR is 83%, indicating that the 8 variables (2 m air temperature, precipitation, soil moisture, atmospheric water deficit, incoming solar radiation, and CF, forest, and cropland areas) can explain 83% of the total LAI variation ($p < 0.05$). Three most important factors in determining the LAI were CF area, forest area, and soil moisture (figure 6). Using the ratio of SSR to SST, it was found that CF area explained 40% of the LAI variability, followed by forest area (12%) and soil moisture (10%). Other variables explained only a small percentage of variability, which was not statistically significant.

Human activities, particularly CF management and forest area changes, are the main contributors to national-scale LAI increases in recent decades in Nepal, followed by change in soil moisture as the only significant hydroclimate factor. The LAI temporal trend in the protected area (figure S3) that could reflect the natural impacts on LAI. It shows that LAI had almost no increasing trend from 1982 to 2020 in protected areas, indicating a limited natural impact

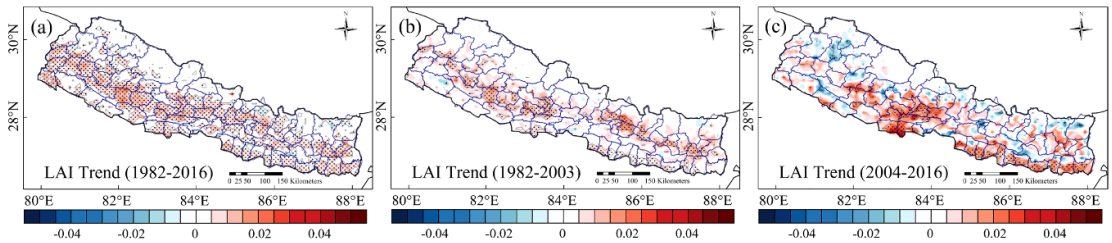

Figure 3. (a) LAI trends during full time series from 1982 to 2016 in Nepal based on GIMMS (unit: $m^2\ m^{-2}\ yr^{-1}$), (b) LAI trends during the first stage from 1982 to 2003, and (c) LAI trends during the second stage from 2004 to 2016.

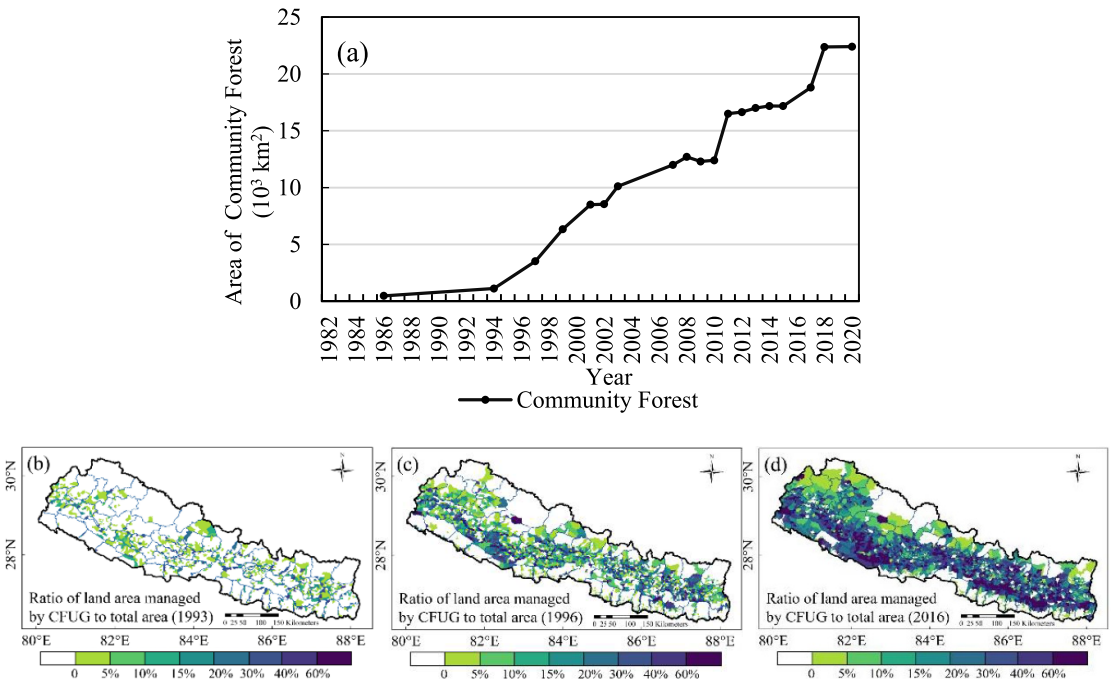

Figure 4. (a) Time series of community forestry managed area in Nepal, (b) spatial pattern of the ratio of community forestry managed land area to total area of each district in 1993, (c) in 1996, and (d) in 2016. The boundary data is from https://gadm.org/ . Data source for (a) is shown in table S4, and for (b)–(d) is from Department of Forests of Nepal and Libois *et al* [42].

on LAI compared to the national-scale increase. This suggests that human activities are critical contributors to LAI increases.

Since 1982, GIMMS LAI indicates a widespread increase with 80.6% of areas showing a positive trend (figure 3(a)). The earlier stage shows an overall widespread spatial pattern of the greening trend, while the latter stage has a much larger and heterogeneous greening trend, mainly concentrated in the southern Terai belt and middle hilly belt around from 82°E to 87°E (figures 3(b) and (c)).

Residual trend analysis (figures 7(a)–(c)) indicates that human activities, such as CF management and forest area change, positively contributed to LAI increases in the middle hilly belt and southeast Terai throughout the study period. Spatial correlations between LAI and hydroclimatic factors at a grid cell level (figure S6) reveal that soil moisture significantly contributed to greening in the northwest Terai region with limited CF or forest area change impacts (figure 7(c)).

The drivers behind the LAI increase in each stage are different. During the first period (1982–2003), the negative role of human activities in land greening is reflected in the residual analysis, primarily due to the decline in forest area during 1998–2001 and the limited impacts of CF management (figure 7(b)). The negative trend is concentrated in the middle hilly area around 84°E (figure 5(e)). However, the increase in soil moisture has a strong positive correlation with LAI (figure 7(e)), contributing to the LAI greening and offsetting the negative impacts of human activities.

During the second period (2004–2020), the residual shows a significant positive trend in the Hilly Belt around from 82°E to 87°E and the southeast Terai (figure 7(c)), which is well matched with the CF area and their committee (figures 1(c) and 4(d).

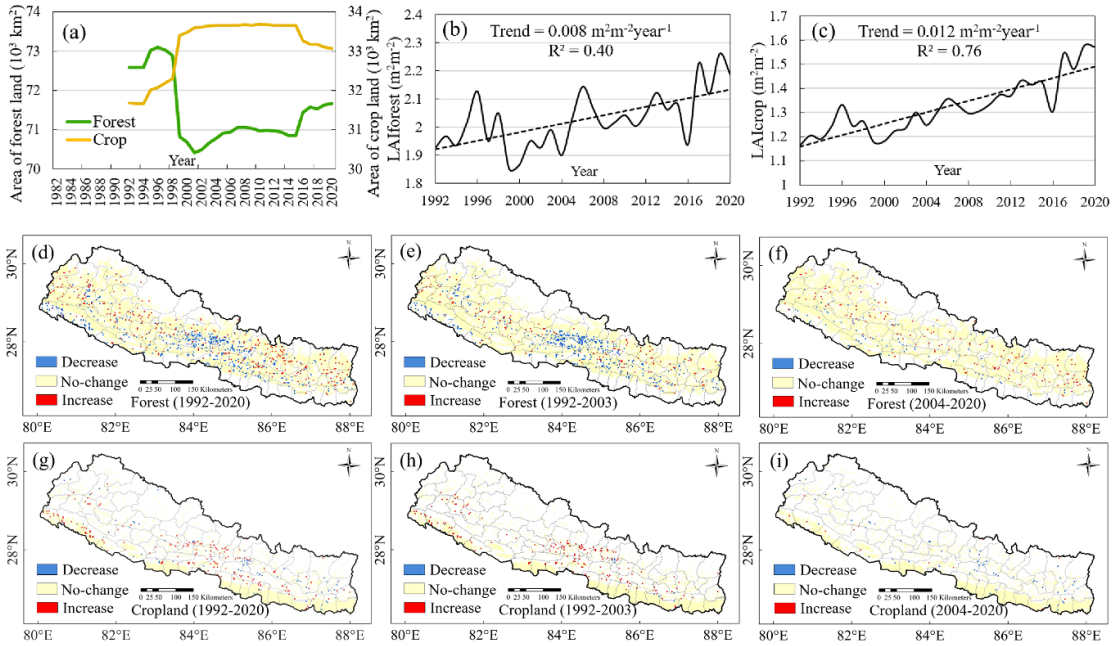

Figure 5. (a) Time series of annual forest area (green) and crop area (orange); (b) and (c) are time series of LAI variations from 1992 to 2020 based on non-change forest and non-change cropland, respectively; (d)–(f) are spatial patterns of forest area changes in 1992–2020, 1992–2003, and 2004–2020, respectively; (g)–(i) are spatial patterns of cropland area changes in the three periods.

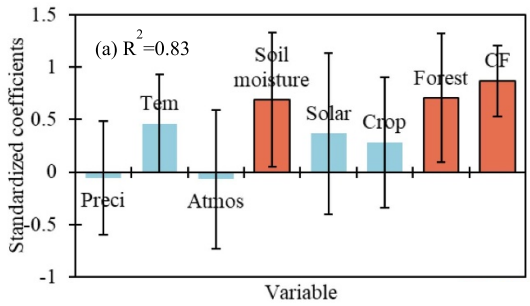

Figure 6. Standardized partial correlation coefficient of MRL between annual averaged LAI and eight considered variables (precipitation, temperature, atmospheric water deficit, soil moisture, solar radiation downward, cropland area, forest area, and community forest area) at national scale; the orange bars mean significant value ($p < 0.05$), while the blue bars mean insignificance in the multiple linear regression.

It indicates CF played a key positive role in promoting Nepal's greening. Moreover, agricultural intensification may have contributed to the LAI greening in the southern Terai, as the cropland area has remained relatively unchanged there (figure 5(i)). The slope of LAI increase in non-change cropland areas was 0.012 m^2 m^{-2} yr^{-1}, much larger than in protected areas, indicating the positive role of agriculture intensification on the local greening. Moreover, the validation of crop yield per unit area as a measure of crop intensification factor was conducted (figure S4). The outcomes indicated ascending trends in the four primary crops predominantly present in Southern Terai, thereby reaffirming the beneficial and localized effects of agricultural intensification on LAI. However, soil moisture's positive correlation with LAI was limited to dry regions like western hilly areas compared to anthropogenic factors (figure 7(f)).

Geodetector showed different drivers for the two LAI stages. For the second period, CF played a more important role in LAI greening than in the first stage (figure 8). It echoes the results that found in residual trend analysis showing the more important role of CF to LAI greening during the second period than it in the first stage. Land cover patterns had considerable q-values in all three years, reflecting the importance of forest area and cropland in LAI spatial distribution (figure 8). Changes in these areas (such as forest reduction in the first stage and recovery in the second stage) were important for LAI changes. Hydroclimatic drivers also had significant q-values, indicating their importance to LAI spatial pattern.

4. Discussion

This study holds significant importance as it examines Nepal's vegetation changes since the 1980s, a task made complex by its challenging mountainous terrain on the southern Himalayan slope and influenced by both human and climatic factors. By pioneering the integration of remote sensing data with on-ground land management information, this study quantifies the drivers of Nepal's vegetation changes. Notably, the research reveals that within Nepal, both human activities and climate change play pivotal roles in shaping vegetation trends and interannual variations. From a human activity perspective, the study underscores the vital contribution of CF programs

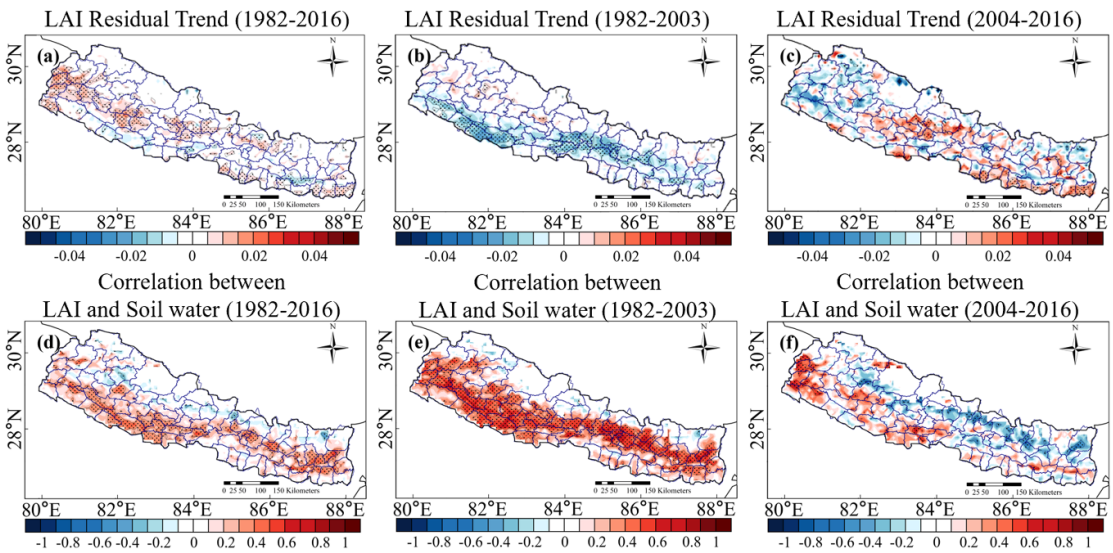

Figure 7. Top panel is the spatial pattern of LAI residual trend during (a) 1982–2016, (b) 1982–2003, and (c) 2004–2016; lower panel is the spatial pattern of correlation coefficient between LAI and soil moisture at 1 m depth during (d) 1982–2016, (e) 1982–2003, and (f) 2004–2016. Dotted area indicates the trend is statistically significant at the 5% level by Mann–Kendall test with p-value (p-MK) < 0.05. Coefficients of other variables can be found in figure S7.

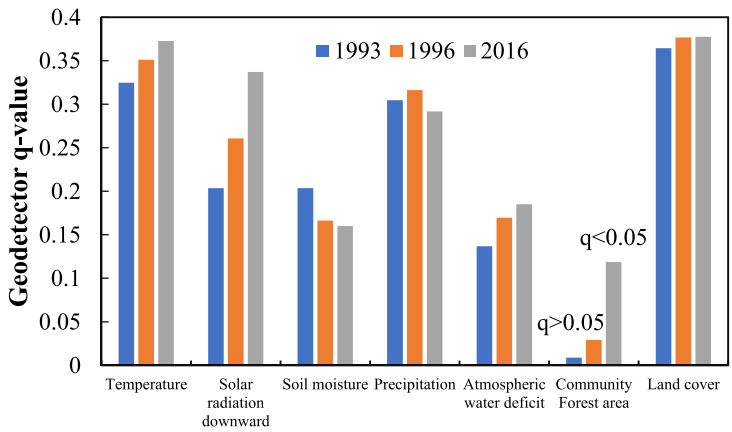

Figure 8. The q-values calculated by geographical detection analysis represent the relative contributions of potential variables to LAI of Nepal in 1993, 1996 and 2016. All values are statistically significant ($p < 0.05$) unless specified. For the hydroclimatic variables, we used 5 year averaged values as 1 year input for geodetector to decrease the risk of climate extreme years of the three selected years: the values in 1993 were based on 1990–1995 average, values in 1996 were based on 1996–2000 average, and values in 2016 were based on 2015–2020. For human factors, we used annual data since human influences are gradual.

in enhancing vegetation conditions, positioning them as promising Nature-based Solutions for sustainable land management, not only within Nepal but also as a model for other regions facing similar challenges.

4.1. Seasonal and interannual vegetation variation and drivers

We also investigated the seasonal and interannual variations of the vegetation and the driving factors (figures S7 and S8). In short, there was no statistical significance between national scale LAI and hydroclimate variables interannually. However, soil moisture in pre-monsoon season (March–May), precipitation and associated incoming solar radiation in winter (December–February) influence LAI.

4.2. Future vegetation dynamics and drivers

We further examined the future LAI trends in Nepal under the SSP2-4.5 scenario using four ESMs CMIP6. The models project a significant LAI increasing trend from 2015 to 2100 (figure S9), with an ensemble mean rate at 0.009 $m^2\ m^{-2}\ yr^{-1}$, similar to the historic rate from 1982 to 2020. For future drivers, the four models considered climate change, land use change and management, and nitrogen cycle (except GFDL-ESM4 for nitrogen cycle). Therefore, future LAI increases are

driven by a combination of these factors. The projected continuous greening trend in Nepal throughout the 21st century could contribute to the global and South Asian greening trend.

4.3. Role of CF and soil moisture in affecting land greening

Satellite observations have indicated 'greening up' in South Asia, and our study show comparable and consistent results with the findings of these studies in Nepal [6, 9, 10]. Compared with the neighbor country India, LAI in Nepal increased by 21% that was much larger than that in India (11.1%) [9] during the same period from 2000 to 2017. We also found that the similar positive roles of human activities on South Asia and Nepal LAI greening. For example, India's vegetation increase has been attributed to agriculture intensification [9] and conservation-centric forest policies that are similar CF policies [55–57]. Our study identified CF and forest cover change (agriculture intensification has local effect over the southern Terai) were the major anthropogenic factors that contributed to the greening up patterns in Nepal.

A recent global study [58] revealed a decline in forest area over the past 60 years (1960–2019), with differing trends in low- and high-income countries. However, Nepal has experienced an increase in forest area since 2001 (figure 5(a)). The national CF policy may play a crucial role in this forest gain by promoting regeneration, preventing illegal activities, and boosting ecotourism [59–64]. Our study highlights the success of CF's conservation efforts on forestry.

For developing countries similar to Nepal with rich forest resources but suffered from significant forest loss, CF can be a natural-based approach for forest conservation and poverty reduction. The success of Nepal's CF in improving vegetation condition relies on strong community participation, a supportive legal framework, technical and financial support, and environmental and economic benefits [55]. Lessons and experience from Nepal can be shared amongst countries to enable them to manage forests sustainably. In Nepal, CF also needs to move forward to the next stage that is beyond the fulfillment of basic needs. For example, CF needs to upgrade the current goals with the emerging challenges such as climate change, soil degradation, deforestation, and biodiversity loss. Governments, civil society, academic institutions, and non-governmental organizations should collaborate with CFUGs to foster innovation and leverage resources to address these challenges.

In addition, ecological restoration projects similar with CF exhibit both advantages and drawbacks for local ecosystems. They often achieve benefits like vegetation restoration [65] and wildlife conservation [66]. However, some projects can strain regional water supplies [67], disturb animal behavior and breeding [68], and increase wildlife mortality [69]. Hence, local implementation of these restorations demands careful consideration.

Compared with other hydroclimatic factors examined, the annual increase in LAI is most related to soil moisture. This highlights Nepal's vegetation growth reliance on soil water, the most direct source compared to other forms like precipitation or atmospheric vapor. Surprisingly, despite Nepal's 'water-rich' image with ample monsoons and glacier melt, irregular precipitation distribution and reduced spring melts from glacier retreat may cause widespread soil moisture stress nationally. Existing research indicates that prolonged droughts are more likely to occur in subtropical regions like Nepal, where high temperatures and low humidity create moisture stress on vegetation [70, 71]. The important role of soil moisture on vegetation trends and variations has been found in various ecosystems under similar climates [10, 17, 72, 73].

4.4. Implications of greening up: opportunities and risks of greening up

'Greening up' on forest lands and croplands can increase ecosystem productivity and carbon sequestration, providing more food, fiber, and fuel for locals while mitigating global warming. Improvement of vegetation can also reduce soil erosion and sedimentation in water bodies [74, 75], benefit water quality for drinking water supply and hydropower plants. Increased vegetation can improve slope stability through enhanced root network and increased soil water removal from soil through ET [76], regulate hydrological cycles by increasing ET and infiltration processes [77, 78], and moderate climate at local to regional scales [24, 79, 80].

Potential risks of greening up on water yield have been debated in Nepal and elsewhere [78, 81]. The increased vegetation cover and ET can lead to a reduction of low flow during dry seasons, which is crucial for irrigation and domestic water uses. Water uses by plants (primarily through ET) are likely to increase when LAI increases [77–79] and especially under a warming future when atmospheric water demand increases [82]. Further increases in ET will have the risk of reduction in water supply and increase in drought hazards. An extended low-flow season due to land greening could exacerbate the shortage of spring water, which could trigger potential conflicts between Nepal and the downstream countries. Forest management options need to be very careful to address these risks. Exotic species (e.g. pines) should be avoided in restoration due to their high water use than native species [83, 84].

Furthermore, forest increase may result in an increase in fuel loads and forest fires risks [85]. With glacier melting and albedo-driven warming, land greening over the Terai zone above the treeline and below the permanent snowline would modulate high-altitude hydrology and increase flash flood risks down

streams [86]. There is an urgent need to uncover the roles of vegetation greening on the high-altitude hydrology in Hindu Kush-Himalayan region including Nepal. Water supply in the local watersheds and the entire river basin across Nepal should be thoroughly assessed under accelerated land greening.

4.5. Assessment uncertainty

First uncertainty is that the LAI datasets have slight variations in specific years. The temporal trend and spatial distribution of the three LAI datasets exhibit coherence. The temporal correlation between GIMMS LAI and MODIS LAI was 0.54 ($p < 0.05$), and GIMMS LAI and GLOMPCAS LAI was 0.61 ($p < 0.05$) in the overlapping years. However, GIMMS LAI dataset is lower after 2001 than others, which may underestimate the LAI value. Secondly, the driving factors have some data availability issues and internal uncertainty, such as the coarse spatiotemporal resolution of the ERA5-Land reanalysis in mountainous regions. Although there are some incomplete anthropogenic datasets used for statistical analysis, the consistency of different LAI products gives confidence in the outcomes of this national scale analysis. It is worth mentioning that current atmospheric CO_2 levels are rising rapidly, which may align more with a high-emissions scenario like SSP 5–8.5 in CMIP6. The study's emphasis on middle-of-the-road economy SSP2-4.5 might not fully account for the potential impacts of climate change on vegetation. This introduces an additional layer of uncertainty when projecting future LAI and its trends.

5. Conclusions

This national scale analysis using multiple data sources showed that Nepal has been greening up rapidly since 1982. Soil moisture was identified as the main greening factor during the initial stage land greening from 1982 to 2003, while the anthropogenic factors (CF and forest increase) contributed to the most to recent greening (2004–2020). Hydroclimate variables are critical for controlling vegetation interannual variability. This greening trend is expected to accelerate under future climate change.

The conclusions highlight the significance of vegetation enhancement in Nepal that provides opportunities for biodiversity conservation, carbon sequestration, improved water resources, and enhanced livelihoods for millions in Nepal. However, it is crucial to recognize the intricate relationship between forests and water, as greening effects can potentially disrupt the water balance. This concern is amplified by rising temperature and LAI, and precipitation variability.

Our study underscores the valuable role of CF programs in elevating vegetation conditions, positioning 'Community Forestry' as a promising 'Nature-based Solution' applicable to similar developing countries. However, challenges persist within the CF framework, including the imperative for mitigating and adapting to emerging climate and ecosystem shifts, addressing soil degradation, and managing forest-water trade-offs. Collaborative efforts among various agencies in the Himalayan region and globally are imperative. Overall, our study provides the much-needed information on vegetation and its underlying drivers, offering a foundation of Nature-based Solutions to respond to climate change and meet the increasing demand for ecosystem services in Nepal.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Acknowledgments

This work was supported by the National Natural Science Foundation of China, International Joint Research Project 'Developing Nature-based Solutions for Nepal Following a Nexus Approach towards Sustaining Forestry, Water Resources and Livelihoods' (Project ID: 42061144004). Partial support was from the Southern Research Station of the USDA Forest Service.

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References

[1] van Zelst V, Dijkstra J T, van Wesenbeeck B K, Eilander D, Morris E P, Winsemius H C and de Vries M B 2021 Cutting the costs of coastal protection by integrating vegetation in flood defences *Nat. Commun.* **12** 1–11
[2] Alkama R, Forzieri G, Duveiller G, Grassi G, Liang S and Cescatti A 2022 Vegetation-based climate mitigation in a warmer and greener World *Nat. Commun.* **13** 1–10
[3] Riis T, Kelly-Quinn M, Aguiar F C, Manolaki P, Bruno D, Bejarano M D and Dufour S 2020 Global overview of ecosystem services provided by riparian vegetation *BioScience* **70** 501–14
[4] Kang Z, Chen J, Yuan D, He S, Li Y, Chang Y and Zhang Q 2020 Promotion function of forest vegetation on the water & carbon coupling cycle in karst critical zone: insights from karst groundwater systems in south China *J. Hydrol.* **590** 125246
[5] Barbosa-Briones E, Cardona-Benavides A, Reyes-Hernández H and Muñoz-Robles C 2019 Ecohydrological function of vegetation patches in semi-arid shrublands of central Mexico *J. Arid Environ.* **168** 36–45
[6] Zhu Z, Piao S, Myneni R B, Huang M, Zeng Z, Canadell J G and Zeng N 2016 Greening of the Earth and its drivers *Nat. Clim. Change* **6** 791–5

[7] Cortés J, Mahecha M D, Reichstein M, Myneni R B, Chen C and Brenning A 2021 Where are global vegetation greening and browning trends significant? *Geophys. Res. Lett.* **48** e2020GL091496
[8] Brandt M, Rasmussen K, Peñuelas J, Tian F, Schurgers G, Verger A and Fensholt R 2017 Human population growth offsets climate-driven increase in woody vegetation in sub-Saharan Africa *Nat. Ecol. Evol.* **1** 1–6
[9] Chen C, Park T, Wang X, Piao S, Xu B, Chaturvedi R K and Myneni R B 2019 China and India lead in greening of the world through land-use management *Nat. Sustain.* **2** 122–9
[10] Piao S, Wang X, Park T, Chen C, Lian X U, He Y and Myneni R B 2020 Characteristics, drivers and feedbacks of global greening *Nat. Rev. Earth Environ.* **1** 14–27
[11] Lian X, Piao S, Chen A, Wang K, Li X, Buermann W and Myneni R B 2021 Seasonal biological carryover dominates northern vegetation growth *Nat. Commun.* **12** 1–10
[12] Zhao L, Dai A and Dong B 2018 Changes in global vegetation activity and its driving factors during 1982–2013 *Agric. For. Meteorol.* **249** 198–209
[13] Pan N, Feng X, Fu B, Wang S, Ji F and Pan S 2018 Increasing global vegetation browning hidden in overall vegetation greening: insights from time-varying trends *Remote Sens. Environ.* **214** 59–72
[14] Zhou L, Tian Y, Myneni R B, Ciais P, Saatchi S, Liu Y Y and Hwang T 2014 Widespread decline of Congo rainforest greenness in the past decade *Nature* **509** 86–90
[15] Mohammat A, Wang X, Xu X, Peng L, Yang Y, Zhang X and Piao S 2013 Drought and spring cooling induced recent decrease in vegetation growth in Inner Asia *Agric. For. Meteorol.* **178** 21–30
[16] Maina F Z, Kumar S V, Albergel C and Mahanama S P 2022 Warming, increase in precipitation, and irrigation enhance greening in High Mountain Asia *Commun. Earth Environ.* **3** 43
[17] Wang X, Wang T, Liu D, Guo H, Huang H and Zhao Y 2017 Moisture-induced greening of the South Asia over the past three decades *Glob. Change Biol.* **23** 4995–5005
[18] Gessner U, Naeimi V, Klein I, Kuenzer C, Klein D and Dech S 2013 The relationship between precipitation anomalies and satellite-derived vegetation activity in Central Asia *Glob. Planet. Change* **110** 74–87
[19] Ukkola A M, Prentice I C, Keenan T F, van Dijk A I, Viney N R, Myneni R B and Bi J 2016 Reduced streamflow in water-stressed climates consistent with CO_2 effects on vegetation *Nat. Clim. Change* **6** 75–78
[20] Ponce-Campos G E, Moran M S, Huete A, Zhang Y, Bresloff C, Huxman T E and Starks P J 2013 Ecosystem resilience despite large-scale altered hydroclimatic conditions *Nature* **494** 349–52
[21] Keenan T F and Riley W J 2018 Greening of the land surface in the world's cold regions consistent with recent warming *Nat. Clim. Change* **8** 825–8
[22] Wang X, Piao S, Ciais P, Li J, Friedlingstein P, Koven C and Chen A 2011 Spring temperature change and its implication in the change of vegetation growth in North America from 1982 to 2006 *Proc. Natl Acad. Sci.* **108** 1240–5
[23] Mo K, Chen Q, Chen C, Zhang J, Wang L and Bao Z 2019 Spatiotemporal variation of correlation between vegetation cover and precipitation in an arid mountain-oasis river basin in northwest China *J. Hydrol.* **574** 138–47
[24] Méndez-Barroso L A, Vivoni E R, Watts C J and Rodríguez J C 2009 Seasonal and interannual relations between precipitation, surface soil moisture and vegetation dynamics in the North American monsoon region *J. Hydrol.* **377** 59–70
[25] Moeslund J E, Arge L, Bøcher P K, Dalgaard T, Odgaard M V, Nygaard B and Svenning J C 2013 Topographically controlled soil moisture is the primary driver of local vegetation patterns across a lowland region *Ecosphere* **4** 1–26
[26] Miguez-Macho G and Fan Y 2021 Spatiotemporal origin of soil water taken up by vegetation *Nature* **598** 624–8
[27] Jiao W, Wang L, Smith W K, Chang Q, Wang H and D'Odorico P 2021 Observed increasing water constraint on vegetation growth over the last three decades *Nat. Commun.* **12** 1–9
[28] Xu J, Grumbine R E, Shrestha A, Eriksson M, Yang X, Wang Y U N and Wilkes A 2009 The melting Himalayas: cascading effects of climate change on water, biodiversity, and livelihoods *Conserv. Biol.* **23** 520–30
[29] Sarmah S, Jia G, Zhang A and Singha M 2018 Assessing seasonal trends and variability of vegetation growth from NDVI3g, MODIS NDVI and EVI over South Asia *Remote Sens. Lett.* **9** 1195–204
[30] Sarmah S, Singha M, Wang J, Dong J, Burman P K D, Goswami S and Niu S 2021 Mismatches between vegetation greening and primary productivity trends in South Asia–a satellite evidence *Int. J. Appl. Earth Obs. Geoinf.* **104** 102561
[31] Baniya B, Tang Q, Pokhrel Y and Xu X 2019 Vegetation dynamics and ecosystem service values changes at national and provincial scales in Nepal from 2000 to 2017 *Environ. Dev.* **32** 100464
[32] Bhutiyani M R 2016 Spatial and temporal variability of climate change in high-altitude regions of NW Himalaya *Climate Change, Glacier Response, and Vegetation Dynamics in the Himalaya* (Springer) pp 87–101
[33] Pokharel B, Wang S Y S, Meyer J, Marahatta S, Nepal B, Chikamoto Y and Gillies R 2020 The east–west division of changing precipitation in Nepal *Int. J. Climatol.* **40** 3348–59
[34] Wiersum K F 2004 *Social and Community Forestry* (Encyclopedia of Forest Sciences) pp 1136–43
[35] Pokharel R K 2012 Factors influencing the management regime of Nepal's community forestry *For. Policy Econ.* **17** 13–17
[36] Oldekop J A, Sims K R, Karna B K, Whittingham M J and Agrawal A 2019 Reductions in deforestation and poverty from decentralized forest management in Nepal *Nat. Sustain.* **2** 421–8
[37] Arnold J E M 2011 Forests and people: 25 years of community forestry (Food and Agriculture Organization of the United Nations)
[38] Anup K C, Manandhar R, Paudel R and Ghimire S 2018 Increase of forest carbon biomass due to community forestry management in Nepal *J. For. Res.* **29** 429–38
[39] Joshi M 2020 Community forestry programs in Nepal and their effects on poorer households (The Food and Agriculture Organization (FAO))
[40] Dai J, Roberts D A, Stow D A, An L and Zhao Q 2020 Green vegetation cover has steadily increased since establishment of community forests in western Chitwan, Nepal *Remote Sens.* **12** 4071
[41] Niraula R R, Gilani H, Pokharel B K and Qamer F M 2013 Measuring impacts of community forestry program through repeat photography and satellite remote sensing in the Dolakha district of Nepal *J. Environ. Manage.* **126** 20–29
[42] Libois F, Baland J M, Delbart N and Pattanayak S 2021 Community forest management: the story behind a success story in Nepal *Technical report* (University of Namur, Development Finance and Public Policies)
[43] Zhu Z, Bi J, Pan Y, Ganguly S, Anav A, Xu L and Myneni R B 2013 Global data sets of vegetation leaf area index (LAI)3g and fraction of photosynthetically active radiation (FPAR)3g derived from global inventory modeling and mapping studies (GIMMS) normalized difference vegetation index (NDVI3g) for the period 1981–2011 *Remote Sens.* **5** 927–48
[44] Myneni R, Knyazikhin Y and Park T 2015 MCD15A2H MODIS/terra+aqua leaf area index/FPAR 8-day L4 global 500m SIN grid V006 (NASA EOSDIS Land Processes DAAC) (https://doi.org/10.5067/MODIS/MCD15A2H.006)
[45] Liu Y, Liu R and Chen J M 2012 Retrospective retrieval of long-term consistent global leaf area index (1981–2011) from combined AVHRR and MODIS data *J. Geophys. Res. Biogeosci.* **117** G04003

[46] Mikolajewicz N and Komarova S V 2019 Meta-analytic methodology for basic research: a practical guide *Front. Physiol.* **10** 203
[47] Muñoz-Sabater J, Dutra E, Agustí-Panareda A, Albergel C, Arduini G, Balsamo G and Thépaut J N 2021 ERA5-Land: a state-of-the-art global reanalysis dataset for land applications *Earth Syst. Sci. Data* **13** 4349–83
[48] Mann H B 1945 Nonparametric tests against trend *Econometrica* **13** 245–59
[49] Kendall M G 1975 *Rank Correlation Methods* (Charles Griffin)
[50] McLeod A I, Yu H and Mahdi E 2012 Time series analysis with R *Handbook of Statistics* vol 30 (Elsevier) pp 661–712
[51] Pettitt A N 1979 A non-parametric approach to the change-point problem *J. R. Stat. Soc.* C **28** 126–35
[52] Burrell A L, Evans J P and de Kauwe M G 2020 Anthropogenic climate change has driven over 5 million km^2 of drylands towards desertification *Nat. Commun.* **11** 1–11
[53] Evans J and Geerken R 2004 Discrimination between climate and human-induced dryland degradation *J. Arid Environ.* **57** 535–54
[54] Wang J F, Li X H, Christakos G, Liao Y L, Zhang T, Gu X and Zheng X Y 2010 Geographical detectors-based health risk assessment and its application in the neural tube defects study of the Heshun Region, China *Int. J. Geogr. Inf. Sci.* **24** 107–27
[55] Kumar N 2002 The challenges of community participation in forest development in Nepal. Operations evaluation department working *Paper No. 27931* (The World Bank)
[56] Singh M P, Bhojvaid P P, Jong W, de Ashraf J and Reddy S R 2017 Forest transition and socio-economic development in India and their implications for forest transition theory *For. Policy Econ.* **76** 65–71
[57] Youn Y-C *et al* 2017 Conditions of forest transition in Asian countries *For. Policy Econ.* **76** 14–24
[58] Estoque R C, Dasgupta R, Winkler K, Avitabile V, Johnson B A, Myint S W and Lasco R D 2022 Spatiotemporal pattern of global forest change over the past 60 years and the forest transition theory *Environ. Res. Lett.* **17** 084022
[59] Jackson W J, Tamrakar R M, Hunt S and Shepherd K R 1998 Land-use changes in two Middle Hills districts of Nepal *Mt. Res. Dev.* **18** 193–212
[60] Beukeboom H, Laan C, Kreveld A V and Akwah G 2010 *Can Community Forestry Contribute to Livelihood Improvement and Biodiversity? Steps on How to Improve Community Forestry Programmes, Lessons from Work in 11 Countries and Communities* (WWF Netherlands)
[61] Nightingale A and Sharma J R 2014 Conflict resilience among community forestry user groups: experiences in Nepal *Disasters* **38** 517–39
[62] Rijal S, Techato K, Gyawali S, Stork N, Dangal M R and Sinutok S 2021 Forest cover change and ecosystem services: a case study of community forest in Mechinagar and Buddhashanti landscape (MBL), Nepal *Environ. Manage.* **67** 963–73
[63] Raik D B and Decker D J 2007 A multisector framework for assessing community-based forest management: lessons from Madagascar *Ecol. Soc.* **12** 14
[64] Gilmour D 2016 Forty years of community-based forestry: a review of its extent and effectiveness *FAO Forestry Papers* p 176
[65] Peng Q, Ranghui W, Jiang Y and Li C 2021 Contributions of climate change and human activities to vegetation dynamics in qilian mountain national park, northwest China *Glob. Ecol. Conserv.* **32** e01947
[66] Barnes M *et al* 2016 Wildlife population trends in protected areas predicted by national socio-economic metrics and body size *Nat. Commun.* **7** 12747
[67] Zhao M, Zhang J, Zhang J, Velicogna I, Liang C and Li Z 2021 Ecological restoration impact on total terrestrial water storage *Nat. Sustain.* **4** 56–62
[68] Freeman S, Taff B D, Miller Z D, Benfield J A and Newman P 2021 Acceptability factors for wildlife approach in park and protected area settings *J. Environ. Manage.* **286** 112276 PMID: 33677344
[69] Bakaloudis D, Bontzorlos V and Kotsonas E 2023 Wildlife mortality on roads crossing a protected area: the case of Dadia-Lefkimi-Soufli National Park in north-eastern Greece *J. Nat. Conserv.* **74** 126443
[70] Dai W, Subedi R, Jin K and Hao L 2023 Spatiotemporal variation of potential evapotranspiration and meteorological drought based on multi-source data in Nepal *Nat. Hazards Res.* **3** 271–9
[71] Simpkins G 2020 A drier future for South Asia *Nat. Rev. Earth Environ.* **1** 557
[72] Niu J, Chen J, Sun L and Sivakumar B 2018 Time-lag effects of vegetation responses to soil moisture evolution: a case study in the Xijiang basin in South China *Stoch. Environ. Res. Risk Assess.* **32** 2423–32
[73] Wang X, Piao S, Ciais P, Friedlingstein P, Myneni R B, Cox P and Chen A 2014 A two-fold increase of carbon cycle sensitivity to tropical temperature variations *Nature* **506** 212–5
[74] Koirala P, Thakuri S, Joshi S and Chauhan R 2019 Estimation of soil erosion in Nepal using a RUSLE modeling and geospatial tool *Geosciences* **9** 147
[75] Uddin K, Murthy M S R, Wahid S M and Matin M A 2016 Estimation of soil erosion dynamics in the Koshi basin using GIS and remote sensing to assess priority areas for conservation *PLoS One* **11** e0150494
[76] Löbmann M T, Geitner C, Wellstein C and Zerbe S 2020 The influence of herbaceous vegetation on slope stability—a review *Earth-Sci. Rev.* **209** 103328
[77] Bruijnzeel L A 2004 Hydrological functions of tropical forests: not seeing the soil for the trees? *Agric. Ecosyst. Environ.* **104** 185–228
[78] Zhang J, Zhang Y, Sun G, Song C, Li J, Hao L and Liu N 2022 Climate variability masked greening effects on water yield in the Yangtze River Basin during 2001–2018 *Water Resour. Res.* **58** e2021WR030382
[79] Xue Y, Ma Y and Li Q 2017 Land–climate interaction over the Tibetan Plateau *Oxford Research Encyclopedia of Climate Science* (UCLA)
[80] Shen M, Piao S, Jeong S-J, Zhou L, Zeng Z, Ciais P and Yao T 2015 Evaporative cooling over the Tibetan Plateau induced by vegetation growth *Proc. Natl Acad. Sci. USA* **112** 9299–304
[81] Zhang J, Zhang Y, Sun G, Song C, Dannenberg M P, Li J, Liu N, Zhang K and Zhang Q 2021 Vegetation greening significantly reduced the capacity of water supply to China's south-north water diversion project *Hydrol. Earth Syst. Sci. Discuss.* **25** 1–28
[82] Goulden M L and Bales R C 2014 Mountain runoff vulnerability to increased evapotranspiration with vegetation expansion *Proc. Natl Acad. Sci.* **111** 14071–5
[83] Ghimire C P, Bruijnzeel L A, Lubczynski M W and Bonell M 2014 Negative trade-off between changes in vegetation water use and infiltration recovery after reforesting degraded pastureland in the Nepalese Lesser Himalaya *Hydrol. Earth Syst. Sci.* **18** 4933–49
[84] Badu M, Nuberg I, Cedamon E and Sharma S 2019 Management of the forested catchments of Nepal's mid-hills amid mismatched perceptions of forest–water relationships: challenges and opportunities *Mt. Res. Dev.* **39** R27
[85] Hallema D W, Sun G, Caldwell P V, Norman S P, Cohen E C, Liu Y, Bladon K D and McNulty S G 2018 Burned forests impact water supplies *Nat. Commun.* **9** 1–8
[86] Anderson K, Fawcett D, Cugulliere A, Benford S, Jones D and Leng R 2020 Vegetation expansion in the subnival Hindu Kush Himalaya *Glob. Change Biol.* **26** 1608–25