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Protected Areas Conserved Forests from Fire and Deforestation in Vietnam's Central Highlands from 2001 to 2020

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Abstract: As a tropical nation with ~40% forested land area and 290 protected areas in the Indo-Burma Biodiversity Hotspot, Vietnam holds an important part of global forests. Despite a complex history of multiple colonial rules, war, rapid economic development and societal growth, Vietnam was one of a few Southeast Asian countries to reverse deforestation trends and sustain net forest cover gain since the 1990s. However, a considerable amount of Vietnam's forest gain has been from plantation forestry, as Vietnam's policies have promoted economic development. In the Central Highlands region of Vietnam, widespread forest degradation and deforestation has occurred recently in some areas due to plantation forestry and other factors, including fire-linked deforestation, but protected areas here have been largely effective in their conservation goals. We studied deforestation, wildfires, and the contribution of fire-linked deforestation from 2001 to 2020 in an area near the Da Lat Plateau of the Central Highlands of Vietnam. We stratified our study area to distinguish legally protected areas and those in the surrounding landscape matrix without formal protection. Using satellite-derived data, we investigated four questions: (1) Have regional deforestation trends continued in parts of the Central Highlands from 2001 to 2020? (2) Based on remotely sensed fire detections, how has fire affected the Central Highlands and what proportion of deforestation is spatiotemporally linked to fire? (3) Were annual deforestation and burned area lower in protected areas relative to the surrounding land matrix? (4) Was the proportion of fire-linked deforestation lower in protected areas than in the matrix? To answer these questions, we integrated the Global Forest Change and FIRED VIETNAM datasets. We found that 3794 fires burned 8.7% of the total study area and 13.6% of the area became deforested between 2001 and 2020. While nearly half of fires were linked to deforestation, fire-linked deforestation accounted for only a small part of forest loss. Across the entire study area, 54% of fire-linked deforestation occurred in natural forests and 46% was in plantation forests. Fire ignitions in the study area were strongly linked to the regional dry season, November to March, and instrumental climate data from 1971 to 2020 showed statistically significant increasing trends in minimum, mean, and maximum temperatures. However, the total area burned did not have a significant increasing trend. Regional trends in deforestation continued in Vietnam's Central Highlands from 2001 to 2020, and nearly half of all detected fires can be spatially and temporally linked to forest loss. However, protected areas in the region effectively conserved forests relative to the surrounding landscape.

Keywords: remote sensing; deforestation; Vietnam; national parks; tropical forest; fire; spatial

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Citation: Ebright, S.J.; Stan, A.B.; Sâm, H.V.; Fulé, P.Z. Protected Areas Conserved Forests from Fire and Deforestation in Vietnam's Central Highlands from 2001 to 2020. *Fire* **2023**, *6*, 164. https://doi.org/10.3390/fire6040164

Academic Editors: Aqil Tariq and Na Zhao

Received: 1 March 2023
Revised: 5 April 2023
Accepted: 12 April 2023
Published: 18 April 2023

1. Introduction

Around the world, humans play a pivotal role in forest management, deforestation, and afforestation. Forests are essential to global nature conservation and climate change adaptation. In 2000, an estimated 4,145,387,000 ha were forested, covering 32.2% of the world's land area [1]. Five percent of these forests were lost by 2012, while forest cover increased by only 2% [1]. While some areas of forest loss recorded by [1] are permanent deforestation or conversion to other land uses, there are also areas of natural regrowth or intentional reforestation. Shifting agriculture and commodity-driven deforestation were the primary drivers in tropical forests, and globally, 27% of permanent forest loss was commodity driven [2]. Tropical deforestation has increased since the 1990s [3,4]. Forest conversion to pasture or cropland is the main deforestation driver in the humid tropics [3,4].

Humans are also directly modifying fire regimes through fire suppression as well as encroaching into forests through development [5,6]. As the climate warms and fire seasons grow in length and severity, understanding global fire regimes is more relevant now than ever to global conservation [7,8]. Longer fire weather seasons were significantly correlated with interannual burned area variability in country-reported burned area data from the United States, Spain, Portugal, France, Italy, Greece, and Latvia from 1980 to 2013 [8]. General circulation models have shown that by the end of the century, global wildfire potential will significantly increase on every continent besides Antarctica [9].

In all the world's major biomes, fire plays an integral role in the distribution and evolution of the natural environment [5]. Every year, fires burn an area roughly the size of the European continent [5,10]. From 2003 to 2012, fires burned approximately 1.7% of the world's forests each year [11]. Fire was related to 38 $\pm$ 9% of global deforestation from 2003 to 2018 [4]. The amount of forest area burned annually was highest in the tropics [11], which underscores the global importance of conserving tropical forests, which hold more than half of Earth's biodiversity [12].

Regional research on the impacts of human perturbation leading to forest degradation and deforestation has shown that the future of Southeast Asia's forests depends heavily on human behavior. By 2050, Southeast Asia's forests could shrink by 5.2 million ha or gain 19.6 million ha, based on the worst- and best-case models [13]. In 2015, old-growth forests held half of Southeast Asia's aboveground forest carbon stocks and projected old-growth forest loss by 2050 would account for 21% of regional losses in sequestered carbon [13]. Forest conversion to croplands or pasture has been the main driver of deforestation in the humid tropics, and fire is an inexpensive tool to effectively clear forests for agriculture [4]. Therefore, effective forest conservation in Southeast Asia and the global tropics requires a deeper investigation of fire's role in global forest dynamics.

In Southeast Asia, growing populations and industrialization occur adjacent to highly diverse tropical forests. The juxtaposition of biodiverse forests and human development leads to competition for limited land area, often causing forest conversion to other land types. Biomass burning contributes heavily to forest loss and air pollution in Southeast Asia. Atmospheric impacts of emissions from fires, both non-human and human-caused, underscore the necessity of studying climate change as a driver of global fires and forest loss, as well as the effects of fire emissions on climate change [14]. Streets et al. [14] estimated forest burning to account for 45% of regional burning and emissions, followed by croplands and savanna. In a typical year, natural and human-ignited fires burned 730 Tg of biomass [14]. From 2003 to 2016, vegetation fires in Vietnam, India, and Cambodia significantly increased [15]. Most fires were human initiated and equally frequent fires occurred in croplands and forests [15].

Vietnam is a biodiversity hotspot, the 16th most biodiverse country in the world, and is part of the core of the Indo-Burma Biodiversity Hotspot [16]. To address overexploitation and habitat loss, the government expanded the national park and nature reserve system in 1995 [16]. Since the mid-20th century, logging and land conversion to non-native plantations of rubber or acacia trees have driven the rapid decline of Vietnam's natural forests [17]. Between 2000 and 2010, 1.77 million ha of deforestation and 0.65 million ha of forest degradation occurred in Vietnam [18]. As of 2010, 42% of Vietnam was under forest cover, but only 1% of the total was primary forest, and 25% was plantation forest [19]. However, "massive deforestation" [20] has continued in the Central Highlands region as lands are converted to agriculture, primarily coffee and rubber [19].

By leveraging the global coverage of satellite data, landscape conservation has gained invaluable insights into global forest stocks [1] and wildfires [4,5,10]. The relationship between global fires and forest loss has been mapped at the 500 m pixel scale by combining burned area and active fire detections with forest loss data [4]. However, the coarse pixel resolution negates the high-resolution 30 m forest loss data by down sampling to the 500 m scale. The first global 30 m resolution map of annual forest loss due to fire used sample-based image classification to differentiate forest loss from fire versus other causes [21]. However, due to the global scale and regional level sampling, the results provide an incomplete picture at the management level for rapidly changing landscapes such as Vietnam's Central Highlands region.

We combined the Global Forest Change (GFC) dataset [1] and FIRED VIETNAM dataset [22] to assess forest change and the role of fire in this change. We analyzed satellite-derived data from protected areas and the surrounding region without formal protection. Within the Central Highlands, our study area is southwest of the Da Lat Plateau. Our study encompassed two large national parks in the area, as well as a UNESCO biosphere reserve and five smaller protected areas. We asked four questions in our study: (1) Have regional deforestation trends continued in parts of the Central Highlands from 2001 to 2020? (2) Based on remotely sensed fire detections, how has fire affected the Central Highlands and what proportion of deforestation is spatiotemporally linked to fire? (3) Were annual deforestation and burned area lower in protected areas relative to the surrounding land matrix? (4) Was the proportion of fire-linked deforestation lower in protected areas than in the matrix? We expected the following outcomes. First, based on regional trends, we expected notable forest loss across the region. Second, based on a preliminary analysis of MODIS burned area [10] data within Cát Tiên and Bidoup-Núi Bà National Parks, we did not expect substantial numbers of fires or burned area in the surrounding landscape. Third, we expected fire to be the primary driver of forest loss in our study area, based on the estimated global prevalence of deforestation caused by fire [4]. Fourth, we expected forest loss and fire occurrences to exist primarily outside of formally protected areas, since these areas are closed to agriculture and forest resource exploitation.

2. Materials and Methods

Our study covered 1,524,783 ha in Vietnam's Central Highlands region with roughly equivalent parts of legally protected areas and the surrounding land matrix. The study area forms an ellipsoid around two of the largest national parks in the region, Cát Tiên and Bidoup-Núi Bà. The study area also includes the entire Đồng Nai Biosphere Reserve, as well as five smaller protected areas and the surrounding land matrix. The study area and protected areas are shown in Figure 1, and Table 1 presents details on the protected area size and establishment years.

Table 1. Sizes of protected areas and protection establishment years.

Location	Protection Designation	IUCN Category [1]
Nui Dai Binh	Nature Reserve	IV
Rung Thong Da Lat	Cultural and Historical Site	V
Cát Tiên	National Park	II
Southwest Lam Dong	Nature Reserve	Not Reported
Đồng Nai Biosphere Reserve	UNESCO Man and Biosphere Reserve	I–VI
Chư Yang Sin	National Park	II
Tà Đùng	Nature Reserve	Not Reported
Đồng Nai Nature Reserve	Nature Reserve	Not Reported
Bidoup-Núi Bà	National Park	II
Phước Bình	National Park	II

[1] International Union for Conservation of Nature (IUCN) categories are listed as reported in the World Database on Protected Areas (WDPA) [17].

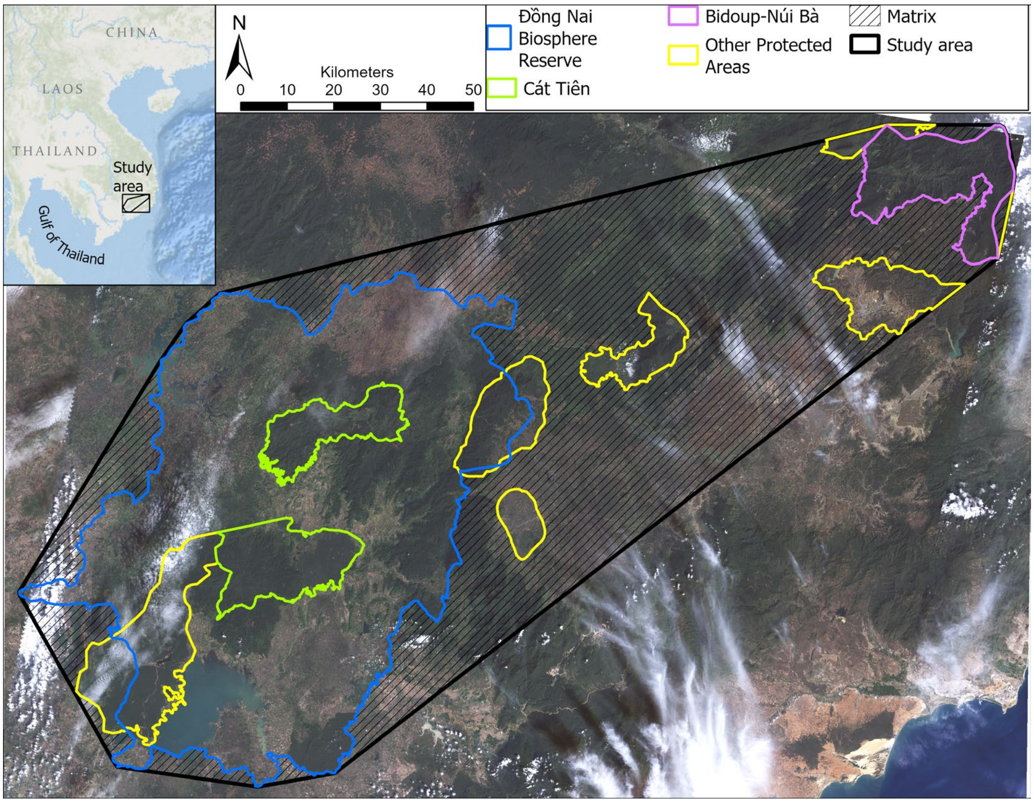

Figure 1. Protected areas and other land use categories in the study area, in Vietnam's Central Highlands region.

Vietnam's National Parks, Nature Reserves, and Cultural, Historical and Environmental sites (Landscape Conservation areas) are part of the national Special-use Forests category [23]. Special-use Forests have specific conservation objectives as opposed to Production Forests, which are set aside for natural resource extraction. The Đồng Nai Biosphere Reserve is a United Nations (UN) management category, under the UN Man and Biosphere Programme. Man and Biosphere Reserves are composed of a core, buffer, and transition zone which may be part of multiple International Union for Conservation of Nature (IUCN) protected area categories [24].

To analyze forest change, we used version 1.8 of the Global Forest Change (GFC) dataset to map deforestation from 2001 to 2020 and forest gain from 2001 to 2012 [1]. Because of the short span of the GFC forest gain data and discrepancy with the deforestation layer, we did not analyze fire relative to forest gain. GFC tracks annual global deforestation by NDVI annual change detection [1]. In the dataset, forest loss is defined as "a stand-replacement disturbance or the complete removal of tree cover canopy at the Landsat pixel scale". Forests are defined as any vegetation with a vertical height >5 m, without a minimum canopy cover [1]. For consistency with the original dataset and to avoid removing any possible forest loss from fire or other causes, we included all forest and forest loss data from GFC.

We used all fire events from 2001 to 2020 in our study area, delineated with the FIREDpy algorithm [25] in the FIRED VIETNAM [22] dataset. FIREDpy is a Python script which quantifies burned area perimeters and fire spread attributes by applying a spread algorithm to fires and burned area detected by MODIS [10,25,26].

We differentiated natural and plantation forests based on their classification in the year 2000 from the High-Resolution Land-Use and Land Cover (HRLULC) map of Vietnam, version 21.09, which was based on national forest survey data and remote sensing [27]. Natural and plantation forests occur in both the protected and unprotected land zones. We grouped the evergreen broadleaf, coniferous, and deciduous forest classifications from the

HRLULC as natural forest. Additionally, we used the plantation forests classification as delineated by the HRLULC [27]. Shapefiles of the protected area boundary were acquired from the World Database on Protected Areas (WDPA) [28]. The WDPA was mandated by the UN in 1959 and established in 1981 [28].

We defined fire-linked deforestation as the 30 m^2 pixel area where deforestation and fire were detected in the same year. By not including deforestation in the year before or after fires, our temporally conservative definition may have underestimated the magnitude of fire's contribution to regional deforestation.

With ArcGIS Pro 3.0, we completed a series of steps and analyses. First, we re-projected the GFC [1] and FIRED VIETNAM [22] datasets to a standard coordinate system of World Geodetic System 84 and clipped them to the study area. Then, to integrate the GFC raster layers and the FIRED fire event polygons, we converted the GFC forest loss raster to polygons and overlaid them with the FIRED polygons. We created annual forest loss and fire layers to calculate the overlapping area of forest loss in each fire. When a deforestation and fire polygon from the same year overlapped, we classified the deforestation area within the fire polygon as fire-linked forest loss. This approach leveraged the finer 30 m^2 resolution of the GFC data, because the FIRED polygons are informed by 500 m^2 MODIS pixels [10]. We extracted the year 2000 forest type, based on a point estimate from the HRLULC raster [27]. Where fire was linked to deforestation, we used Zonal Statistics to extract the majority canopy cover percentage from the GFC tree cover % 2000 layer [1].

We verified annual to sub-annual changes in forest cover visually by manually selecting 200 ground control points through stratified random sampling in ArcGIS Pro and then exporting them to Google Earth Pro as a KML file [19]. In Google Earth Pro, we zoomed in to each point to review the available cloud-free imagery to verify whether deforestation occurred at the point and surrounding pixels.

To reduce commission errors of biomass fires outside of forests, we removed fires where the HRLULC year 2000 map was classified as agricultural or shrubland. Because the GFC forest cover 2000 mask does not discriminate between natural and plantation forest, we deferred to the HRLULC map to classify natural forests and woody plantations. The natural forest class included deciduous broadleaf, evergreen broadleaf, and conifer forests. In forests below 1000 m in the southern half of the Truong-Son Range, these forest types often occur without clear boundaries due to microclimatic and soil moisture variation over small areas [16]. In our analysis, if deforestation occurred in a pixel, deforestation was treated as a complete loss in forest cover for the rest of the study period, and subsequent fires in the same pixel were not associated with further forest loss. Reburn fires detected in the same pixel(s) multiple times between 2001 and 2020 were accounted for in the burned area total, but forest loss was associated with the first fire to overlap forest loss in the same year.

We acquired monthly climatic data for Lam Dong province, nearby our study area, from the ERA5 reanalysis dataset [29]. Based on 30-year climate normals and observed monthly patterns, we aggregated monthly temperature and precipitation values for Lam Dong province into a 'wet-season' from May to October and a 'dry-season' from November to April.

We exported tables from ArcGIS Pro for data compilation and cleaning. In the R V4.2.1 statistical software, we used the 'tidyverse' package to clean and plot our data. We informally checked linear model assumptions of linearity, normality and homoscedasticity with diagnostic plots from the 'ggfortify' package. We used the 'stats' package to perform a Shapiro–Wilks test on the dataset to formally check data normality and to visually inspect the data with normal QQ plots. We checked variable collinearity and computed pairwise variable correlation coefficients with the 'corrplot' package. We built a linear regression model based on scaled and centered variables with the 'lm' function in the 'stats' package. Our model fits annual area burned as a function of 'wet' and 'dry' season temperature and precipitation, and intra-season variable interactions. We used stepwise model selection and the Akaike information criterion to choose a model with the highest predictive power.

Our model is as follows: where BA is annual area burned in ha, subscript 'w' refers to 'wet' and subscript 'd' refers to 'dry' season variables, PRCP is accumulated seasonal precipitation, TMIN is the minimum seasonal temperature, and TMAX is the maximum seasonal temperature. Descriptive statistics of the model parameters in Table 2 characterize the mean values, standard deviation, and standard error.

$$\text{BA} \sim \text{wPRCP} + \text{dPRCP} + \text{wTMIN} + \text{dTMAX} + \text{wPRCP} \times \text{wTMIN} + \text{dPRCP} \times \text{dTMAX}$$

Table 2. Model descriptive statistics.

Parameter	Mean	Standard Deviation	Standard Error
Burned area (BA)	35.94 (ha)	40.01	0.65
Wet-season precipitation (wPRCP)	234.22 (cm)	75.95	6.93
Dry-season precipitation (dPRCP)	87.43 (cm)	82.07	7.49
Wet-season min. temperature (wTMIN)	20.89 (°C)	0.88	0.08
Dry-season max. temperature (dTMAX)	28.39 (°C)	0.99	0.09

'Wet-season' is May to October; 'dry-season' is November to April.

3. Results

An estimated 208,356 ha of total forest loss occurred within the study area between 2001 and 2020, which covered 13.7% of the 1,524,783 ha study area (Figure 2). Forest gain was only mapped from 2000 to 2012 and occurred in 16,131 ha, covering about 1% of our study area (Figures 2 and 3; Table 3). Forest loss during the same period was 116,213 ha (7.6% of study area), nearly an order of magnitude higher than forest gain (Figure 3; Table 3).

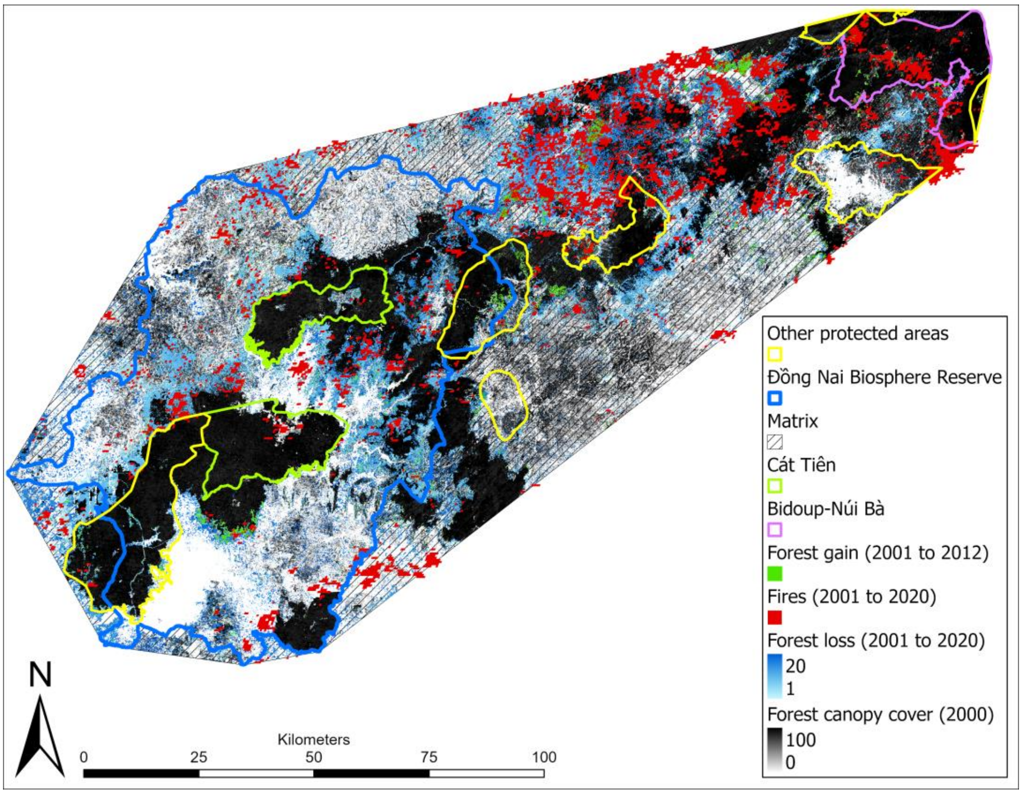

Figure 2. Forest loss and fires mapped across the study area from 2001 to 2020, and forest gain from 2001 to 2012.

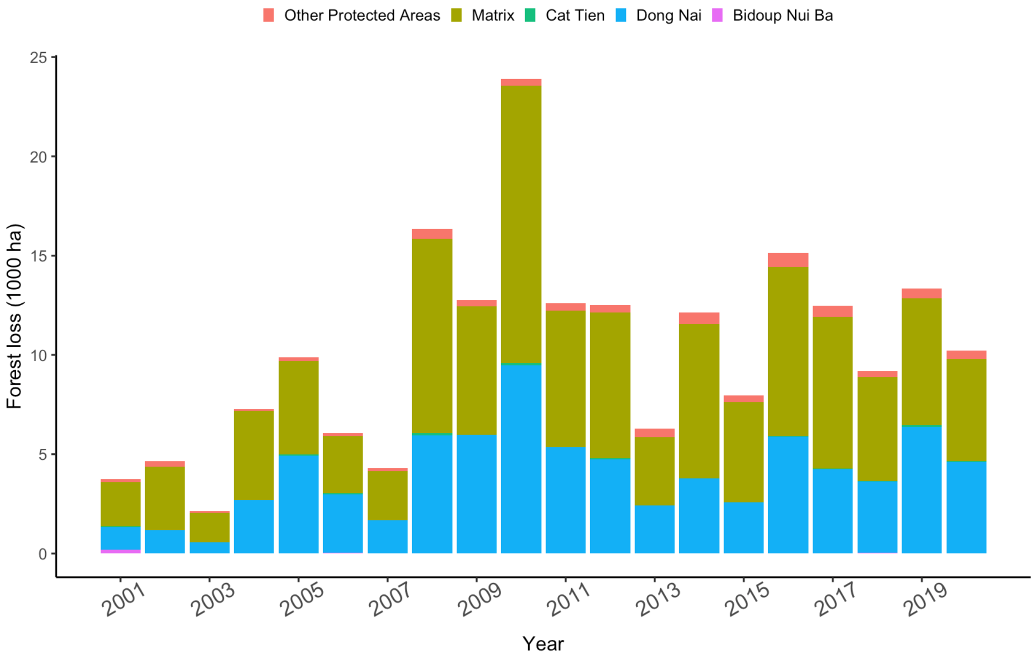

Figure 3. Total area of forest loss in the study area from 2001 to 2020.

Table 3. Summary of forest loss, fire, and fire-associated forest loss areas in our study area and categories.

Category	Total Category Area (ha)	Forest Loss (ha, % of Category Area)	Burned Area (ha, % of Category Area)	Fire-Linked Forest Loss (ha, % of Category Area)
Đồng Nai Biosphere Reserve	661,955	79,988 (12%)	25,136 (3.8%)	1688 (0.25%)
Cát Tiên	69,862	779 (1.1%)	1545 (2.2%)	2 (<0.1%)
Bidoup-Núi Bà	52,275	199 (0.4%)	9895 (18.9%)	2 (<0.1%)
Other Protected Areas *	171,048	12,497 (7.3%)	7856 (4.6%)	44 (<0.1%)
Matrix	721,992	114,893 (15.9%)	93,784 (13%)	4956 (0.7%)

* Other Protected Areas includes: Nui Dai Binh, Rung Thong Da Lat, Southwest Lam Dong, Chư Yang Sin and Phước Bình.

Annual forest loss averaged 9981 ha year^{-1}, with a peak in 2010 (Figure 3). Absolute area of forest loss, and as a relative percentage of the category area, were highest in the matrix, followed closely by Đồng Nai Biosphere Reserve (Table 3). Relative to the total category area, deforestation occurred in 15.9% of the matrix, 12% of Đồng Nai Biosphere Reserve, 6.8% of the other protected areas, 1.1% of Cát Tiên, and 0.4% of Bidoup-Núi Bà (Table 3).

FIRED VIETNAM delineated 3794 fires in our study area from 2001 to 2020 that burned a portion of land in each of our five categories (Table 3) [15]. Thirty percent of fires in our study occurred in formally protected areas but only burned 2.6% of their total area. In the matrix, 2652 fires burned ~13% (93,784 ha). Seven hundred eighty-five fires burned 25,136 ha or ~4% of the Đồng Nai Biosphere Reserve. One hundred and sixty-nine fires burned 9895 ha or ~19% of Bidoup-Núi Bà National Park. In Cát Tiên National Park, 45 fires burned 1545 ha, ~2.2%. While more than three times as many fires occurred in Bidoup-Núi Bà National Park as in Cát Tiên National Park, a larger proportion of Cát Tiên National Park burned. In the other protected areas, 143 fires burned 7856 ha, ~4% of the total area. Mean fire size was 35.9 ha across the study period and annual means ranged from 28.9 ha in 2006 to 60.8 ha in 2017 (Figure 4A). Fires occurred in every year of our study, with a relatively constant annual mean fire size of 35.9 ha (Figure 4A). However, large fires did occur in the study area, and the largest fire (665 ha in 2010) was 18.5 times larger than the

20-year annual mean. Nearly all fires (96.9%) occurred between November and April, with 40.9% of ignitions in March and 27.6% in April (Figure 4B).

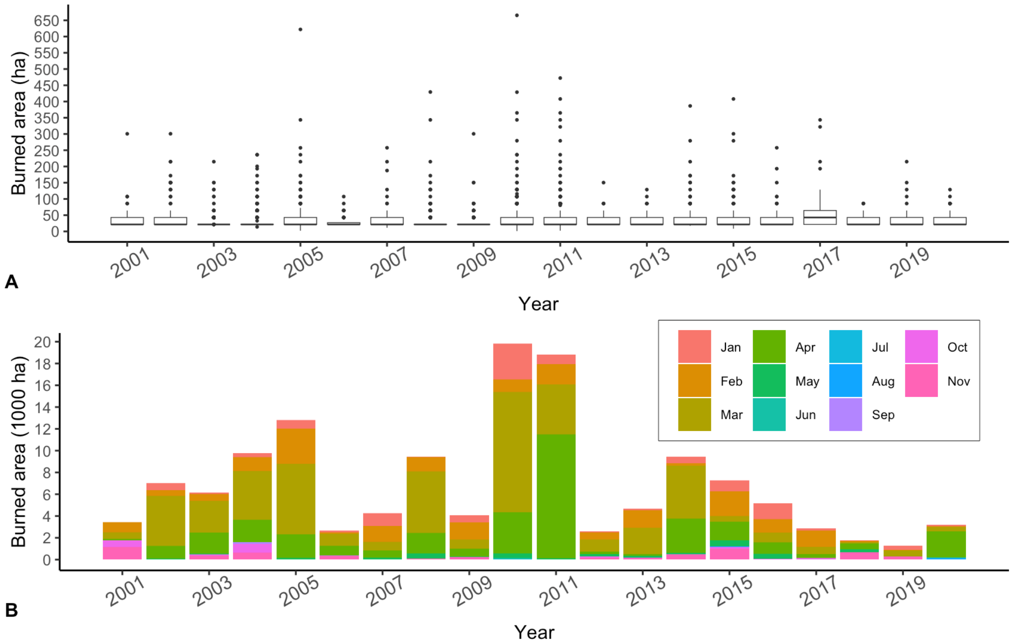

Figure 4. (**A**) Burned area of individual fires detected in our study area, 2001 to 2020. (**B**) Total area burned annually and by month.

Forty-three percent of all fires were associated with forest loss in our study, but the actual area of forest loss associated with fires was <1% of the total study area (Table 4). Areas of fire-linked deforestation in natural and plantation forests, within each management category, are shown in Table 4. Fire-linked deforestation was largely absent in Cát Tiên, Bidoup-Núi Bà, and the other protected areas. Deforestation, fire-linked and otherwise, within the Đồng Nai Biosphere Reserve may be related to sanctioned land use within the reserve. Overall, deforestation and fire-linked deforestation was highest in the land matrix surrounding the protected area network.

Table 4. Fires linked to forest loss in natural and plantation forests in protected areas and the surrounding land matrix.

Category	Total Category Area (ha)	Area of Natural Forest Loss, Fire-Linked (ha)	Area of Plantation Forest Loss, Fire-Linked (ha)
Đồng Nai Biosphere Reserve	661,955	847	841
Bidoup-Núi Bà	52,275	1	1
Cát Tiên	69,862	0	2
Other Protected Areas	171,048	8	36
Matrix	721,992	2780	2176

Precipitation was strongly consistent in amounts and did not show significant trends between 1971 and 2020 (Figure 5A). Mean (Figure 5B), minimum (Figure 5C), and maximum (Figure 5D) temperatures have been rising steadily ($p < 0.001$). Mean temperature increased by 0.03 °C per year between 1971 and 2020. Annual minimum temperature showed an even steeper increase of 0.04 °C per year, and annual maximum temperature increased by 0.03 °C per year. Even though precipitation has remained relatively constant, simultaneously increasing temperatures have resulted in a drier local climate. However, fire ignitions and burned area did not increase at the same rate as regional temperatures. Fire ignitions and burned area did not show statistically significant trends from 2001 to 2020. Ignitions and burned area increased from 2001 until a peak in 2010, but the trend was not significant. Despite increasing temperatures, fire ignitions and area burned declined from 2011 to 2020.

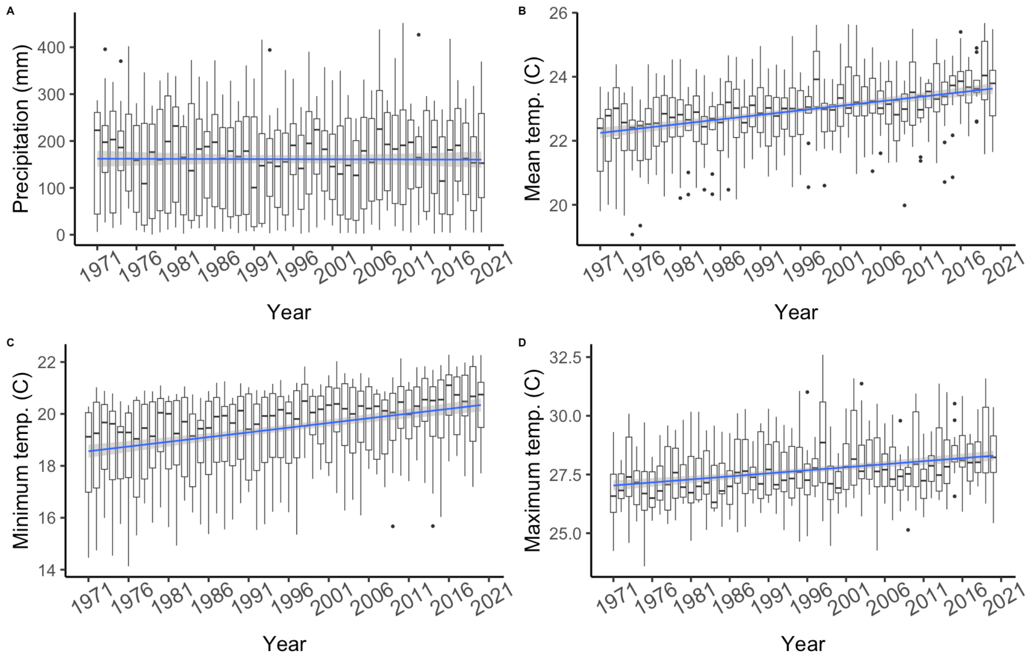

Figure 5. ERA5 climate data for Lam Dong, Vietnam from 1971 to 2020; (**A**) monthly precipitation, (mm) presented annually; (**B**) monthly mean temperature, (°C) presented annually; (**C**) monthly minimum temperature, (°C) presented annually; (**D**) monthly maximum temperature, (°C) presented annually.

The driest months are December to March, and fires occurred almost exclusively in the dry season. Almost all fires (Figure 4B) occurred in January through March, which are consistently the hottest and driest months. Fire seasonality was driven primarily by 'dry season' precipitation and temperature. In terms of annual precipitation, 2004 and 2014 were the driest years in our study and corresponded to increases in burned area (Figure 4B) and fire-linked loss. Mean monthly temperatures in 2004 and 2014 differed by <0.1% from the mean of 2001 to 2020 (23.3 °C).

Despite a strong correlation between fire ignitions and seasonal precipitation, fire ignitions and burned area did not increase at the same rate as regional temperature. Fire ignitions and burned area trends were also insignificant between 2001 and 2020. Ignitions and burned area increased from 2001 until a peak in 2010, but the trend was not significant. Despite increasing temperatures, fire ignitions and area burned declined from 2011 to 2020. Fires and fire-linked forest loss both peaked in our study in 2010, when 'dry season' precipitation was 40.9% lower than the seasonal averages between 2001 and 2020. Averaged across the calendar year, precipitation and mean temperature were unremarkable in 2004, 2010, and 2014. However, precipitation was especially low, and temperatures were high, during the regional dry season, November to March.

Our linear model of annual burned area as a function of seasonal accumulated precipitation, minimum temperature, maximum temperature, and intra-season precipitation–temperature interactions resulted in an adjusted R^2 of 0.4269 ($p \leq 0.05$). We predicted the annual burned area from 2000 to 2020 using annual mean values for each variable in our model, and our results closely match the trend and magnitude of observed values. In our model, seasonal climatic variables explained approximately 40% of the variability in burned area. Estimated model coefficients, standard error, and statistical significance are shown in Table 5.

Table 5. Linear model summary.

Parameter	Estimate	Standard Error	Pr. (>|t|)
Burned area (BA)	147,605.03	251,203.08	0.57
Wet-season precipitation (wPRCP)	−335.70	210.38	0.13
Dry-season precipitation (dPRCP)	782.86	219.98	0.004 *
Wet-season min. temperature (wTMIN)	−26,382.39	12,856.23	0.06
Dry-season max. temperature (dTMAX)	13,593.51	3945.25	0.004 *
Wet-season precipitation (wPRCP) × Wet-season min. temperature (wTMIN)	17.16	10.31	0.12
Dry-season precipitation (dPRCP) × Dry-season max. temperature (dTMAX)	−28.48	7.98	0.003 *

'Wet-season' is May to October; 'dry-season' is November to April. * Statistically significant at $p \leq 0.05$.

4. Discussion

We addressed four questions in our study. (1) Have regional deforestation trends continued in parts of the Central Highlands from 2001 to 2020? We expected substantial forest loss in this region based on national and regional analyses. Approximately 13% of the forest cover present on the landscape in 2000 was lost by the end of 2020. (2) Based on remotely sensed fire detections, how has fire affected the Central Highlands and what proportion of deforestation is spatiotemporally linked to fire? We did not expect to detect many fires on the landscape due to it being a humid tropical environment, but we found 3794 fires between 2001 and 2020, which burned 8.7% of our ~1.5 million ha study area. (3) Were annual deforestation and burned area lower in protected areas relative to the surrounding land matrix? We expected that most fires in the region would be linked to forest loss. By analyzing forest loss and fires occurring in the same space and the same year using different data products, we identified that 43.6% of fires were linked to forest loss. Fire-linked forest loss was greater in the combined natural forest area than in the plantation forests. (4) Was the proportion of fire-linked deforestation lower in protected areas than in the matrix? We expected forest loss, fires, and fire-linked forest loss in the region to be greatest in the matrix outside of the national parks and nature reserves in our study, and relatively lower in the Đồng Nai Biosphere Reserve compared to the matrix. We found that less than half of fires in the region were associated with forest loss, and more fire-related forest loss occurred in natural forest types than plantations. Additionally, we found that the total areas of deforestation, burned area, and fire-linked deforestation were lower in protected areas than in the matrix from 2001 to 2020 (Table 3). Compared to the surrounding landscape, protected areas in the Da Lat Plateau have become islands of primary forest in the first two decades of the 21st century, as the matrix surrounding the protected areas has declined notably in natural forest cover.

Vietnam's forest cover in 2000 comprised 0.81% of global tropical forests with >25% cover, but deforestation in Vietnam between 2001 and 2012 accounted for 1.1% of global tropical deforestation (tree cover > 25%) [1]. From 2015 to 2016, deforestation increased in tropical Asia but has since decreased annually through 2021 [30]. Currently, tropical Asia is the only region on track to reach international goals of halting and reversing deforestation by 2030, as declared by the New York Declaration on Forests [31] and the Glasgow Leaders' Declaration on Forests and Land Use [32]. Van Wees et al. [4] found that forest loss in the Amazon accounted for 9% of global forest loss, and forest loss in Southeast Asia accounted for 14% of global forest loss between 2003 and 2018, based on GFC V1.6 forest loss data [1,4]. Between 2001 and 2020, 13.6% (208,356 ha) of our ~1.5 million ha study area became non-forested. The relative deforestation rates in our study are comparable to long-term deforestation rates in the Brazilian Amazon [4].

Vietnam's deforestation trend has continued in recent years (2018 to 2020), but the rate did decline in 2021 [30]. Prior studies [19,20] have shown continued net forest gain in Vietnam since the 1990s. However, Phan et al. [27] recorded a net loss in forest area, declining from 17,045,800 ha in 1990 to 15,051,700 ha in 2020. Despite the discrepancies in forest inventories, our findings support that forest loss has continued in Vietnam's Central Highlands. From 1990 to 2020, forest conversion to croplands drove a reduction in Vietnam's forest cover while residential areas and aquaculture expanded [21]. In the Central Highlands, coffee and rubber plantation expansion drove deforestation [33]. Our study supports previous findings by showing that commodity-driven deforestation has resulted in land-use change in Vietnam, especially in the Central Highlands region. While agricultural encroachment is a major deforestation driver in our study region [19], trends of deforestation in Southeast Asia are largely driven by forest conversion to oil-palm plantations in Indonesia and Malaysia [2].

In our study, absolute and relative values of deforestation were highest in the matrix (114,893 ha, 15.9%) (Table 3). Đồng Nai Biosphere Reserve, a United Nations management area, also showed high rates of deforestation (79,988 ha, 12%) (Table 3), but most loss occurred in the buffer and transition zones of the Reserve, where resource extraction is permitted. Forest loss in these parts of our study area is evidence of conversion to croplands or plantations. In addition, forest loss was higher across the five smaller protected areas (12,497 ha, 7.3%) compared to Cát Tiên (779 ha, 1.1%) and Bidoup-Núi Bà (199 ha, 0.4%) National Parks (Table 3). These results suggest that larger, higher profile protected areas are more effective at conserving forests. This greater protection afforded to higher profile areas is particularly noticeable in Cát Tiên National Park (Figure 2), which is part of the core area of Đồng Nai Biosphere Reserve and has strict biodiversity conservation goals.

Most of the fires in the protected areas occurred in Đồng Nai Biosphere Reserve, which was the largest protected area we analyzed. Excluding Đồng Nai Biosphere Reserve, which allows sustainable resource extraction in the buffer and transition zones, <1% of all the protected areas in our study were burned.

The higher concentration of fires outside rather than inside protected areas provides evidence that Vietnam's Central Highlands is a socio-ecological system with an anthropogenic fire regime. Vietnam had a significantly increasing fire trend from 2003 to 2016 [15], but our study area did not have significant trends in annual fire ignitions between 2003 and 2016 or 2001 and 2020. Although fires peaked in our study area in 2010, the trend in yearly fire ignitions between 2001 and 2010 was not statistically significant.

Fire-linked forest loss, defined as fire and forest loss in the same year, accounted for <1% of all deforestation in our study. In comparison, Liu et al. [34] defined fire-induced forest loss as deforestation in the fire year and up to two years after and estimated 14.8 $\pm$ 3.3% of global forest loss was fire-induced from 2003 to 2014. During this same period, losses in tropical forests represented 25% of global fire-induced loss and 4% of global deforestation. South America and Southeast Asia's increasing forest loss and decreasing burned area from 2003 to 2014 indicated the prevalence of human-caused deforestation [9].

Our results from Vietnam's Central Highlands agree with Southeast Asian trends from 2003 to 2018 [9], showing that forest loss and fire are spatiotemporally related, but a higher proportion of human-caused deforestation occurs independent of fire [9]. Our results differ from Liu et al. [9] in the quantity and proportion of forest loss associated with fire, primarily due to our study only attributing forest loss to fire in the same year. By not including forest loss that occurred in years adjacent to fires, we may be underestimating the region's proportion of fire-linked forest loss. Due to GFC's annual forest loss estimates, our methods may underestimate deforestation by failing to capture forest loss that occurs in the year directly after a fire. However, Tyukavina et al. [21] also attributed forest loss only to fires that occurred in the same year and found an increasing trend in forest loss due to fire between 2001 and 2019 across Vietnam. Our study area, compared to Vietnam as a whole, has a much larger proportion of protected areas that have effectively prevented deforestation and fire-linked deforestation within their boundaries.

In another global study, Van Wees et al. [4] used a 1-year temporal lag and defined fire-related forest loss as forest loss overlapping with fires that occurred the year of forest loss or the year prior. Van Wees et al. [4] estimated that fire-related forest loss comprised 38 ± 9% of global deforestation, 34 ± 14% of deforestation in the tropics, and 26 ± 11% of deforestation in Southeast Asia [4]. While our study may contain omission errors due to only attributing forest loss to fire in the same year, these errors are potentially balanced by the commission errors of including areas where fire is related to, but not a driver of, forest loss. In our study, we intended to quantify how fire was directly linked to deforestation. In contrast, Van Wees et al. [4] "focus on quantifying the fraction of forest loss that is related to fire, regardless of what mechanism is at play".

The Central Highlands is an area of rapid LULC, and our results support claims that agricultural encroachment has been the primary driver of forest loss in Cát Tiên and Bidoup-Núi Bà National Parks [19]. In the Central Highlands, deforestation has occurred in protected areas but at a much slower rate than in the surrounding matrix. Our results contrast with Bach Ma National Park in central Vietnam, where Yen et al. [35] estimated forest loss was equally concentrated inside and outside Bach Ma's boundaries from 1973 to 2001. The fact that protected areas in the Central Highlands remained intact from 2000 to 2020 shows progress towards Vietnam's continued commitment to protecting their natural environment.

While the Central Highlands have become significantly warmer for at least the past 50 years, fires have not increased at the same rate. From 1971 to 2010, Vietnam's mean annual temperature increased by 0.026 ± 0.01 °C, roughly twice the rate of global temperature increases [24]. In Lam Dong province, mean annual temperature increased by 0.027 °C from 1971 to 2010 and by 0.028 °C from 1971 to 2020 [29]. While highly variable across Vietnam, minimum and maximum temperatures have significantly increased in Lam Dong and the rest of the Central Highlands since 1971 [29,35]. Although precipitation has generally declined across Vietnam and in the Central Highlands, trends have been insignificant [29,35].

Despite insignificant annual trends, fire seasonality in Vietnam is closely related to monsoonal precipitation during the distinct 'wet' and 'dry' seasons across the country's climatic sub-zones. In our study, fire ignitions coincided with the driest months, November to April. Our linear model predicted more than 40% of annual variation in burned area from seasonal climate, demonstrating the importance of intra-annual variability to drive inter-annual fire patterns.

Vietnam's mean annual temperature peaked during most El Nino phases, including 1987 to 1988, 1997 to 1998, and 2009 to 2010 [36]. El Niño is marked by drought conditions in central and southern Vietnam, while La Nina phases are much wetter [37]. The climatic effects of ENSO are much more pronounced in central and southern Vietnam than in the north [37]. Central Vietnam's precipitation is strongly affected by ENSO, with a 10 to 30% reduction and a 9 to 19% increase in autumn rainfall during the El Niño and La Nina phases [38]. Fire ignitions, burned areas, and fire-linked forest loss peaked in our study area in 2010 and 2011, evidence that warm, dry El Niño conditions are strong drivers of the regional fire regime. Sustained high temperatures and low precipitation during the El Nino phase have affected the regional fire climate into at least the following year.

A primary limitation of our study was omission and commission errors from remotely sensed data. Forest loss is defined in GFC as "a stand-replacement disturbance or the complete removal of tree cover canopy at the Landsat pixel scale". We chose not to use a canopy cover threshold to define forest loss to keep all forest loss data available from GFC and for consistency with the dataset's original methods [1]. Our approach to delineating fire-related forest loss was deliberately conservative and possibly underestimates deforestation by fires in the years directly before or after a fire. We used this method to avoid compounding errors between multiple years of distinct data products. Inherently, integration of distinct datasets produced from distinct source data at different resolutions can propagate errors and introduce non-uniform bias to any study.

Furthermore, Vietnam has a consistently high cloud cover, which can complicate cloud-free image acquisition at regular intervals [19]. Our study's integration of remotely sensed data and GIS analyses required converting raster to vector data, which may result in area differences from the original raster format [39,40]. This type of error was unavoidable in our study because GFC [1] and the LULC maps [27] are rasters and FIRED VIETNAM [22] is a database of polygons. There is no universal answer, and while quantitative differences between raster and vector analyses may be statistically significant, they are unlikely to affect the interpretation of landscape assessment [28]. Ground-truthing was impossible due to COVID-19 travel restrictions, but we manually verified 200 deforestation points with Google Earth imagery, following the verification methods of prior studies in the region [19].

5. Conclusions

Tropical forest ecosystems sequester carbon and are often biodiversity hotspots, with uncertain futures owing to climate change and land-use conversion. As temperatures and aridity increase, it is essential to understand how fire regimes will change and how these changes will subsequently impact the planet's forests. Vietnam has committed to forest conservation by expanding its protected area network, and our results show regional success.

Our study combined remotely sensed datasets to examine regional relationships of deforestation and fire in Vietnam's Central Highlands region. We found that protected areas have been effective in shielding forests from deforestation, fires, and fire-linked deforestation in a region with a history of commodity-driven forest loss. Long term deforestation trends continued in the Central Highlands region from 2001 to 2020. However, in our study of protected areas and the land matrix, we found that, although the corridor between protected areas has become largely deforested since 2000, forest cover in protected areas has remained relatively intact. Additionally, while fires frequently occurred across the landscape, only a small fraction were related to forest loss. Based on the prevalence of fires in the matrix compared to protected areas, our study provides evidence of a primarily human-driven fire regime.

Author Contributions: Co-Authors of this paper contributed in the following capacities. Conceptualization, S.J.E., H.V.S. and P.Z.F.; methodology, S.J.E., A.B.S. and P.Z.F.; software, S.J.E., A.B.S. and P.Z.F.; validation, S.J.E., A.B.S., H.V.S. and P.Z.F.; formal analysis, S.J.E., A.B.S. and P.Z.F.; investigation, S.J.E., A.B.S. and P.Z.F.; resources, S.J.E., A.B.S., H.V.S. and P.Z.F.; data curation, S.J.E., A.B.S. and P.Z.F.; writing—original draft preparation, S.J.E., A.B.S. and P.Z.F.; writing—review and editing, S.J.E., A.B.S., H.V.S. and P.Z.F.; visualization, S.J.E., A.B.S. and P.Z.F.; supervision, P.Z.F.; project administration, S.J.E. and P.Z.F.; funding acquisition, S.J.E. and P.Z.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Northern Arizona University, Minor Professorship and the International Association of Wildland Fire (IAWF) Graduate Student Scholarship.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All parent datasets used in this project are publicly available. Data layers and analysis scripts will be hosted at the NAU OpenKnowledge portal.

Acknowledgments: The authors acknowledge the late Yeon-Su Kim, who was part of S. Ebright's graduate advisory committee. Kim helped to make valuable personal connections and provided insight from her ecological economic research in Southeast Asia. We would also like to acknowledge Alicia Azpeleta-Tarancón who stepped up as a graduate committee member, to fill Yeon-Su Kim's role; and who has supported the research group. We thank two anonymous reviewers who helped improve the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Hansen, M.C.; Potapov, P.V.; Moore, R.; Hancher, M.; Turubanova, S.A.; Tyukavina, A.; Thau, D.; Stehman, S.V.; Goetz, S.J.; Loveland, T.R.; et al. High-resolution global maps of 21st-century forest cover change. *Science* **2013**, *342*, 850–853. [CrossRef] [PubMed]
2. Curtis, P.G.; Slay, C.M.; Harris, N.L.; Tyukavina, A.; Hansen, M.C. Classifying drivers of Global Forest Loss. *Science* **2018**, *361*, 1108–1111. [CrossRef]
3. Kim, D.-H.; Sexton, J.O.; Townshend, J.R. Accelerated deforestation in the humid tropics from the 1990s to the 2000s. *Geophys. Res. Lett.* **2015**, *42*, 3495–3501. [CrossRef] [PubMed]
4. van Wees, D.; van der Werf, G.R.; Randerson, J.T.; Andela, N.; Chen, Y.; Morton, D.C. The role of fire in global forest loss dynamics. *Glob. Change Biol.* **2021**, *27*, 2377–2391. [CrossRef] [PubMed]
5. Andela, N.; Morton, D.C.; Giglio, L.; Paugam, R.; Chen, Y.; Hantson, S.; van der Werf, G.R.; Randerson, J.T. The global fire atlas of individual fire size, duration, speed and direction. *Earth Syst. Sci. Data* **2019**, *11*, 529–552. [CrossRef]
6. Moritz, M.A.; Batllori, E.; Bradstock, R.A.; Gill, A.M.; Handmer, J.; Hessburg, P.F.; Leonard, J.; McCaffrey, S.; Odion, D.C.; Schoennagel, T.; et al. Learning to coexist with wildfire. *Nature* **2014**, *515*, 58–66. [CrossRef]
7. Flannigan, M.; Cantin, A.S.; de Groot, W.J.; Wotton, M.; Newbery, A.; Gowman, L.M. Global wildland fire season severity in the 21st century. *For. Ecol. Manag.* **2013**, *294*, 54–61. [CrossRef]
8. Jolly, W.M.; Cochrane, M.A.; Freeborn, P.H.; Holden, Z.A.; Brown, T.J.; Williamson, G.J.; Bowman, D.M. Climate-induced variations in global wildfire danger from 1979 to 2013. *Nat. Commun.* **2015**, *6*, 7537. [CrossRef]
9. Liu, Y.; Stanturf, J.; Goodrick, S. Trends in global wildfire potential in a changing climate. *For. Ecol. Manag.* **2010**, *259*, 685–697. [CrossRef]
10. Giglio, L.; Boschetti, L.; Roy, D.P.; Humber, M.L.; Justice, C.O. The Collection 6 MODIS burned area mapping algorithm and product. *Remote Sens. Environ.* **2018**, *217*, 72–85. [CrossRef]
11. van Lierop, P.; Lindquist, E.; Sathyapala, S.; Franceschini, G. Global Forest area disturbance from fire, insect pests, diseases and severe weather events. *For. Ecol. Manag.* **2015**, *352*, 78–88. [CrossRef]
12. Lewis, S.L. Tropical forests and the changing earth system. *Philos. Trans. R. Soc. B Biol. Sci.* **2005**, *361*, 195–210. [CrossRef] [PubMed]
13. Estoque, R.C.; Ooba, M.; Avitabile, V.; Hijioka, Y.; DasGupta, R.; Togawa, T.; Muryama, Y. The future of Southeast Asia's forests. *Nat. Commun.* **2019**, *10*, 1829. [CrossRef] [PubMed]
14. Streets, D.G.; Yarber, K.F.; Woo, J.H.; Carmichael, G.R. Biomass burning in Asia: Annual and seasonal estimates and atmospheric emissions. *Glob. Biogeochem. Cycles* **2003**, *17*, 1099. [CrossRef]
15. Vadrevu, K.P.; Lasko, K.; Giglio, L.; Schroeder, W.; Biswas, S.; Justice, C. Trends in Vegetation fires in South and Southeast Asian Countries. *Sci. Rep.* **2019**, *9*, 7422. [CrossRef]
16. Sterling, E.J.; Hurley, M.M.; Minh, L.D. *Vietnam: A Natural History*; Yale University Press: London, UK, 2006.
17. Ngo, D.T.; Le, A.V.; Le, H.T.; Stas, S.M.; Le, T.T.C.; Tran, H.D.; Pham, T.; Le, T.T.C.; Spracklen, B.D.; Langan, C.; et al. The potential for REDD+ to reduce forest degradation in Vietnam. *Environ. Res. Lett.* **2020**, *15*, 074025. [CrossRef]
18. Khuc Q van Tran, B.Q.; Meyfroidt, P.; Paschke, M.W. Drivers of deforestation and forest degradation in Vietnam: An exploratory analysis at the national level. *For. Policy Econ.* **2018**, *90*, 128–141. [CrossRef]
19. Vogelmann, J.E.; van Khoa, P.; Lan, D.X.; Shermeyer, J.; Shi, H.; Wimberly, M.C.; Duong, H.T.; van Huong, L. Assessment of forest degradation in Vietnam using Landsat time series data. *Forests* **2017**, *8*, 238. [CrossRef]
20. Meyfroidt, P.; Lambin, E.F. The causes of the reforestation in Vietnam. *Land Use Policy* **2008**, *25*, 182–197. [CrossRef]
21. Tyukavina, A.; Potapov, P.; Hansen, M.C.; Pickens, A.H.; Stehman, S.V.; Turubanova, S.; Parker, D.; Zalles, V.; Lima, A.; Kommareddy, I.; et al. Global trends of forest loss due to fire from 2001 to 2019. *Front. Remote Sens.* **2022**, *3*, 825190. [CrossRef]
22. Mahood, A.L.; Lindrooth, E.J.; Cook, M.C.; Balch, J.K. Country-level fire perimeter datasets (2001–2021). *Sci. Data* **2022**, *9*, 458. [CrossRef] [PubMed]
23. Rambaldi, G.; Bugna, S.; Geiger, M. Review of the Protected Area System of Vietnam. *Asean Biodivers.* **2015**, *1*, 43–51.
24. Bridgewater, P.; Phillips, A. *Biosphere Reserves and the IUCN System of Protected Area Management Categories*; IUCN: Gland, Switzerland, 1996.
25. Balch, J.K.; St Denis, L.A.; Mahood, A.L.; Mietkiewicz, N.P.; Williams, T.M.; McGlinchy, J.; Cook, M.C. FIRED (Fire events delineation): An open, flexible algorithm and database of us fire events derived from the modis burned area product (2001–2019). *Remote Sens.* **2020**, *12*, 3498. [CrossRef]
26. Giglio, L.; Schroeder, W.; Justice, C.O. The collection 6 MODIS active fire detection algorithm and fire products. *Remote Sens. Environ.* **2016**, *178*, 31–41. [CrossRef] [PubMed]
27. Phan, D.C.; Trung, T.H.; Truong, V.T.; Sasagawa, T.; Vu, T.P.T.; Bui, D.T.; Hayashi, M.; Tadono, T.; Nasahara, N.K. First comprehensive quantification of annual land use/cover from 1990 to 2020 across mainland Vietnam. *Nature* **2021**, *11*, 9979. [CrossRef] [PubMed]
28. UNEP-WCMC; IUCN. *Protected Planet: [The World Database on Protected Areas (WDPA)] [On-Line], [October 2022]*; UNEP-WCMC and IUCN: Cambridge, UK, 2022.
29. Hersbach, H.; Bell, B.; Berrisford, P.; Hirahara, S.; Horányi, A.; Muñoz-Sabater, J.; Nicolas, J.; Peubey, C.; Radu, R.; Schepers, D.; et al. The ERA5 global reanalysis. *Q. J. R. Meteorol. Soc.* **2020**, *146*, 1999–2049. [CrossRef]

30. Forest Declaration Assessment Partners. Forest Declaration Assessment: Are We on Track for 2030? *Climate Focus (Coordinator and Editor)*. 2022. Available online: https://www.forestdeclaration.org (accessed on 25 October 2022).
31. UN Climate Summit 2014. The New York Declaration on Forests. 23 September 2014. Available online: https://forestdeclaration.org/wp-content/uploads/2021/08/NYDF_Declaration.pdf (accessed on 3 November 2022).
32. UN Climate Change Conference 2021. Glasgow Leaders' Declaration on Forests and Land Use. 2 November 2021. Available online: https://ukcop26.org/glasgow-leaders-declaration-on-forests-and-land-use (accessed on 3 November 2022).
33. Cochard, R.; Ngo, D.T.; Waeber, P.O.; Kull, C.A. Extent and causes of forest cover changes in Vietnam's provinces 1993-2013: A review and analysis of official data. *Environ. Res. Lett.* **2017**, *25*, 199–217. [CrossRef]
34. Liu, Z.; Ballantyne, A.P.; Cooper, L.A. Biophysical feedback of global forest fires on surface temperature. *Nat. Commun.* **2019**, *10*, 214. [CrossRef]
35. Yen, M.C.; Chen, T.C.; Hu, H.L.; Tzeng, R.Y.; Dinh, D.T.; Nguyen, T.T.T.; Wong, C.J. Interannual variation of the fall rainfall in Central Vietnam. *J. Meteor. Soc. Jpn.* **2011**, *89A*, 259–270. [CrossRef]
36. Nguyen, D.-Q.; Renwick, J.; McGregor, J. Variations of surface temperature and rainfall in Vietnam from 1971 to 2010. *Int. J. Climatol.* **2013**, *34*, 249–264. [CrossRef]
37. Vu-Thanh, H.; Ngo-Duc, T.; Phan-Van, T. Evolution of meteorological drought characteristics in Vietnam during the 1961–2007 Period. *Theor. Appl. Climatol.* **2014**, *118*, 367–375. [CrossRef]
38. Vu, T.V.; Nguyen, H.T.; Nguyen, T.V.; Nguyen, H.V.; Pham, H.T.; Nguyen, L.T. Effects of ENSO on autumn rainfall in central Vietnam. *Adv. Meteorol.* **2015**, *2015*, 264373. [CrossRef]
39. Wade, T.G.; Wickham, J.D.; Nash, M.S.; Neale, A.C.; Ritters, K.H.; Jones, K.B. A Comparison of Vector and Raster GIS Methods for Calculating Landscape Metrics Used in Environmental Assessments. *Photogramm. Eng. Remote Sens.* **2003**, *12*, 1399–1405. [CrossRef]
40. Auradkar, P.K.; Raykar, A.; Agarwal, I.; Sitaram, D.R. Accuracy assessment and performance analysis of raster to vector conversions on LULC data—India. *J. Eng. Des. Technol.* **2021**, *20*, 1787–1809. [CrossRef]