Photo: Slocomb (2010)

Effects of armed conflict on forest cover and vegetation seasonality in Cambodia

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Abstract

Armed conflicts have definitive wide-ranging and diverse impacts on the environment. This thesis examines associations between conflict and land cover change in Cambodia, focusing on the last decade (1989 - 1998) of a thirty-year long Civil War. This was done by comparing trends in forest cover and vegetation seasonality between two regions of Cambodia; one conflict zone, and one no-conflict zone, as well as comparing trends over conflict and post-conflict periods. A satellite-based remote sensing approach of changes in the maximum and integrated normalized difference vegetation index (NDVI) was used to construct time-series and perform regression analysis for both zones on a provincial level. Maximum NDVI was used to classify forest cover, while the integrated NDVI was used to define vegetation seasonality. The results show that trends in forest cover and vegetation seasonality were not significantly different between the conflict and no-conflict zones during the conflict. Vegetation seasonality in the conflict zone increased significantly after the conflict, and significantly more so than in the no-conflict zone.

Acknowledgements

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Introduction

The number of armed conflicts with at least one thousand reported casualties annually more than tripled between 2007 and 2018 (World Bank and United Nations, 2018). Research identifying and examining the impact armed conflicts have on ecosystems and the environment has increased accordingly (Baumann & Kuemmerle, 2016). This has highlighted both the drastic effects armed conflicts have had on respective ecosystems and land use, while also showing the diverse nature of these consequences (Baumann & Kuemmerle, 2016; Machlis & Hanson, 2008).

Armed conflicts typically have a detrimental effect on ecosystems; oil spills, destruction by bombs and weapons, as well as the use of defoliation agents such as napalm are major components of environmental damage due to modern warfare (Freedman, 2003). Studies have confirmed a causative link between environmental degradation and recent wars; their occurrence amplifying interactions between ecosystem vulnerability, and resource dependence (Dudley et al., 2002; Machlis & Hanson, 2008). A study conducted by the United Nations Environment Programme (UNEP) in 2007 concerning the still ongoing armed conflict in Darfur, Sudan found that the conflict had contributed directly to land degradation and desertification (Programme des Nations Unies pour l'environnement, 2007; Machlis & Hanson, 2008). Armed conflicts have been associated with negative effects on biodiversity; areas under conservation enveloped in the fighting can lead to armies on both sides using natural resources to fund the continuation of the war (Baumann & Kuemmerle, 2016; Gleditsch, 1998; Hanson et al., 2009; Irland, 2008). Natural resources often become subject to collateral damage or are deliberately selected as targets to undermine a nation's ability to continue the war (Lamb 1985; United Nations Environment Program 2007). Political instability and the resulting lack in authority and organization to effectively govern resource extraction coupled with rising corruption is common both during and after a conflict (Gleditsch *et. al.* 1998). Especially in war-torn zones, local economies and the financing of the conflict are often tied to the export of natural resources (Collier, 2000).

Loss of forest ecosystems represents the greatest detriment to the environment suffered from armed conflicts (Baumann & Kuemmerle, 2016). Forests are key to the functionality of water, carbon and energy cycles on earth (Pan et al., 2018). Forests specifically are important sites of biodiversity and provide ecosystem services, functioning as a natural buffer to both soil erosion and flooding. Forests represent a major carbon sink, storing large amounts of organic carbon (Gibbs, and Herold, 2007). Conversely, their destruction results in the release of carbon dioxide, methane, and nitrous oxides, leading to an increased heat absorption potential in the atmosphere (Fearnside and Laurance, 2004). Deforestation of tropical forests threatens ecological sustainability and socioeconomic development in the long term, while presenting adverse economic and social effects (Mertens & Lambin 1997; Myers, 1980; Grainger 2013). Land use change, and particularly the conversion of forests to cropland affects plant and soil nitrogen dynamics, as well as carbon-nitrogen interactions (Smith et al. 2014). Globally, the expansion of agriculture has created greater vegetation seasonality and variability (Baldi et al 2015), resulting in decreasing carbon residence times (Zhang et al. 2016), and changes in carbon use efficiency (Tang et al. 2019). This leads to an alteration of the land carbon balance and presents risks to ecosystem health (Zhou & Luo, 2008; Smith et al. 2014).

Armed conflicts have also been shown to maintain complex relationships with ecosystem and land use change, and have been associated with both cases of increased deforestation rates, and cases of forest recovery (Baumann & Kuemmerle, 2016). Increases in conflict intensity between warring factions in Cambodia in 1989 has been associated with a decrease in the exports of Cambodian timber in that year, fighting disturbing logging operations (Le Billon 1999). Robin Burgess et al. (2015) utilized satellite data coupled with data from a conflict mapping project to find that deforestation decreased during the civil war in Sierra Leone between 1991 and 2002 when compared to before the conflict. This was linked to the conflict causing movements of refugees away from the area. This phenomenon is known as the "warzone-refuge" effect; where displacement of populations away from the area essentially can allow for ecosystem regeneration as economic activities such as timber production and clear cutting of forested areas to make way for cropland are halted (Dudley et al., 2002). Consequently, large scale abandonment of cultivated areas can become common, allowing forest to regenerate (Dudley et al., 2002).

An analysis of remaining forested areas in Columbia in relation to armed conflict noted that paramilitary groups employ both "gunpoint conservation" of forested areas, and conversion of forests and crops to make room for coca plantations and cattle ranches (Alvarez, 2003: Burgess *et al* 2014). Thus, the state of conflict can drive simultaneous opposing patterns from forest conservation to destruction; armed groups may be motivated to maintain vegetation cover masking the movement of troops and supplies from opposing forces; while logging or clearing forests and cropland in other areas to make room for more lucrative land use types as sources of income to fund the continuation of the respective conflict also occurs (Alvarez, 2003: Burgess *et al* 2014). Eklund *et al.* (2017) used remote sensing techniques studying vegetation seasonality, and found that in the areas seized by the Islamic State (IS) in Syria and Iraq, vegetation seasonality has increased because of cropland expansion. Agriculture became a major source of income for the IS; cropland abandoned by people fleeing the fighting was cultivated by the IS, while remaining landowners were motivated to keep cultivating and even increase harvesting intensity as more areas became double cropped (with two harvest periods annually), as opposed to single cropped (one harvest period) (Eklund *et al.* 2017). Thus, conflicts have diverse impacts on land use change and forest cover.

The effect of the Civil War in Cambodia on the nation's forests are disputed (Le Billon 1999; Slocomb 2010). The conflict has been described as having had a dampening effect on the loss of forest cover in the 1980's, due to economic sanctions imposed on Cambodia by the United Nations limiting export of timber abroad (Le Billon 1999). Despite this, literature on the topic of conflict has also pointed out that during the 1990's, the conflict was fueled largely by the commodification of the nation's forests (Le Billon 1999, 2000, & 2001). Both sides; the Khmer Rouge and allied factions, and the Cambodian government forces conducted logging as a major source of income (Slocomb 2010). The conflict displaced hundreds of thousands of people, causing both permanent and temporary emigration, mainly to Thailand (Slocomb 2010). Forests that historically covered three-quarters of Cambodian land area, declined considerably throughout the conflict, although sources differ on the severity of the loss (Cambodian Forestry Administration; Tsujino et al. 2019). Following the end of the conflict, the trend of declining forest cover and loss of ecosystems did not improve, with data showing a continued decline at times even more drastic than throughout the conflict, as palm oil and rubber plantations, as well as seasonal crops began to expand at unprecedented rates (Cambodian Forestry Administration; Tsujino et al. 2019).

This study aims to examine the effects of conflict on forest cover and land use change in Cambodia, a nation that is underrepresented in this area of research despite having registered the highest deforestation rate among Southeast Asian nations between 1990 and 2015; losing forest cover at a rate of -0.79 % /year (Tsujino et al. 2019: FAO 2015), and suffering from a Civil War that lasted three decades (Slocomb 2010).

A conflict georeferenced event dataset is applied on a provincial level within Cambodia, for the period of the conflict where data is available, from 1989 - 1998, to identify areas with the greatest share of the fighting. Thus, a conflict zone comprising five provinces with the highest conflict intensity is selected for comparison against five provinces with low to no conflict intensity.

A satellite imagery-based remote sensing approach with ordinary least-squares (OLS) regression and time-series analysis is used to investigate trends in forest cover and vegetation seasonality during and after the conflict. The trends are then compared between both zones during the conflict period (1989 - 1998), and with trends after the conflict (1999 - 2015), to discern differences between conflict and no-conflict zonal, and inter and post-conflict trends.

I hypothesize the following relationships in forest cover and vegetation seasonality between the conflict and no-conflict zones in Cambodia during the conflict period (1989 - 1998):

(1) More forest cover loss in the no-conflict zone than in the conflict zone as the pace of timber extraction is disrupted by the fighting, and since refugees also leave the conflict region, decreasing pressure on forest resources.
(2) Loss in vegetation seasonality in the conflict zone as abandonment of cropland leads to a decline in vegetation growth over the growing season.

I hypothesize the following relationships in forest cover and vegetation seasonality trends between the conflict (1989 - 1998) and post-conflict (1999 - 2015) periods:

(3) (a) Higher forest cover loss rates in the conflict zone during the post-conflict period as compared to during the conflict as timber production is no longer disrupted by the fighting. (b) Gains in vegetation seasonality in the conflict zone during the post-conflict period as populations previously displaced by the conflict return, increasing pressure on forest resources and converting forests to agricultural land, and recultivating formerly abandoned land.
(4) (a) A greater change in forest cover between the conflict to post-conflict period in the conflict zone than in the no-conflict zone; for the same reasons as in hypothesis 3a. (b) A greater change in vegetation seasonality between the conflict to post-conflict periods in the conflict zone than in the no-conflict zone for the same reasons as stated in hypothesis 3b. Conditions affecting forest cover and crop cultivation are assumed to remain constant over the conflict and post-conflict periods in the no-conflict zone.

Theoretical Background

Uppsala University's Conflict Data Program (UCDP) database is the leading global standard for crisis reporting concerning casualties in relation to specific conflict events (Croicu & Sundberg, 2015; Sundberg & Melander, 2013). The UCDP defines an armed conflict as *"any incident where armed force was used by an organized actor against another organized actor, or against civilians, resulting in at least one direct death at a specific location and a specific date"* (Sundberg & Melander, 2013). The UCDP Georeferenced Event Dataset (GED) differentiates between three types of conflicts: state-based, non-state, and one-sided conflict for conflict events within the period 1989–2014 on global soils. Identified conflict events and respective casualty reporting utilizes an interconnected web of international news reporting as well as of local media reporting such as radio; which was a prevalent method within the data gathered for the Cambodian Civil War. Casualty estimates range between a minimum and maximum count, while a "best-guess" estimate is based on data cross-referenced between sources giving a corresponding value.

State-based conflict is defined as a "*contested incompatibility that concerns government and/or territory where the use of armed force between two parties, of which at least one is the government of a state*" (Sundberg & Melander, 2013).

One-sided violence is defined as "*The deliberate use of armed force by the government of a state or by a formally organized group against civilians which results in at least 25 deaths in a year"* (Sundberg & Melander, 2013).

Conflict background

Cambodia and the Cambodian people were subjected to nearly three decades of civil war that facilitated the rise of the Khmer Rouge (Slocomb 2010). Initially, conflict in Vietnam spilled over into Cambodia, leading to political instability and a civil war in 1968 that took until 1998 to subside completely (Pike 2020).

The conflict and continued activity by the Khmer Rouge in the 1980's made Cambodia a pariah state in terms of international relations; enduring heavy embargoes on development aid and international trade by Western countries and the Association of Southeast Asian Nations (ASEAN) (Le Billon 1999). This limited the export of Cambodian timber to western markets (Slocomb 2010; Le Billon 1999). Phillipe le Billon makes the argument that the conflict may have had an effect of conservation on the nation's forests by delaying their commodification. The economic sanctions placed on Cambodian timber may have spared forests from the scale of timber exploitation fueling economic growth in other Southeast Asian countries throughout the 1980's (Le Billon 1999). The end of the Cold War however, marked a change in global policy; as international influence in Cambodia waned, timber became the source of domestic political and economic power (Le Billon 1999; Slocomb 2010). Cambodian timber as a prized commodity internationally motivated growing commercial logging operations, which began to take their toll on Cambodian forests (Slocomb 2010; Le Billon 1999). At the same time, peace negotiations resulting in the signing of the Comprehensive Political Settlement of the Cambodia Conflict by Cambodia, members of the UN Security Council, and ASEAN countries in Paris on October 23, 1991, gradually allowed for improved access to international markets and improved Cambodian economic relationships abroad as trade embargoes lifted, even though the Peace Agreements were continually breached, with fighting continuing until 1998 (Le Billon 2000; Slocomb 2010). The timber trade in Cambodia has been described as facilitating the continuation of the conflict during the 1990's (Le Billon 1999; le Billon 2000).

Even though the fighting during the conflict period (1989-1998) did not persist on the same scale as it had earlier in the conflict, the conflict continued to displace populations (Pike 2020). When the fighting began to subside, refugees returning to the Northwestern Tonlé Sap region resulted in an up to 40% increase in population in some provinces, with over 100,000 "very recent" rural migrants reported in 1998 according to a population census (Slocomb 2010).

Upon the dissolution of the Khmer Rouge by 1998 and the onset of peace, the forested lands used as bases by the Khmer Rouge in the Northwest changed hands to the government of Cambodia, which were to be included in the nation's economic reconstruction (Slocomb 2010; Le Billon 2000). The economic reconstruction rested largely on the expropriation of the country's forested land, with officially over 4,7 million hectares (47,000 square kilometers, over a quarter of the country's total area of 181,000 square kilometers) granted to private companies for long-term investment by the year 2000 according to the Cambodian Ministry of Agriculture, Forestry, and Fisheries (MAFF) (Slocomb 2010). The concession system in place drew increased international attention to Cambodian forests. Land concessions in Cambodian forests to private companies for long-term development became a major source of income for the Cambodian government and facilitated large scale overexploitation of forests (Slocomb 2010).

Development initiatives also lead to agricultural expansion via conversion of forested land to croplands (Slocomb 2010; *Le Cambodge Économique* (LCE). This is reflected in Cambodia's gross domestic product (GDP) of agricultural origin showing consistent increases as reported by the World Bank during this time (Slocomb 2010; *Le Cambodge Économique* (LCE). Timber production figures range considerably, although typically showing the highest figures during the conflict (Tsujino et al. 2019). Estimated export values reach record highs between 2009 and 2011; the estimated value of timber exports reported by the RGC, Thai Forestry Department and Global Witness from 1990 - 1998, and World Bank from the year 2000 - 2016 (Slocomb 2010; The World Bank 2000) reaching three to four times that of the highest estimated export values during the conflict. Increases in estimated timber export value may not necessarily equate to an increase in production however, as the value of Cambodian timber likely fluctuated with changing demand centers.

Estimates of forest cover losses nationally range considerably, declining from the 1960's forestry reports listing 73% of Cambodia's area being covered by forests to widely ranging estimates of forest cover set at 30% and 63% in 1995 respectively by Global Witness and Japan Forest Technical Association (JAFTA), with a reconstruction of forest loss in Cambodia estimating 47,3% coverage remaining in 2016 (Tsujino et al. 2019). Statistics on timber production show the highest figures throughout the conflict during the 1990's, declining following the end of the conflict in 1998 and remaining significantly lower until the end of the dataset in 2016 (Cambodian Forestry Administration). Illegal and unreported logging however played a role in timber production, estimated to be responsible for 62% of the forest loss between 2009 and 2014 alone, over 1 million hectares (Tsujino et al. 2019). The remaining 38% is explained by arable land expansion, including permanent crops such as palm oil and rubber plantations (Tsujino et al. 2019). Tsujino et al. note that the Food and Agriculture Organization of the United Nations (FAO) list Cambodian timber production exported abroad in 1997 at 468,000 m^3, while other analysts estimate 3-4 million m^3 illegally harvested timber during that year alone (Lang & Chan 2006; Tsujino et al. 2019).

Remote sensing & NDVI

The Normalized Difference Vegetation Index (NDVI) has been implemented to facilitate monitoring of vegetation since the early 1980s, and is the most commonly applied vegetation index of all satellite-based vegetation indices (Gandhi et al., 2015). The calculation of NDVI relates the amount of reflected near-infrared and red light received by a satellite sensor in the following way:

$$\text{NDVI} = (\text{NIR} - \text{Red}) / (\text{NIR} + \text{Red}) \tag{1}$$

Where NIR is the reflectance in the near-infrared wavelength range and Red is the reflectance in the red visible light wavelength range.

NDVI values range between values of +1.0 to -1.0. Negative values are attributed to water and cloud interference, while values between 0 and 0.1 define open soil, rock or sand (Gandhi et al., 2015). Values greater than 0.1 correspond to areas of increasing vegetation density. These values vary geospatially and seasonally in response to the plant growth phase (Jiang et al., 2008; Gandhi et al., 2015). The usage of NDVI and related indices provide an indication of vegetation type, density and health (Beck 2006). It is also the favored vegetation monitoring index on a global scale, as its standardized algorithm relating the absorption properties of near-infrared and red bands make-up for variable illumination conditions, surface slopes and viewing angles (Huete et al., 2002).

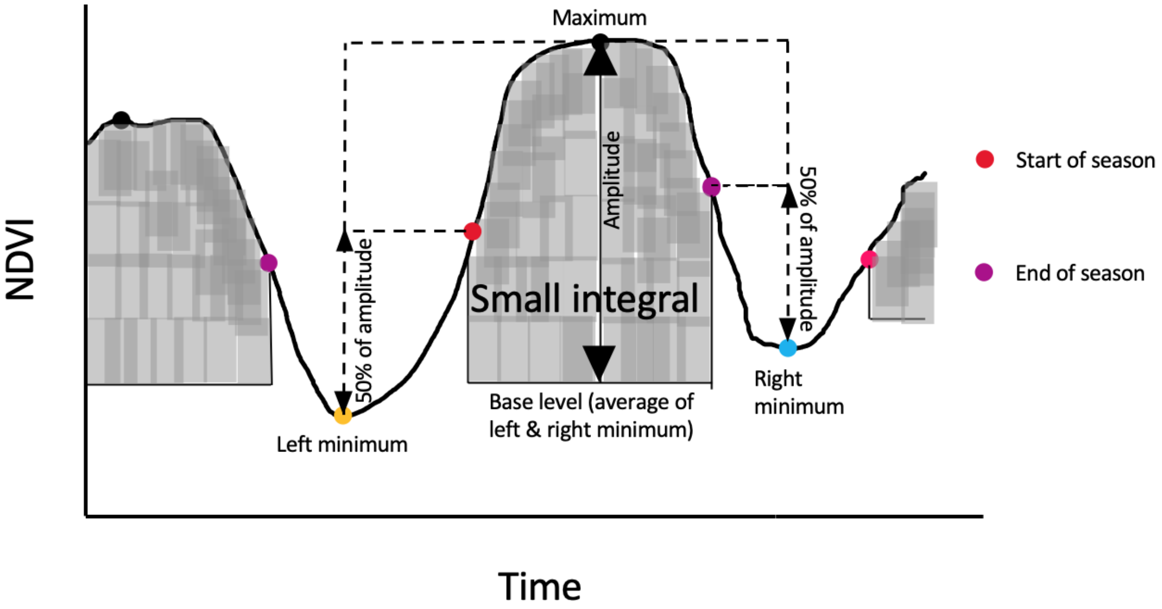
Sensors separate the radiance reflected by the ground surface into different spectral bands. Chlorophyll and other vegetation pigments absorb much of the visible light reaching the earth's surface, while near-infrared light is reflected back into the atmosphere (Gandhi et al., 2015). The reflective properties of vegetation are governed by the absorption spectra of chlorophylls a and b, as well as accessory pigments b-keratin, phycoerythrin and phycocyanin (Gandhi et al., 2015; Maggioni & Massari, 2019). For chlorophyll, the wavelengths with high absorption have been shown to be between 450 and 520 nanometers, as well as between 630 and 690 nanometers (Gandhi et al., 2015; Maggioni & Massari, 2019). A low amount of these pigments in a given plant tissue typically indicates poor health and results in a greater reflective reaction of red light, resulting in a lower NDVI value. Hence, reflected radiance can be used as an indicator of canopy cover, and to detect changes in the vegetation health and stage of growth (Jiang et al., 2008; Gandhi et al., 2015). By combining the reflective properties of red and near-infrared bands into a vegetation index, an indicator of vegetation density and productivity is created (Jiang et al., 2008; Gandhi et al., 2015). This is commonly used to differentiate between dense canopy cover versus more sparsely vegetated areas, as well as change over time (Jiang et al., 2008; Gandhi et al., 2015).

Time series analysis of NDVI allows for a standardized value related to vegetation type, health, and productivity to indicate change over space and time, and is thus valuable to global ecological and environmental applications (de Jong, de Bruin, de Wit, Schaepman, & Dent, 2011; Fensholt et al., 2015; Tian et al., 2013; Tian et al. 2016).

In this study, maximum annual NDVI and the small integral of the annual growing season NDVI were investigated.

The maximum annual NDVI is representative of the maximum rate of photosynthesis in the canopy extent of a region throughout a given year as a parameter of vegetation density (Jönsson, P. and Eklundh, L. 2004). Annual maximum NDVI has been shown to reflect the gradients of foliage and herbaceous biomass, and is commonly used to identify and track changes in forest cover (Tian et al. 2016). Nguyen Trong et al. (2020) utilized maximum NDVI in the remote sensing of tropical lowland forests in Vietnam, finding typical values to be 0.84 ± 0.02.

The small integral of the growing season NDVI is effectively the sum of the integral functions fitted to each respective growing season occurring throughout a respective year, minus the area below the base level (El-Vilaly et al. 2018). A schematic illustrating the calculation of the seasonal small integral NDVI is illustrated in ***figure 1*** (Jönsson, P. and Eklundh, L., 2004; Djurfeldt et al. 2018). This is a reflection of the green biomass produced over the entire growing season. (Djurfeldt et al., 2018; Jönsson, P. and Eklundh, L. 2004). The beginning of each growing season is defined by the point at which the left edge of the NDVI curve rises to a certain percent threshold of the seasonal amplitude. The end of season is defined as the point at which the right edge of the curve declines to a certain percent threshold of the seasonal amplitude from the right minimum (Djurfeldt et al., 2018; Jönsson & Eklundh 2004). The calculation of the integrated sum is defined as the area under the curve between the peak NDVI value and the average of the left and right minimum NDVI values for the season (Figure 1; Jönsson, P. and Eklundh, L. 2004).



Based on a sketch by Djurfeldt et all., (2018), in turn adapted from Jönsson & Eklundh (2004)

Figure 1: *TIMESAT parameters associated with the cumulative small integral of the growing season(s); amplitude, start and end of season, left and right minima, base level, small integral (Jönsson & Eklundh, 2004: Djurfeldt et al., 2018).*

Integrated NDVI has been shown to accurately estimate biomass increase during a season, and has been widely applied to the study of long term spatial patterns of vegetation greenness and productivity in relation to climatic factors (Zhang et al. 2016: De Jong et al. 2011; Tian et al., 2015; Tian et al. 2016). The integrated sum is a good indicator for vegetation seasonality and net primary production over the desired period (Jönsson, P. and Eklundh, L., 2004, Running and Nemani, 1988, Goward and Dye, 1987, Ruimy et al.,1994, Pettorelli et al. 2006, Justice et al. 1985, Myneni et al. 1997, Boelman et al. 2003). Vegetation seasonality is a combination of the amplitude and length of the growing season. A simultaneous decline in forest cover, yet an increase in small integral NDVI for example would imply a conversion of forested lands to cropland, as opposed to a loss in both parameters, which would indicate solely a logging of forests.

Material and Methods

Study area and conflict/post-conflict periods

The study area consists of a conflict zone and a no-conflict zone (***Figure 2***). The conflict zone includes the most heavily conflict-affected areas by reported casualties, located primarily in the Northwest. The provinces of Pailin, Battambang, Banteay Meanchey, Oddar Meanchey, and the central Cambodian province of Kampong Thom (Khmer: បៃលិន, បាត់ដំបង, បន្ទាយមានជ័យ, ឧត្តរមានជ័យ, កំពង់ធំ) are included in the conflict zone; representing the provinces with the highest reported casualties between 1989 and 1998. The least conflict-affected areas by reported casualties are located primarily within the eastern parts of the country; the provinces of Stung Treng, Ratanak Kiri, Mondul Kiri, Kratie, and Tboung Khmum (Khmer: ស្ទឹងត្រែង, រតនគិរី, ក្រចេះ, មណ្ឌលគិរី, ត្បូងឃ្មុំ) are included in the no-conflict zone.

Casualty reports stem from the Uppsala Conflict Data Program's (UCDP) georeferenced event dataset (Croicu & Sundberg, 2015; Sundberg & Melander, 2013). The UCDP database provides reports between 1989 and 2011 for Cambodia; yielding a total of 5,049 casualties attributed to primarily state-based violence; the vast majority of which occurred between 1989 and 1998, thus representing the conflict period. 1999 is the first year with zero reported casualties, and thus marks the beginning of the post-conflict period.

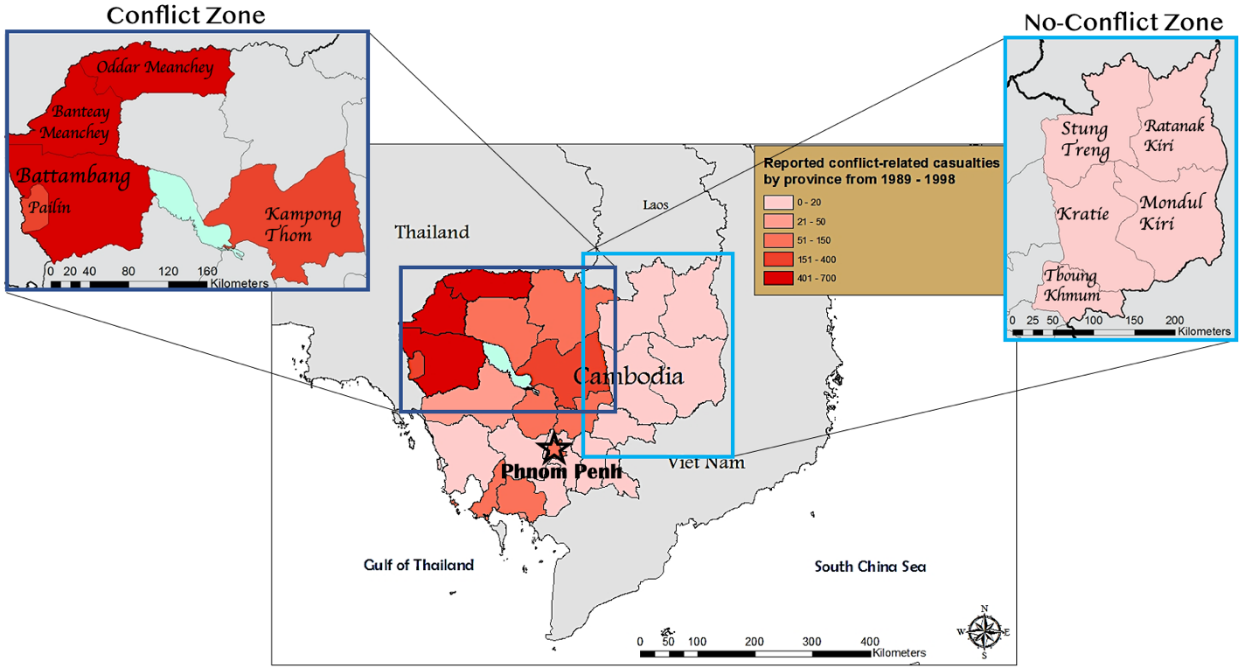


Figure 2: *Shown in red, Cambodian provinces are marked according to the number of casualties reported by the UCDP database during the period 1989 - 1998. Darker red signifies provinces with high amounts of casualties Lighter colors signify provinces least affected by the conflict.*

Data acquisition and preprocessing

Satellite based data acquired for this study stems from the Global Inventory Modeling and Mapping Studies (GIMMS) NDVI (Pinzon 2005). The GIMMS data spans from 1981 to 2015 on a global bi-monthly basis, and provides a maximum NDVI value for the first fifteen days of the month, and the maximum value for the remainder of the month (Pizon 2005). The spatial resolution of this data is one-twelfth of a degree. The data set features an NDVI product available for a 35-year period spanning from 1981 to 2015. The data set is derived from imagery obtained from the Advanced Very High Resolution Radiometer (AVHRR) instrument onboard the United States National Oceanic and Atmospheric Administration (NOAA) satellite series 7, 9, 11, 14, 16, and 17, and has been corrected for calibration, view geometry, volcanic aerosols, and other effects not related to vegetation change (Pizon 2005).

For gap-filling and smoothing of the quality filtered GIMMS 3g NDVI time series, the TIMESAT software was used with the double logistic fitting method (Jönsson and Eklundh 2004). The double logistic method smoothes curves of the seasonality based on intervals around maxima and minima in the time series, lowering sensitivity to noise (Jönsson and Eklundh 2004). This method was reported to perform well on time series that do not have a well-known quality and are prone to noise contamination caused by long periods of snow cover and persistent cloud cover (Beck et al. 2006; Jönsson and Eklundh 2004; Zeng et al. 2011). The parameters applied in TIMESAT were: seasonal parameter = 0.5, number of envelope iterations = 2, adaptation strength = 2, Savitzky–Golay window size = 4, start of growing season = 0.2, end of growing season = 0.2. For a description of the meaning of the parameters, see Jönsson and Eklundh (2004). To remove outliers from the NDVI time series, a spike method of median filter was employed with the spike parameter set to two. From these smoothed time series, the annual maximum NDVI was extracted as a proxy of the density of green vegetation, and the small seasonal integral was extracted as a proxy for vegetation seasonality (Pizon, 2005).

Data are consolidated pixel-wise annually; to be represented as a pixel with natural pristine forest cover (hereinafter simply forest cover), a pixel must reach a maximum NDVI of at least 0.8 (Nguyen et al., 2020). The total forest cover and vegetation seasonality are summed for each province annually, and then organized into time series, with both a forest cover and cumulative vegetation seasonality value discerned for each year between 1989 and 2015. Changes in forest cover were estimated as a percentage of the amount of initial forest cover from the first year of the time-series in 1989 for each respective province. This was done to convert an absolute change into a relative one, to normalize for provinces with large and small forest cover. A similar procedure was done for the vegetation seasonality; provinces of larger areas typically have more vegetative cover; thus, absolute changes in vegetation seasonality are converted to a relative percentage change of the vegetation seasonality observed in 1989.

Statistical analysis

Hypothesis 1: Differences in forest cover trends between zones during the conflict

The first hypothesis states that the trends of forest cover loss during the conflict period (1989 – 1998) will be greater in the no-conflict zone than in the conflict zone. Ordinary Least-Squares linear (OLS) Regressions were fitted to estimate trends in forest cover change for each province; the rates of forest cover change of the five provinces in the conflict zone are compared against the five rates of forest cover change associated with the five provinces of the no-conflict zone. A two-sample t-test is performed, to test for trends in forest cover loss being significantly greater in the no-conflict zone compared to the conflict zone. A p-value (α) of 0.05 was used throughout the statistical analysis as the significance threshold to test the hypotheses.

Hypothesis 2: Differences in vegetation seasonality trends between zones during the conflict

The second hypothesis states that vegetation seasonality during the conflict period will decline more in the conflict zone than in the no-conflict zone. Ordinary Least-Squares linear regressions are fitted to the vegetation seasonality data during the conflict period to estimate trends for each province during the conflict. The rates of change in vegetation seasonality of the five provinces in the conflict zone are compared against the rates change in vegetation seasonality associated with the five provinces of the no-conflict zone. A two-sample t-test is performed, to test for trends in vegetation seasonality being significantly lower in the conflict zone when compared to the no-conflict zone.

Hypothesis 3a & 3b: Differences in trends between conflict and post-conflict periods for the conflict zone

Ordinary Least-Squares Linear Regressions are fitted to the change in forest cover and vegetation seasonality for the post-conflict (1999-2015) period in the conflict zone to estimate trends for each province and compare with trends in both parameters during the conflict period (1989-1998). The net difference in trends from the conflict to post-conflict period is calculated for each province.

Hypothesis 3a is tested by performing a two-tailed paired t-test testing for the net difference in trends in forest cover being negative (<0) from the conflict to post-conflict period.

Hypothesis 3b is tested by performing a two-tailed paired t-test testing for the net difference in trends in vegetation seasonality being positive (>0) from the conflict to post-conflict period.

Hypothesis 4a & 4b: Differences in trends between conflict and post-conflict periods compared between zones

Ordinary Least-Squares Linear Regressions are fitted to the change in forest cover and vegetation seasonality post-conflict in the no-conflict zone to compare with trends during the conflict period for that zone as well. For each province, the net difference in trends in both parameters between the conflict and post-conflict periods was calculated. The differences between trends in both parameters from the conflict to post-conflict periods are then compared between zones. Two-sample t-tests are performed to compare net differences in trends in forest cover and vegetation seasonality from the conflict to post-conflict period between the five provinces in the conflict zone and the five provinces in the no-conflict zone.

Hypothesis 4a is tested by performing a two-sample t-test testing for a greater net difference in forest cover trends between periods in the conflict zone than in the no-conflict zone.

Hypothesis 4b is tested by performing a two-sample t-test testing for a greater net difference in vegetation seasonality trends between periods in the conflict zone than in the no-conflict zone.

Results

Differences in forest cover trends between zones during the conflict

The mean forest cover loss rate in the conflict zone was -0,51% ± 0,85% (± one standard deviation) annually, while the mean trend for the no conflict zone was a slight gain rate annually of +0,01% ± 2,05% (***Table 1; Figure 3***). Hence, there was not a significantly higher forest cover loss rate in the no conflict zone during the conflict period. The two-sample t-test testing for greater forest cover loss rates in the no-conflict zone than in the conflict zone returned a p-value of 0,69. While the forest cover in the conflict zone declined on average, forest cover in the no-conflict zone did not decline.

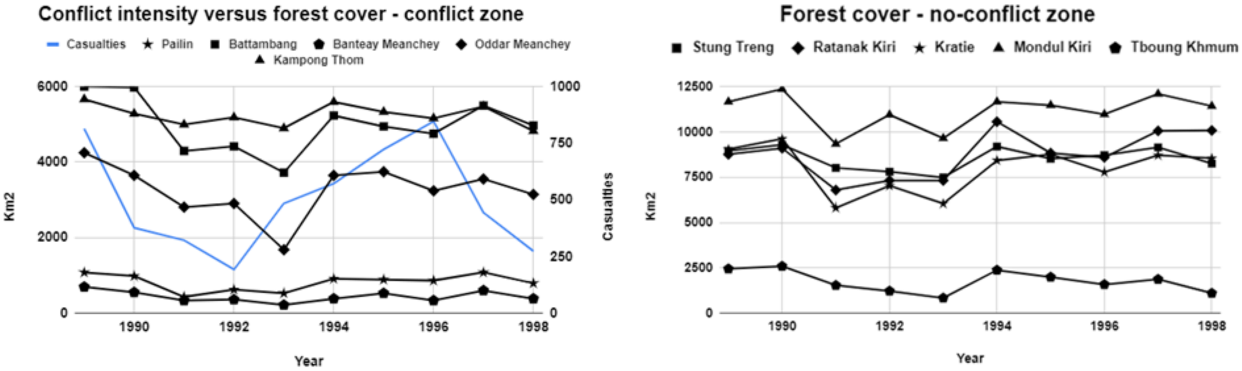


Figure 3: *Conflict intensity alongside forest cover time-series for both the conflict zone (left), and no-conflict zone (right) throughout the conflict period for each province of each respective zone.*

Forest cover trends during the conflict (1989 – 1998)						
Conflict zone	**Province**	Pailin	Battambang	Banteay Meanchey	Oddar Meanchey	Kampong Thom
	Trend (%, + gain, - loss)	+0,79	-0,74	-1,57	-0,57	-0,46
No conflict zone	Trend	+0,01	+2,45	+0,43	+0,40	-3,23
	Province	Stung Treng	Ratanak Kiri	Kratie	Mondul Kiri	Tboung Khmum

Table 1*: Trends in OLS modeled forest cover gain/loss rates annually in % relative to observed forest cover in 1989 for every province. Trends are compared between the 5 provinces of the conflict zone and the 5 provinces of the no conflict zones. Positive trends are shown in green, negative trends are shown in red.*

Differences in vegetation seasonality trends between zones during the conflict

In the conflict zone, vegetation seasonality declined at an average rate of -1,27% ± 1,53% annually, compared to an average decline of -0,46% ± 1,10% annually in the no-conflict zone. Trends in vegetation seasonality were not found to be significantly lower in the conflict zone; the two-sample t-test testing for lower trends in vegetation productivity in the conflict zone compared to the no-conflict zone returned a p-value of 0,18.

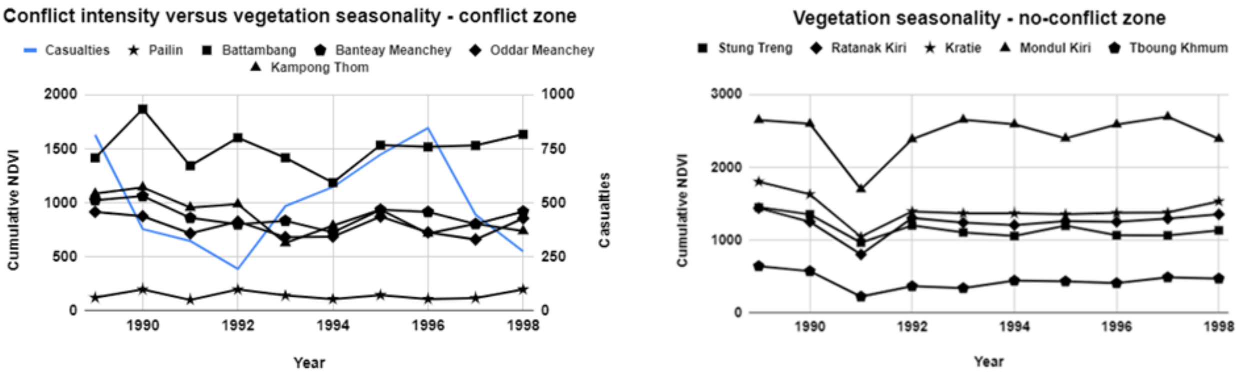


Figure 4: *Conflict intensity alongside vegetation seasonality time-series for both the conflict zone (left), and no conflict zone (right) throughout the conflict period for each province of each respective zone.*

Vegetation seasonality trends during the conflict (1989 – 1998)						
Conflict zone	**Province**	Pailin	Battambang	Banteay Meanchey	Oddar Meanchey	Kampong Thom
	Trend (%, + gain, - loss)	-0,10	+0,02	-1,30	-1,20	-3,79
No conflict zone	Trend	-1,86	+0,69	-0,90	+0,63	-0,86
	Province	Stung Treng	Ratanak Kiri	Kratie	Mondul Kiri	Tboung Khmum

Table 2*: Trends in vegetation seasonality giving the OLS modeled rate of vegetation seasonality gain/loss rates in % relative to values observed in 1989 for every province. Trends are compared between the conflict and no conflict zones. Positive trends are shown in green, negative trends are shown in red.*

Differences in trends between conflict and post-conflict periods for the conflict zone

(a) Forest Cover

In the conflict zone, the mean difference in forest cover change from the conflict to post-conflict period was a decline of -0,34% ± 1,98% annually, indicating more negative trends during the period after the conflict. However, a significant loss in forest cover from the conflict to post-conflict period could not be verified as the paired t-test returned a p-value of 0,36.

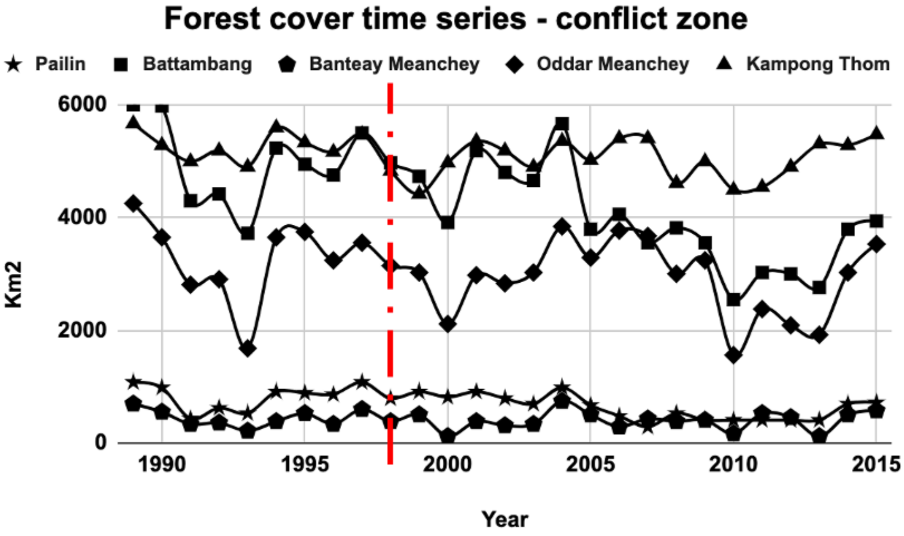
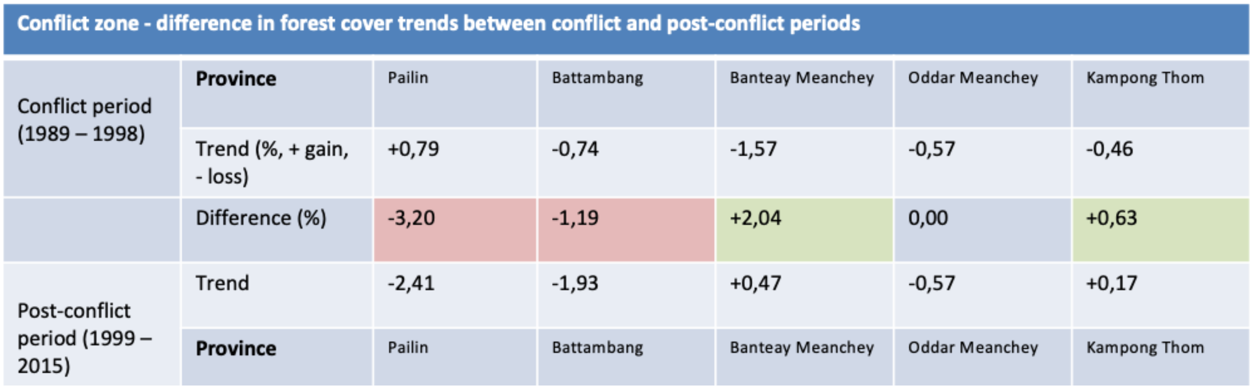


Figure 5: *Forest cover time-series for all provinces within the conflict zone. The vertical, dashed red line represents the end of the conflict period.*



Conflict zone - difference in forest cover trends between conflict and post-conflict periods						
Conflict period (1989 – 1998)	**Province**	Pailin	Battambang	Banteay Meanchey	Oddar Meanchey	Kampong Thom
	Trend (%, + gain, - loss)	+0,79	-0,74	-1,57	-0,57	-0,46
	Difference (%)	-3,20	-1,19	+2,04	0,00	+0,63
Post-conflict period (1999 – 2015)	Trend	-2,41	-1,93	+0,47	-0,57	+0,17
	Province	Pailin	Battambang	Banteay Meanchey	Oddar Meanchey	Kampong Thom

Table 3*: Differences in forest cover trends in the conflict zone from the conflict (1989 - 1998) to post-conflict (1999 - 2015) period. Results are presented in gain/loss rates in % relative to values observed in 1989 for every province. Trends are compared between the conflict and post-conflict periods. Positive differences in trends are shown in green, negative differences in trends are shown in red.*

(b) Vegetation Seasonality

In the conflict zone, vegetation seasonality increased at an average of +3,55% ± 1,96% annually from the conflict to post-conflict period. A significant increase in vegetation seasonality during the post-conflict period was verified as the paired two sample t-test returned a p-value of below 0,01.

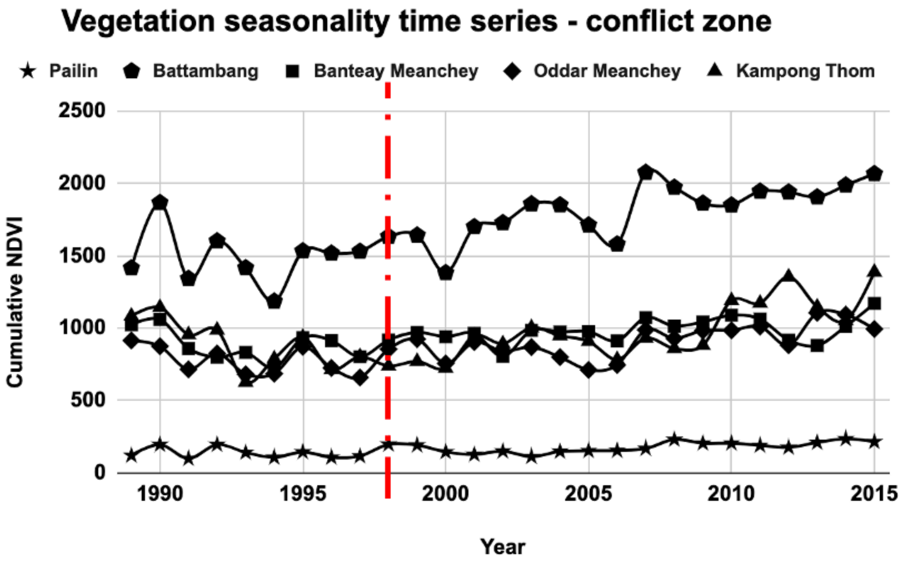


Figure 6: *Vegetation seasonality time-series for all provinces within the conflict zone. The vertical, dashed red line represents the end of the conflict period.*

Conflict zone - difference in vegetation seasonality trends between conflict and post-conflict periods						
Conflict period (1989 – 1998)	**Province**	Pailin	Battambang	Banteay Meanchey	Oddar Meanchey	Kampong Thom
	Trend (%, + gain, - loss)	-0,10	+0,02	-1,30	-1,20	-3,79
	Difference (%)	+4,44	+1,89	+2,03	+2,84	+6,56
Post-conflict period (1999 – 2015)	Trend	+4,34	+1,91	+0,73	+1,64	+2,77
	Province	Pailin	Battambang	Banteay Meanchey	Oddar Meanchey	Kampong Thom

Table 4*: Differences in vegetation seasonality trends in the conflict zone from the conflict (1989 - 1998) to post-conflict (1999 - 2015) period. Results are presented in gain/loss rates in % relative to values observed in 1989 for every province. Trends are compared between the conflict and post-conflict periods. Positive differences in trends are shown in green, negative differences in trends are shown in red.*

Differences in trends between conflict and post-conflict periods compared between zones

(a) Forest Cover

In the conflict zone, the mean difference in forest cover change from the conflict to post-conflict period was a loss rate of -0,34% ± 1,98% annually with respect to the conflict period. In the no-conflict zone, the mean difference in forest cover change from the conflict to post-conflict period was a gain rate of +1,01% ± 2,37% annually with respect to the conflict period. A significantly greater loss in forest cover in the conflict zone than in the no-conflict zone from the conflict to post-conflict period could not be verified; the two-sample t-test testing for a difference in trends in forest cover change post-conflict in the conflict zone as compared to in the no-conflict zone returned a p-value of 0,18.

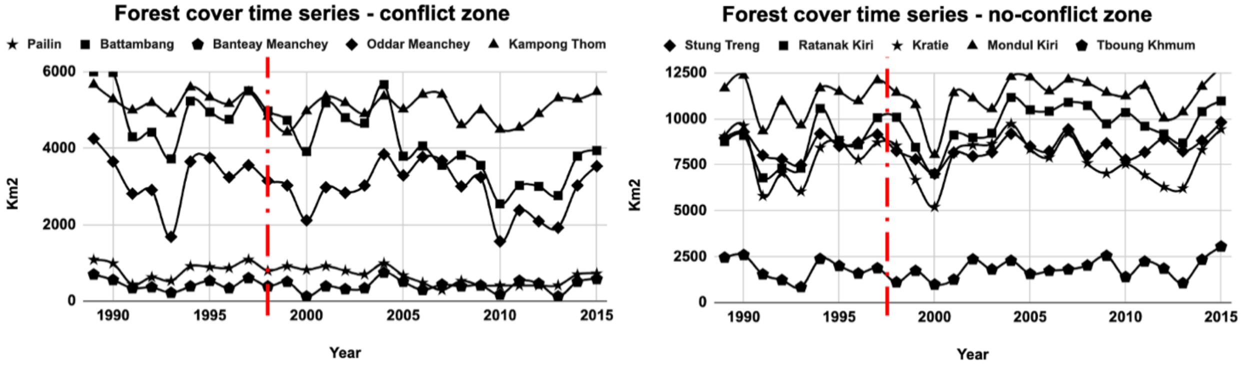
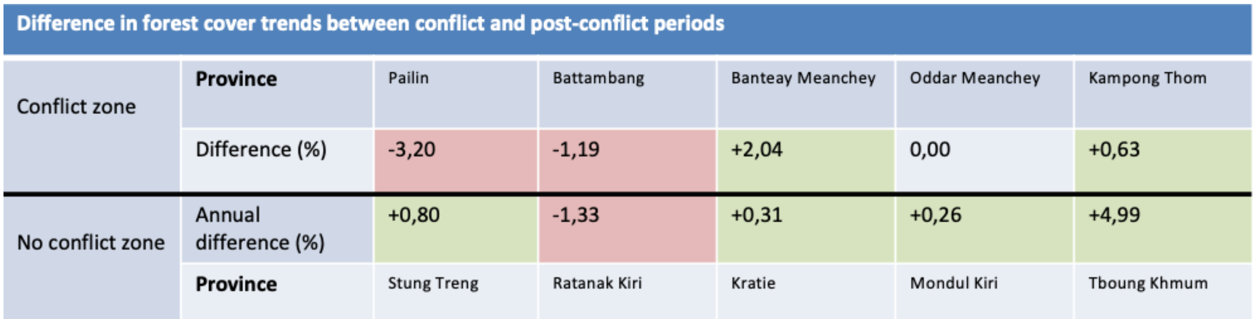


Figure 7: Forest cover time-series for both the conflict zone (left), and no conflict zone (right) across both periods for each province of each respective zone. The vertical dashed red line represents the end of the conflict period in 1998.



Difference in forest cover trends between conflict and post-conflict periods

Conflict zone	**Province**	Pailin	Battambang	Banteay Meanchey	Oddar Meanchey	Kampong Thom
	Difference (%)	-3,20	-1,19	+2,04	0,00	+0,63
No conflict zone	Annual difference (%)	+0,80	-1,33	+0,31	+0,26	+4,99
	Province	Stung Treng	Ratanak Kiri	Kratie	Mondul Kiri	Tboung Khmum

***Table 5**: Differences in forest cover trends from the conflict to post-conflict period for both zones. Results are presented in gain/loss rates in % relative to values observed in 1989 for every province. Positive differences in trends are shown in green, negative differences in trends are shown in red.*

(b) Vegetation seasonality

In the conflict zone, vegetation seasonality increased by an average of +3,55% ± 1,96% annually from the conflict to post-conflict period. In the no-conflict zone, vegetation seasonality increased by an average of +0,58% ± 1,71% annually from the conflict to post-conflict period. The gain in vegetation seasonality from the conflict to post-conflict period in the conflict zone was found to be significantly greater than in the no-conflict zone; the two-sample t-test testing for a significantly difference in trend in forest cover post-conflict in the conflict zone as compared to in the no-conflict zone returned a p-value of 0,02.

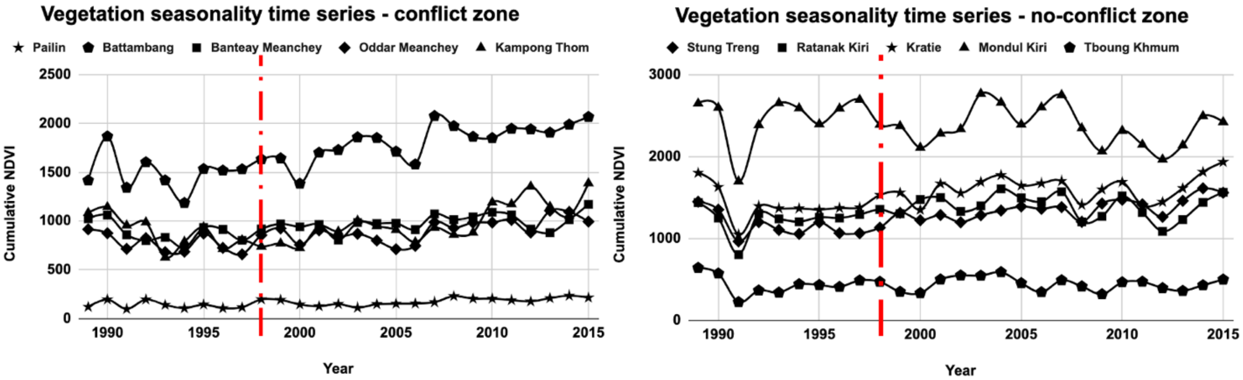


Figure 8: *Vegetation seasonality time-series for both the conflict zone (left), and no-conflict zone (right) across both periods for each province of each respective zone. The vertical dashed red line represents the end of the conflict period in 1998.*

Difference in vegetation seasonality trends between conflict and post-conflict periods						
Conflict zone	**Province**	Pailin	Battambang	Banteay Meanchey	Oddar Meanchey	Kampong Thom
	Difference (%)	+4,44	+1,89	+2,03	+2,84	+6,56
No conflict zone	Annual difference (%)	+2,98	-1,08	+1,39	-1,01	+0,62
	Province	Stung Treng	Ratanak Kiri	Kratie	Mondul Kiri	Tboung Khmum

Table 6: *Differences in vegetation seasonality trends from the conflict to post-conflict period for both zones. Results are presented in gain/loss rates in % relative to values observed in 1989 for every province. Positive differences in trends are shown in green, negative differences in trends are shown in red.*

Discussion

Impact of the conflict on forest cover

Losses in forest cover were not found to be greater in the no-conflict zone than in the conflict zone during the conflict period (1989 - 1998). In the conflict zone, an average annual loss of -0,51% ± 0,85% annually in forest cover shows little difference from a near constant, 0,01% ± 2,05% slight average gain in annual forest cover in the no-conflict zone. Interestingly, the Tboung Khmum province in the no-conflict zone registered by far the greatest annual loss in forest cover however, with a trend of -3,23% annually. The next greatest forest loss trend was observed in the Banteay Meanchey province, in the conflict zone, with -1,57% loss in forest cover annually. A time-series showing forest cover throughout the conflict period (***Figure 3***) for both zones also does not indicate any visible difference in trends between zones.

Despite this, four out of five provinces in the conflict zone showed declines in forest cover, while four out of five provinces in the no-conflict zone showed gains. It is the decline in forest cover of -3,23% annually in Tboung Khmum that stands out in this pattern. Overall however, the pattern is in opposition to the initial hypothesis (1) that the conflict zone would show fewer losses in forest cover due to a disruption in economic activities such as logging and conversion of forest to agriculture, and an ease in pressure on forest resources as people seek refuge from the fighting. As four out of five provinces in the conflict zone show negative trends in forest cover and four out of five provinces in the no-conflict zone show positive trends, it seems that the conflict likely had a net negative impact on forest cover. Logging was a main source of income for warring factions on both sides, facilitating the continuation of the conflict in the 1990's; logging was conducted by the military on both sides (Slocomb 2010; le Billon 1999; le Billon 2000). The effect of population movement on forest cover is overshadowed by logging rates, and is difficult to discern.

Throughout the Cambodian Civil War, battles were rarely continuous, instead mainly fought by relatively short offensives lasting days or weeks during the dry season (Croicu & Sundberg, 2015; Slocomb 2010; Pike 2020; le Billon 1999). It is likely this variability in fighting intensity that can be attributed to forest cover trends over the entire period 1989-1998 appearing similar between both the conflict and no-conflict zones; logging funding the war effort and political administrations on both sides likely increased during the years when less fighting was taking place, subsiding when fighting picked up again. This relationship is mirrored in ***figure 3***; initially negative trends in forest cover change across all provinces from 1989 to 1993 as fighting intensity declined is followed by positive trends in forest cover change during increases in fighting intensity. There also seems to be a lag of one year in the relationship between fighting intensity and forest cover; an increase in fighting intensity in the election year 1993 takes until the next year's forest cover data to register an increase; this effect is not necessarily immediate depending on the timing of the fighting. However, this trend can also be observed in the no-conflict zone, which supports the conclusion that trends in forest cover change throughout the conflict in the conflict zone did not differ significantly from trends in the no-conflict zone; the state of the conflict did not only affect forests local to the event. The dynamic between conflict intensity and forest cover thus seems to not be limited to the conflict zone.

Logging has been cited as a major source of income for the Khmer Rouge, funding both the conflict and the political administration (Slocomb 2010). The conflict zone's proximity to Thailand also may have played a geographic factor in logging in this area, as the timber trade across the border represented a sizable market (Slocomb 2010). It is estimated that the Khmer Rouge generated a revenue of around twenty million U.S. dollars every month leading up to the 1993 elections, causing an alarming toll on the environment (Slocomb 2010). Bans implemented to combat this trend were simply evaded by moving sawmills just inside the Thai border (Slocomb 2010).

Overall changes in net forest cover trends between the conflict (1989 - 1998) and post-conflict (1999 - 2015) periods in the conflict zone offer little explanation in terms of the effects of the fighting on forest cover. Pailin (-3,20%) and Battambang (-1,19%) provinces registered an annual loss in annual forest cover trends post-conflict, Banteay Meanchey (+2,04%) and Kampong Thom (+0,63) registered an annual gain, while Oddar Meanchey (0,00%) showed even trends between periods. It was hypothesized that forest cover trends in the conflict zone would be more negative post-conflict, as logging and patterns in forest to cropland conversion would no longer be disrupted by fighting, and the return of former refugees would drive increased pressure on forest resources. However, differences in forest cover trends from the conflict to post-conflict period were not found to be significantly lower in the conflict zone (-0,34% ± 1,98% annually), than in the no conflict zone (+1,01% ± 2,37%). ***Figure 5*** also does not seem to indicate any change in trend connected to the end of the conflict.

Figure 7 shows a rapid increase in forest cover for each province in the no-conflict zone during the final two years of the series. However, such large increases in areas classified as forest cover throughout the time-series are dubious; while vegetation seasonality can vary greatly from year to year, forest cover should register more subtle changes. It is possible for a large loss in forest cover to be observed from year to year, but a sudden gain is more unrealistic. Such large interannual variability in the forest cover is more likely to be caused by other factors causing differences in maximum NDVI. Variability in climate does not seem to explain any variation in forest cover (***Supplementary Fig A2 – A5***), it is likely that the large inter-annual variability is caused by the threshold for defining forest cover being set at a value of 0.8 in maximum NDVI. The imagery from the AVHRR instrument aboard the NOAA satellite series has been corrected for calibration, angular and spectral variability, and other relevant effects (Jönsonn & Eklundh, 2004), but it might be that this still causes some of the variability. In using solely NDVI to identify changes in forest cover rather than a land cover classification scheme with validation data, sources of variability such as underlying soil color, to which NDVI can be sensitive, are left in, as well as the saturation of NDVI at high values (Gandhi et al., 2015).

Although figures for both estimates of annual national timber production and changes in forest cover do exist, Tsujino et al. (2019) emphasize the large discrepancies in the nature of these estimates, with different sources varying considerably. Estimates of timber export values also exist, however the market values for Cambodian timber are likely not constant; the comparison of timber export and results from this study are thus difficult to make. During the conflict years, estimated timber export values do seem to mirror the pattern in estimated timber production, however after the conflict, the datasets diverge considerably, likely due to evolving markets and prices for Cambodian timber; the World Bank notes that over 95% of timber exports throughout the peak years between 2009 and 2011 were to Hong Kong, which up until then had not been a major destination for Cambodian timber (***Supplementary figure A7)***. National timber production figures from the Cambodian Forestry Administration show a decline after the end of the fighting in 1998, which is not mirrored by the results of this study. Thus, it is difficult to draw conclusions from cross-referencing remotely-sensed forest cover changes with estimates of annual timber production or exports.

Impact of the conflict on vegetation seasonality

Trends in vegetation seasonality were not found to be significantly different between the conflict and no-conflict zones during the conflict period (1989 -1998). In the conflict zone, an average annual loss of -1,27% ± 1,53% annually in vegetation seasonality compares to an average loss of -0,46% ± 1,10% in annual vegetation seasonality in the no-conflict zone. The greatest loss in vegetation seasonality was found in the Kampong Thom province in the conflict region, with a loss rate of -3,79% annually throughout the conflict. The next highest loss is registered by the Stung Treng province in the no-conflict region with a loss rate of -1,86% annually. The time-series showing vegetation seasonality throughout the conflict period (***Figure 4***) for both zones also does not indicate any visible difference in trends. There does thus not appear to be a trend indicating land abandonment in the conflict zone as refugees leave the area as was initially hypothesized. It is likely that refugees fleeing the fighting left before 1989, as the conflict had been ongoing throughout the 1980's, and therefor people leaving the conflict zone from 1989 - 1998 may have been smaller in their numbers, thus not enough to have a clear effect on seasonal dynamics (le Billon 2000; Pike 2020; Slocomb 2010).

In the former conflict zone however, vegetation seasonality trends were found to be significantly greater during the post-conflict period; all five provinces showing increasing trends. The time series of the vegetation seasonality over both periods illustrates this (***Figure 6***), with all provinces in the conflict zone showing positive trends during the post-conflict period, although this does not seem to be related directly to the end of the conflict as the rise is not sudden, but instead is a gradual positive trend indicative of expansion of agricultural land. This is likely attributable to growing permanent croplands such as palm oil and rubber plantations in the conflict zone, as well as growing land cover of seasonal crops such as the more common rice, cassava, and maize (Cambodian Forestry Administration; Tsujino et al. 2019). Interestingly, the gain in vegetation seasonality post-conflict in the conflict zone is also significantly greater than in the no-conflict zone, where two out of five provinces showed a decline, and increases in the other three remained low compared to in the former conflict zone. Thus, there may have been some dynamic in the conflict zone that was not present in the no-conflict zone. It is possible that the fighting may have initially limited agricultural activity during the conflict, which then was able to grow following the end of the conflict period with the return of people to the area. The lack of fighting in the no-conflict period during the conflict mirrors the more consistent fluctuations in vegetation seasonality throughout both periods.

Discerning overall landscape trends

Satellite-based remote sensing has been proven to be effective in analyzing broader associations between conflict and forest cover, and conflict and land use change (Eklund et al., 2017; Burgess et al., 2015; Ordway 2015). However, spatial and temporal resolution is definitive in its capability in capturing the details in these relationships. Further studies of the effect of conflict on the Cambodian landscape would thus benefit from data of higher resolutions both spatially and temporally. The low spatial resolution of the GIMMS NDVI data (8*8Km2), is a very likely reason for the trends in forest cover captured in the analysis. The GIMMS NDVI is spatially averaged over this large area, limiting its capability to capture deforestation occurring at a much smaller spatial scale. In addition, data on battles and attacks occurring in a given area at a given time, as well as locations of army bases such as Burgess et al. (2015) implemented in their analysis of impacts of the war in Sierra Leone during a similar time period as in this study would add a level of intricacy to the analysis. Discerning between natural forest and permanent planted crops such as palm oil and rubber plantations would add insight into the true scale of conversion of natural forests to planted ones (Ordway 2015). This would likely indicate differences in planted forest cover between the conflict and no-conflict zones, and conflict and post-conflict periods in the conflict zone. NDVI used in this study to indicate forest cover does tend to saturate at high values, and it is likely that measurements of forest cover were periodically subject to error in their identification; planted forests were likely included in the forest cover estimates; both rubber and oil palm trees in Southeast Asia have been shown to periodically reach an NDVI in excess of 0.8 (Gandhi et al., 2015; Razak et al. 2018; Srestasathiern & Rakwatin 2014)

The significant increase in vegetation seasonality during the post-conflict period in the conflict zone is worthy of mention, and does indicate a change in land cover in these provinces; each province registers positive differences in trends in seasonality when compared to during the conflict period. As differences in forest cover trends from the conflict to the post-conflict period in the conflict zone do not decrease significantly while vegetation seasonality increases significantly, this does not indicate a pattern of conversion of forest to cropland, but instead indicates simply an expansion of agriculture, likely including the cultivation of land previously abandoned during the conflict. Slocomb (2010) mentions that over 100,000 very recent rural migrants were counted in the Tonlé Sap lowlands in 1998 alone, an area which is represented in the conflict zone. Many likely worked in agriculture, the main occupation in Cambodia during this time (Slocomb 2010). The conversion of natural forest to forest plantations is a pattern that cannot be quantified by this analysis. Changes in climate alone cannot account for the rising trends in vegetation seasonality in the conflict zone during the post-conflict period, as no significant trends in either increasing mean annual precipitation or mean annual temperature were found throughout the range of the climate data (***Supplementary Fig A1)***. No significant relationship between either mean annual precipitation or mean annual temperature and vegetation seasonality was found in the conflict zone, although a significant positive linear relationship between mean annual temperature and vegetation seasonality was found in the no-conflict zone (***Supplementary Fig A6)***. As vegetation seasonality in the conflict zone increased significantly during the post-conflict period, and significantly more so than in the no-conflict zone, the increase in vegetation seasonality in the conflict zone is most likely not due to changes in climate.

Climate change, particularly the gradual warming of global surface temperatures and lengthening of growing seasons, represents a factor that theoretically improves growing conditions for vegetation (Chapin III, F.S., 2011). A longer growing season galvanized by an earlier rise in temperatures in the spring and greater temperatures throughout the growing season allows for a potentially greater growth of vegetation and thereby productivity of an ecosystem (Kerkhoff et al., 2005). For increasing carbon dioxide concentrations in the atmosphere, plants are able to acquire the carbon dioxide needed for growth and maintenance of existing plant structures at a lower stomatal conductance, thus losing less water to the atmosphere via transpiration (Bernhardt & Schlesinger 2020). This in turn improves the water-use efficiency of plants and allows for potentially greater growth (Bernhardt & Schlesinger 2020). The results of this study indicate that climate conditions did not account for the gains found in vegetation seasonality in the conflict zone during the post-conflict period; the difference in vegetation seasonality from the conflict to post-conflict period was found to be significantly greater in the conflict zone than in the no-conflict zone. Rising atmospheric carbon dioxide levels also do not explain this; vegetation seasonality would be expected to increase across all areas in response to the carbon fertilization effect. Rising vegetation seasonality in the conflict zone during the post-conflict period is instead likely connected to the enhanced ability of returning rural populations to practice agriculture without having to fear damage and confiscation of their crops, or conflict itself.

Conservation efforts with the purpose of reversing the trend of deforestation have been implemented more recently in Cambodia (Samek et al. 2012). The final years of the forest cover time-series in ***figure 7*** illustrating large gains when compared to the end of the conflict may be partly due to this. These initiatives have seen mixed success; total forest cover has remained relatively constant in some regions, but also the pattern of converting natural forests to oil palm and rubber plantations remains a growing phenomenon (Samek et al. 2012). This remains a danger to Cambodia's rich natural forests that support diverse species and offer a host of ecosystem services. In addition, forest degradation remains a threat to forest cover alongside conversion to agriculture, as is common in many tropical areas (Achard et al. 2002; Tsujino et al. 2019). Pressures on forests and natural ecosystems continues to increase (Ordway 2015). Thus, the continued study of land use patterns and their impact on the environment continue to be of interest, especially as global climate conditions continue to diverge from optimal levels (IPCC 2014).

Conclusions

This thesis investigated the broadscale impacts of the final stage of the conflict in Cambodia on changes in forest cover and vegetation dynamics.

Initially, it was hypothesized that population dynamics and fighting throughout the conflict would have the effect of disrupting logging and agricultural activities, thus improving conditions for forest cover while leading to cropland abandonment and thus lower vegetation seasonality. Results indicate that the conflict did not have a definitive effect on forest cover in Cambodia over the conflict period examined. However, it is of note that the fighting intensity was not constant and varied between years, which led to rapid fluctuations in logging and thus timber production rates as armies on both sides utilized breaks in fighting to conduct timber extraction in order to fund their war efforts, which may have masked differences in forest cover dynamics between the conflict and no-conflict zone. Vegetation seasonality did not decline more in the conflict zone than in the no-conflict zone, during the conflict period but did increase significantly in the conflict zone during the post-conflict period, and also significantly more so than in the no-conflict zone. This may indicate an expansion in both permanent and seasonal crops post-conflict, and may be an indication that agriculture was to an extent stifled by the conflict.

As the number of conflicts is increasing globally throughout the 21st century, and climate continues to change, remote sensing of satellite data in determining the effects of conflict on natural systems, populations of people, and the integrity of the climate system becomes more and more relevant. In analyses concerning the effects of war on natural ecosystems and land cover, time invested in maximizing spatial and temporal resolution of satellite data, and availability of battle logs and other information on conflict intensity and timing greatly enhances the ability in capturing the detailed relationships involved. Research in this area also benefits from knowledge on conflict-induced population shifts and changes in climate local to the event.

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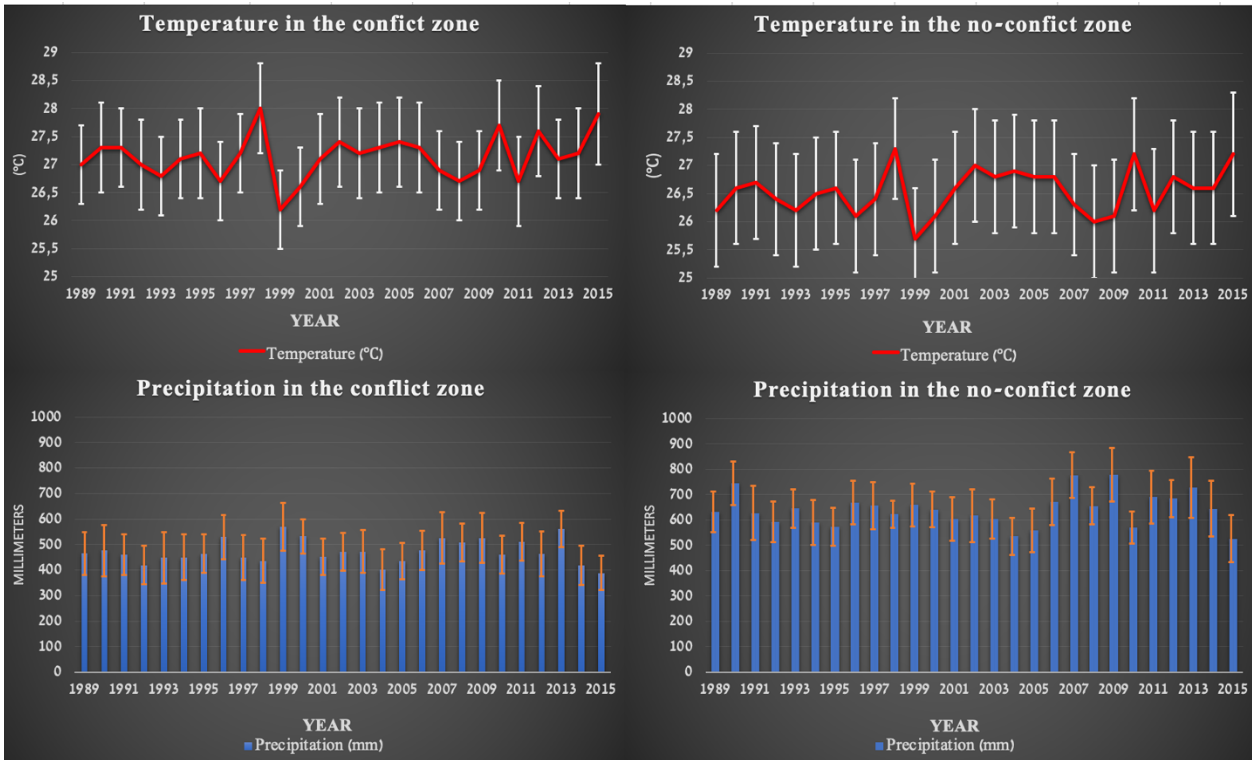
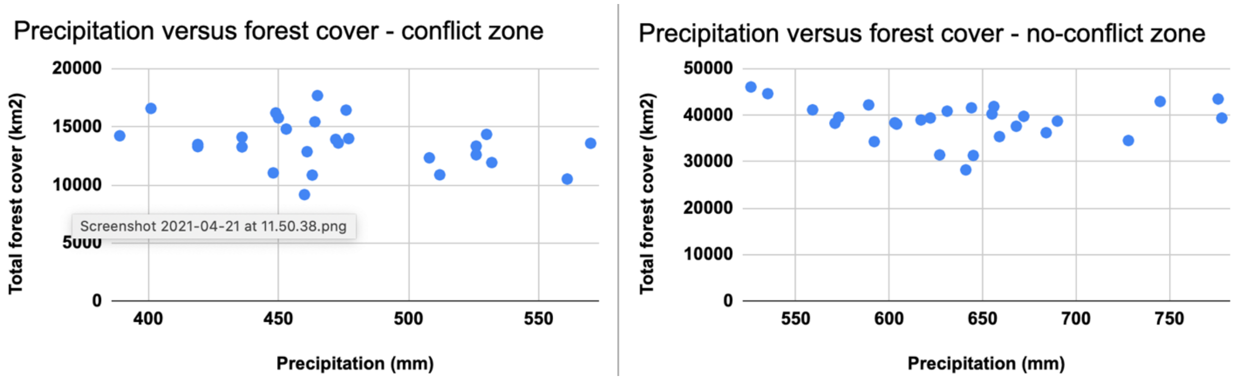
Appendix

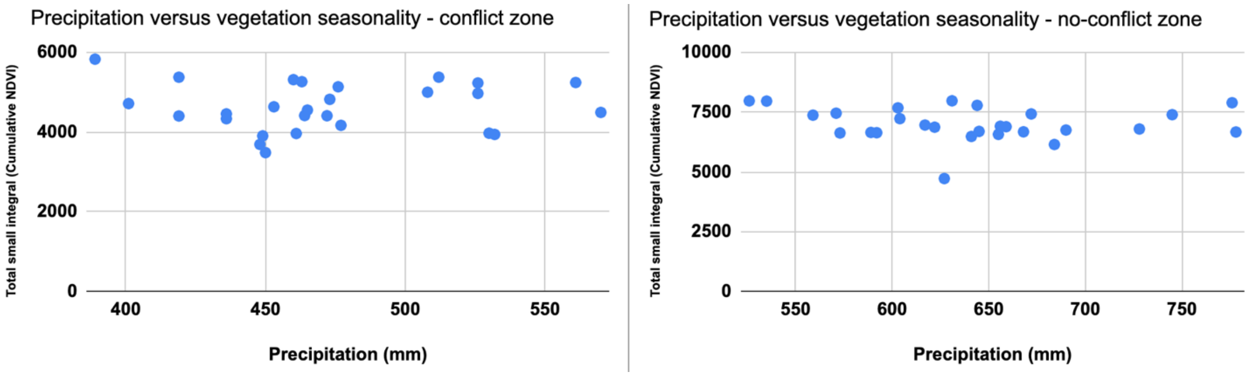
Climate Data



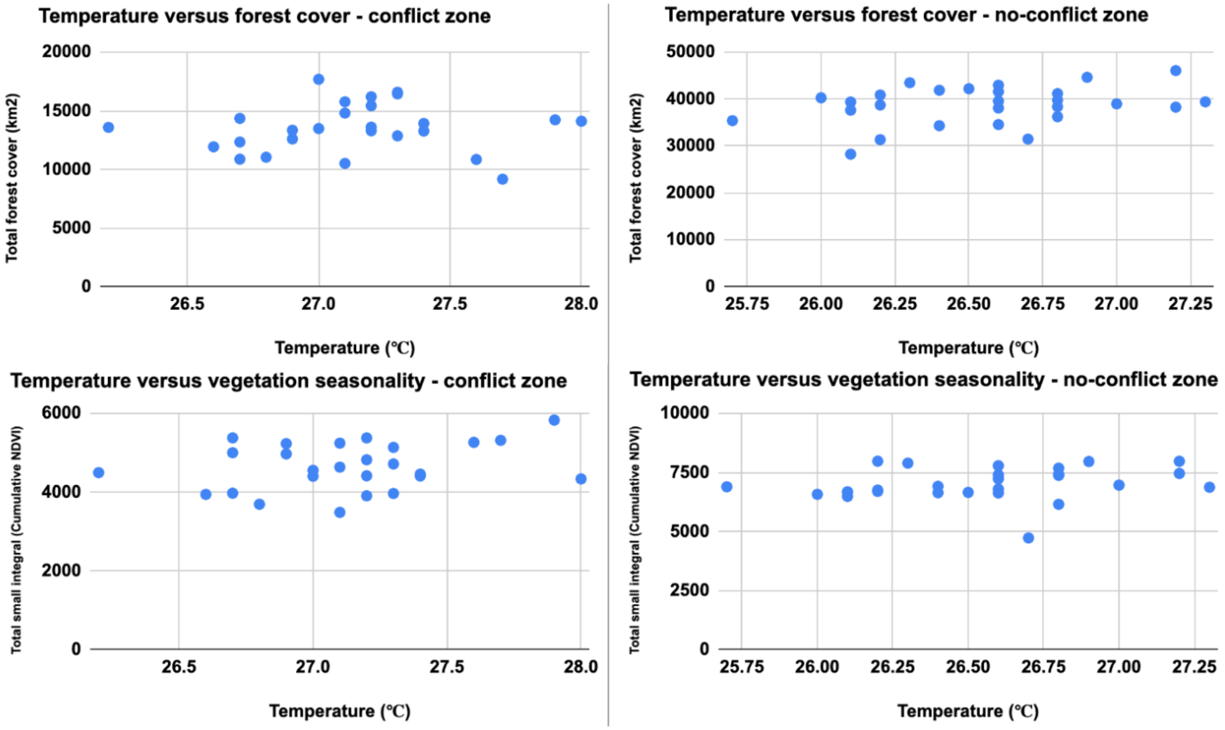
Supplementary figure A1: *Mean annual temperature and mean annual precipitation in both zones over both conflict and post-conflict periods (1989 – 2015). One positive and one negative standard deviation is shown for each year. Climate data originates from the European ReAnalysis, ERA5-Land monthly averaged global reanalysis dataset. Positive trends in mean annual temperature during the post-conflict period (1999 – 2015) were found to be non-significant for both zones.*



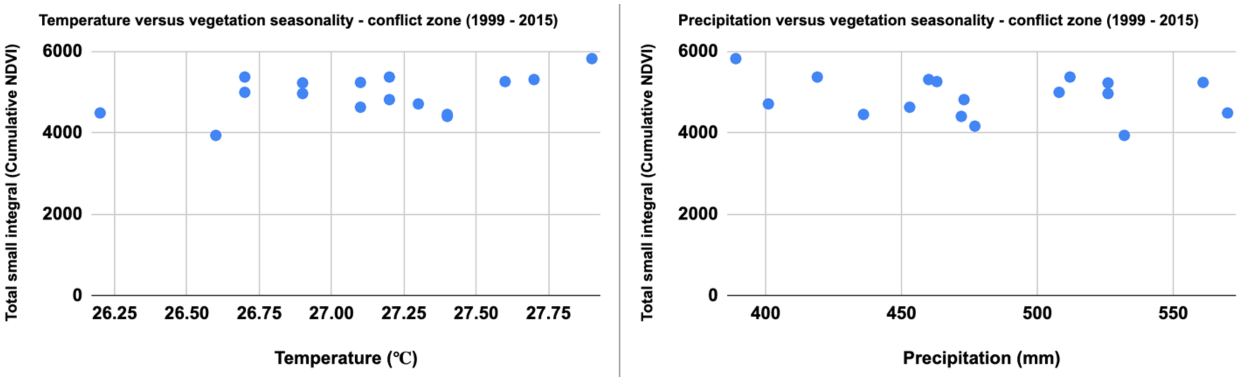
Supplementary figure A2: *Scatter plots showing variation of total forest cover over both conflict and post-conflict periods (1989 – 2015) in the conflict zone (left), and the no-conflict zone (right), as a function of mean annual precipitation in the respective zone.*



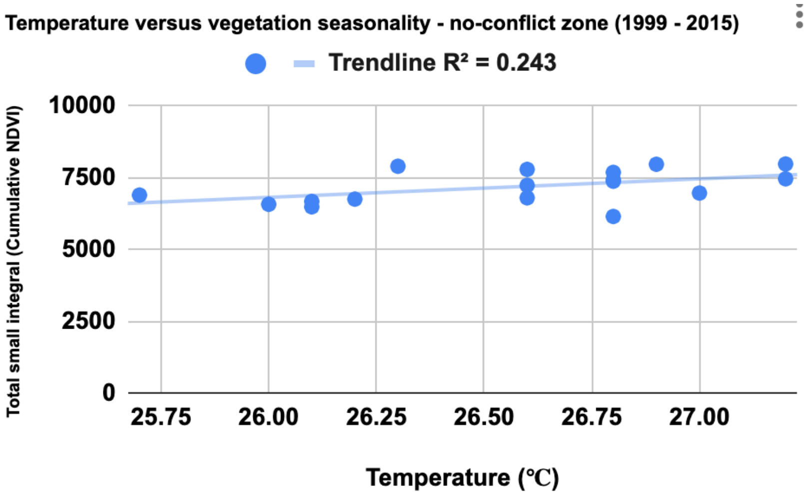
Supplementary figure A3: *Scatter plots showing variation of total vegetation seasonality over both conflict and post-conflict periods (1989 – 2015) in the conflict zone (left), and the no-conflict zone (right), as a function of mean annual precipitation in the respective zone.*



Supplementary figure A4: *Scatter plots showing variation of total forest cover and vegetation seasonality over both conflict and post-conflict periods (1989 – 2015) for all provinces of both zones as a function of mean annual temperature. The positive trends in forest cover as a function of temperature in the no-conflict zone, and the positive trends in vegetation seasonality as a function of temperature in the conflict zone were found to be non-significant.*



Supplementary figure A5: *Scatter plots showing variation of vegetation seasonality over both conflict and post-conflict periods (1989 – 2015) in the conflict zone during the post-conflict period as a function of mean annual temperature (left), and mean annual precipitation (right) in the conflict zone. The positive trend in vegetation seasonality as a function of mean annual temperature was found to be non-significant.*



Supplementary figure A6: *Scatter plot showing variation of vegetation seasonality during the post-conflict period (1999 – 2015) as a function of mean annual temperature. The positive linear trend was found to be significant via a regression analysis.*

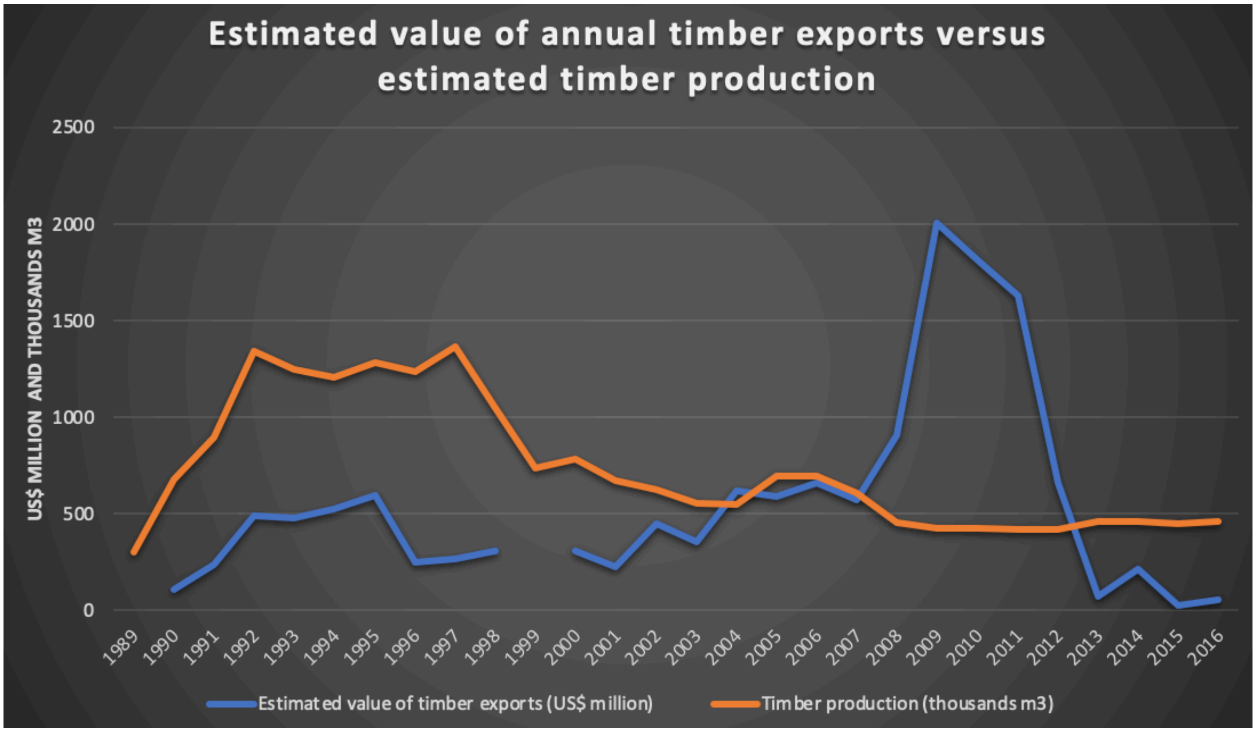
Climate data originates from the European ReAnalysis, ERA5-Land monthly averaged global reanalysis dataset made available by the European Centre for Medium-Range Forecasts (ECMWF) within the Copernicus Climate Change Service of the European Commission (Muñoz-Sabater et al. 2021). Enhanced to a horizontal resolution of 9 km from earlier ERA products, ERA5-Land is designed to feed climate models and support research for a broad range of applications (Muñoz-Sabater et al. 2021).

Data variables “Two-meter temperature” and “Total precipitation” were allocated into yearly means for both the conflict and no-conflict zones over all pixels in Esri’s ArcGIS, Arcmap component.

Scatter plots were constructed to observe possible relationships between climate factors temperature and precipitation, and both total forest cover and vegetation seasonality respectively across all provinces in both zones. Plots were constructed to test for relationships between both climate variables and parameter data from both zones individually, and both periods individually for both zones.

A significant relationship was found between mean annual temperature and vegetation seasonality in the no-conflict zone during the post-conflict period (1999 – 2015); increasing annual mean temperatures seems to be associated with increasing vegetation seasonality. No other significant relationships between mean annual temperature or mean annual precipitation and forest cover or vegetation seasonality were found during either the conflict period, the post-conflict period, or over both periods from 1989 to 2015.

Timber production and export figures



Supplementary figure A7*: Estimated value of national timber exports from reports from the RGC, Thai Forestry Department, and Global Witness for years 1990 - 1998. Values from 2000 to 2016 are from the World Bank. Data is missing for 1989 and 1999. National timber production figures are from the Cambodian Forestry Administration, Ministry of Agriculture, Forestry and Fishery, Phnom Penh, Cambodia. The y-axis is in both increments of millions of US dollars in annual export value, and thousands of cubic meters in annual timber production.*