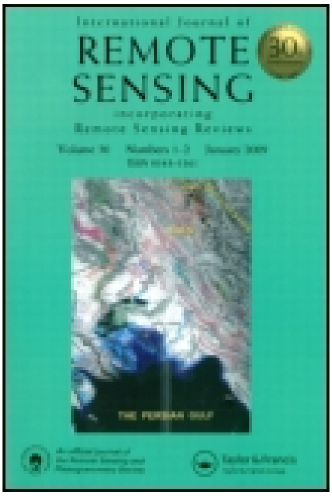

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The Lower Mekong Basin (LMB) has a typical monsoon climate, with high temperatures and an uneven distribution of precipitation throughout the year. This climate, combined with the geographic position of the LMB, has led to an increase in the frequency of extreme weather events over last decade. However, few previous studies have used remote-sensing data to investigate the impact of such weather events, particularly severe droughts, on biological productivity in the LMB. To address this, we assessed the impact of drought on vegetation productivity in the LMB during 2000–2011 using MOD17 products. Several drought events were identified during this period. Of these, the most severe occurred during 2005 and 2010, although the 2005 drought was both more extensive and more intense. Net primary productivity (NPP) exhibited considerable variation during 2000–2011: the droughts in 2005 and 2010 reduced NPP by 14.7% and 8.4%, respectively. The impact of drought on NPP in 2005 was much greater than that in 2010, likely owing to the longer duration and larger deficit of precipitation in 2005 (which lasted from winter 2004 to spring 2005). Our results demonstrate that severe drought had a greater impact on NPP than mild drought, especially for forests, woodlands, and shrublands. Comparatively, little variation in NPP was found for croplands, even under drought conditions, which were attributed to the wide use of irrigation and the exploitation of water sources during drought periods. Moreover, multi-season croplands in Vietnam experienced only a small reduction in gross primary productivity (GPP) in 2005 compared to one-season croplands in Cambodia, which can be related to the shorter growing periods of the former impacted by droughts.

1. Introduction

Global climate change has received increasing public attention during the past few decades owing to the associated loss of human life and increasing economic costs (Karl and Easterling 1999). In particular, extreme climate events have increased in both frequency and magnitude and are projected to become more frequent and severe during the remainder of the twenty-first century (IPCC 2007). Under the influence of both the Pacific and Indian Oceans, countries in Asia (particularly coastal Southeast Asia) are facing an increased frequency of climate change-related risks owing to the concentration

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of population and economic activity in coastal areas, the low per capita income, and high reliance on agriculture and natural resources (Paw and Thia-Eng 1991; ADB 2009; Sovacool et al. 2012). In fact, it has been predicted that, under a business-as-usual scenario, countries in Southeast Asia (including Indonesia, the Philippines, Thailand, and Vietnam) could lose 6.7% of their GDP annually owing to climate change; this is more than twice the global average loss (ADB 2009).

Increases in the frequency and magnitude of extreme climatic events (e.g. flood, drought, and tropical cyclones) could potentially have significant impacts on vegetation ecosystems through declining crop yields, delays in agricultural planting schedules, increased forest losses, higher plant vulnerability, and insect infestation and diseases (Rosenzweig et al. 2001; IPCC 2007; ADB 2009). Of these issues, the problems caused by drought in particular cannot be neglected. Drought is a complex natural disaster that has not yet been defined precisely and universally (Wilhite 2000). Unlike floods, typhoons, and storms, droughts have complex formation mechanisms, develop slowly over several months, and tend to be more widespread geographically (Te 2007). Severe drought can disturb the photosynthetic function of plants and even destroy vulnerable individuals (Hanson and Weltzin 2000); such conditions can also alter the distribution, composition, and abundance of different vegetation ecosystems, increase the probability of pest and disease infestations in forests (Hanson and Weltzin 2000), and trigger forest fires (Westerling et al. 2006) and tree mortality. In this manner, drought can cause large reductions in vegetation productivity (Hanson and Weltzin 2000; Ciais et al. 2005; Asner and Alencar 2010; Zhao and Running 2010; Chen et al. 2012), crop yields (Pantuwan et al. 2002), and carbon sequestration capability (Scott et al. 2009). On the global scale, a recent study found that a reduction in net primary productivity (NPP) in the southern hemisphere was very closely related to a drying trend between 2000 and 2009 (Zhao and Running 2010). Similarly, other studies at continental or national scales have reported drought-induced reductions in vegetation productivity in North America (Pennington and Collins 2007; Kwon et al. 2008; Noormets et al. 2009; Zhang et al. 2010), the Amazon region (Lewis et al. 2011; Potter et al. 2011), Europe (Rambal et al. 2003; Ciais et al. 2005; Pereira et al. 2007; Gilgen and Buchmann 2009), inner Asia (Mohammat et al. 2012), and China (Saigusa et al. 2010; Zhang, Xiao, et al. 2012; Pei et al. 2013; Zhou et al. 2013).

The LMB is located in the tropical monsoon ecosystem and is affected greatly by the monsoon climate (Xue, Liu, and Ge 2011). About 90% of the precipitation in this region is concentrated during the wet periods; this uneven temporal distribution leads to extensive flooding during the wet season and water shortages during the dry season (Leinenkugel, Kuenzer, and Dech 2013). Accordingly, the LMB is very vulnerable to climate change. Extreme floods and droughts, which are considered to be two of the most significant consequences of climate change, have occurred frequently in the LMB during the last decade and are projected to become increasingly frequent in future (Eastham et al. 2008; MRC 2009). This predicted extreme weather is likely to have significant effects on the lives and livelihoods of people living in the region and on plant yield and economics (MRC 2003; Son et al. 2012; Kuenzer et al. 2013). Drought events occurred several times in the 1990s and have become a widespread concern for farmers in the LMB over recent decades (MRC 2005; Son et al. 2012). For example, drought during 1997–1998 and 2003–2005 caused water shortages and huge crop reductions, induced forest fires (IPCC 2007), and affected the livelihoods of local people (MRC 2010). In this context, investigation of the impact of drought on vegetation ecosystems in the LMB is crucial, particularly for the forests and croplands, which are primary sources of income for the majority of people living in this region.

Previously, a number of studies have focused on monitoring drought in the LMB using different indices. Zhou et al. (2011) analysed the spatial and temporal distributions of droughts during the period 1977–2010 in the Mekong River area based on a standardized precipitation index (SPI), whereas Buckley et al. (2007) analysed tree ring and climate data in conjunction with Palmer drought severity index (PDSI) data and suggested that El Niño might play an important role in controlling droughts in this region. Similarly, Naeimi et al. (2013) monitored spatial and temporal drought conditions in the LMB during 1991–2000 and 2007–2011 and demonstrated the high correlation between El Niño conditions and monthly soil moisture. Son et al. (2012) detected large drought-affected areas during the 2003–2006 dry seasons using MODIS normalized difference vegetation index (NDVI) and land-surface temperature (LST) data. However, the above studies focused primarily on monitoring drought using remote sensing or meteorological data, and few previous studies have investigated the impact of drought on vegetation productivity.

Productivity is a fundamental parameter in the study of ecology (Matsushita and Tamura 2002). In particular, it is integral to the understanding of carbon dynamics within the atmosphere−vegetation−soil continuum for different ecosystems and their responses to future climate change (Matsushita et al. 2004). NPP is a crucial ecological variable that represents the difference between the levels of carbon used in photosynthesis and respiration and quantifies the amount of carbon fixed by plants and accumulated as biomass (Field et al. 1998; Zhao and Running 2010). Similarly, gross primary productivity (GPP) is the total carbon gained by the system through net photosynthesis (Zeng et al. 2008). Most previous studies investigating Southeast Asia have focused on the analysis of productivity for local areas or specific vegetation types (Matsushita and Tamura 2002; Zhang, Ju, et al. 2012) or on the potential forces driving NPP variations. Studies of plant-related productivity focusing on climatic factors have typically found a clear relationship between productivity and temperature (Hirata et al. 2008) and the strength of the monsoon (Fu and Wen 1999) across East Asia. Furthermore, it has been shown that net ecosystem productivity is highly related to climate change associated with El Niño–Southern Oscillation (ENSO) events in tropical Asia (Patra et al. 2005), and large NPP anomalies in Southeast Asia have been associated (at least in part) with large reductions in photosynthetically active radiation (PAR) owing to forest fires (Kobayashi, Matsunaga, and Hoyano 2005). In addition, anthropogenic factors such as land-use change were identified as playing an important role in carbon storage in monsoon Asia during 1860–1990 (Tian et al. 2003).

Although previous studies have focused on monitoring droughts and on characterizing productivity variations in LMB, few have focused on the impacts of extreme drought on vegetation productivity using remote-sensing methods. To address this, the present study aims to detect droughts in LMB and identify their impacts on vegetation productivity during 2000–2011. We believe that this will improve an understanding of the impacts of extreme weather events on tropical and subtropical forest and farmland ecosystems in LMB.

2. Data and methods

2.1. Study area

The LMB is located in the downstream area of the Mekong River, which is the longest river in Southeast Asia. The LMB encompasses parts of five countries: Myanmar, Lao People's Democratic Republic (Lao PDR), Thailand, Cambodia, and Vietnam (Figure 1).

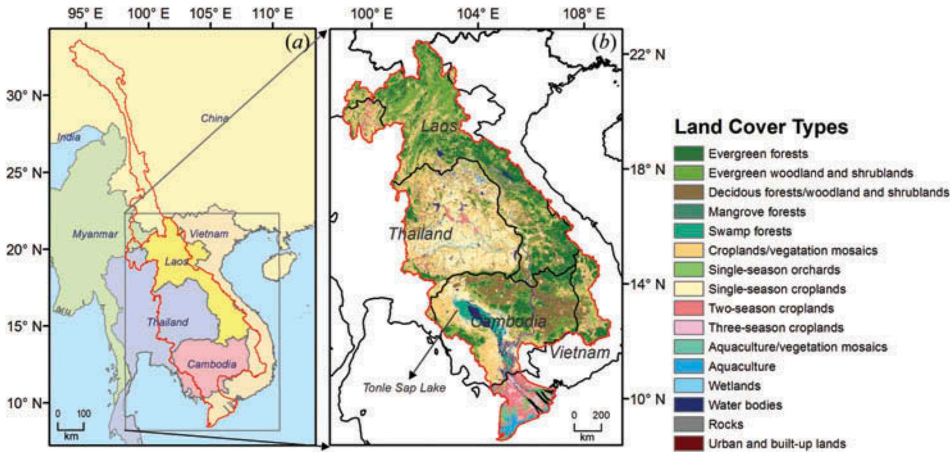

Figure 1. (*a*) Location of the Lower Mekong Basin and (*b*) spatial distribution of land-cover types. The boundary of the Mekong River Basin is adapted from Kuenzer et al. (2012). The land-cover product (Mekong LC2010) is adapted from Leinenkugel, Kuenzer, and Dech (2013).

The topography of the LMB is highly complex and can be divided into four parts: the Northern Highlands, Khorat Plateau, Tonle Sap Basin, and Mekong Delta (MRC 2010). Over 55 million people live in the LMB; of these, an estimated 75% depend on agriculture in combination with fishery, livestock, forestry, and other activities for their livelihoods (MRC 2010).

The LMB is characterized by a tropical monsoon climate influenced by the moist Southwest Monsoon and the dry Northeast Monsoon and experiences two distinct seasons: the wet season from June to October and the dry season from December to the following May (MRC 2010). This climatic pattern has a significant influence on plant growth in the region (Dudgeon 2000; Xue, Liu, and Ge 2011). As with its temporal distribution, the spatial distribution of precipitation is relatively heterogeneous, ranging from 1000 mm in northeast Thailand to 3000 mm in Cambodia (MRC 2003). Higher temperatures (average: 30–38°C) can be observed during March–April, with lower temperatures (average for the high-altitude region of Lao PDR: 15°C) during November–February (MRC 2003).

The Mekong River Basin is one of the most biodiverse regions globally and contains many ecoregions; accordingly, it is regarded as a crucial landscape of international biological importance (MRC 2010). Vegetation in the LMB varies depending on the distribution of precipitation and landforms; according to the Mekong LC2010 product, forests and croplands are two of the main vegetation types in the LMB (Leinenkugel et al. 2013). The spatial distribution of forests is controlled primarily by altitude and rainfall (MRC 2003), such that forests are found primarily in Lao PDR and Cambodia. Of the forests in the region, the greatest proportion is evergreen woodland and shrublands, and evergreen forests (16.4% and 20.3%, respectively), which are distributed primarily in Lao PDR and central Cambodia, followed by the deciduous forests/woodland and shrublands (8.9%) that are spread extensively throughout Cambodia. Unusual forest types, including swamp forests (1.5%) and mangrove forests (0.04%), are concentrated in small areas of the basin along Tonle Sap Lake and the Vietnam Mekong Delta, respectively. Croplands are distributed primarily within Thailand (single-season croplands, croplands/vegetation mosaics, and two-season croplands along the Mun River, which is the largest tributary of the Mekong River), Cambodia (single-season croplands and croplands/vegetation mosaics), and the Vietnam Mekong Delta (two-season croplands and three-season croplands). Croplands/vegetation mosaics constitute the highest areal proportion of the basin (29.2%), followed by single-season croplands (12.3%), two-season croplands (3.6%), and three-season croplands (0.8%). The most important crop type in the LMB is rice: rain-fed rice is distributed mainly in the central highlands of Vietnam, northeastern and parts of northern Thailand, and Cambodia, whereas fully or partially irrigated rice is grown in large parts of the Vietnam Mekong Delta (Nesbitt, Johnston, and Solieng 2003).

2.2. Data

2.2.1. Drought index

Drought indices have been used widely to detect drought intensity, duration, and spatial distribution. Drought characteristics and their impacts are very complex. Accordingly, various drought indices have been developed previously, including the Palmer drought severity index (PDSI) (Palmer 1965), drought area index (DAI) (Bhalme and Mooley 1980), Rainfall Anomaly Index (RAI) (Van Rooy 1965), and standardized precipitation index (SPI) (McKee, Doesken, and Kleist 1995). In the present study, we adopted the PDSI to detect drought conditions in the LMB during 2000–2011. We obtained the PDSI product at 0.5° × 0.5° spatial resolution from the Numerical Terradynamic Simulation Group (ftp://ftp.ntsg.umt.edu/pub/MODIS/NTSG_Products).

PDSI is a good indicator of soil moisture fluctuations (Mika et al. 2005), where PDSI values of –1.0 to –1.9, –2.0 to –2.9, –3.0 to –3.9, and below –4.0 represent mild, moderate, severe, and extreme drought, respectively (Palmer 1965). PDSI was used originally to monitor drought in the USA and is now one of the most widely used drought-monitoring indices (Heim 2000). In particular, PDSI has been applied to detect drought in regions of the world including Europe (Domonkos, Szalai, and Zoboki 2001), Africa (Ntale and Gan 2003), and Brazil (Dos Santos and Pereira 1999). In contrast to many drought indices that are based solely on precipitation information, PDSI uses both precipitation and temperature as inputs. Previous studies have demonstrated that PDSI is correlated significantly with observed soil moisture data over large areas worldwide (Dai, Trenberth, and Qian 2004). A detailed description of PDSI can be found in Palmer (1965) and Alley (1984).

2.2.2. MODIS productivity products

Biological productivity represents productivity at different organic levels (e.g. individual, community, ecosystem, region, and biome) and indicates the overall health condition of ecological systems. Typically, GPP and NPP are two of the concepts representing biological productivity. In the present study, we obtained annual NPP information from the MOD17A3 NPP product and monthly GPP information from the MOD17A2 GPP product for the period 2000–2011 from the Numerical Terradynamic Simulation Group (http://www.ntsg.umt.edu). The current version (5.5) of the MODIS product offers improved data accuracy, achieved through the temporal infilling of cloud-contaminated pixels of MODIS MOD15 LAI/FPAR data products and the spatial interpolation of meteorological input data down to 1 km MODIS resolution. In addition, the modified Biome Parameter Look-Up Table (BPLUT), which is based on recent synthesized NPP data and observed GPP from flux tower measurements, has also been used to improve the MOD17 product's accuracy (Zhao et al. 2005; Zhao and Running 2010). The MOD17 product is the first regular, near-real-time satellite-driven dataset monitoring global vegetation productivity at 1 km resolution on a global scale (Zhao et al. 2005). The quality of the MOD17 product has been validated for different climatic regimes and vegetation types (Zhao, Running, and Nemani 2006; Turner et al. 2006), and this product has already been adopted in a wide variety of applications, including detecting drought impacts on vegetation productivity (Zhao and Running 2010; Shiba and Apan 2011; Zhang, Xiao, et al. 2012; Mu et al. 2013), calculating carbon-use efficiency (Kwon and Larsen 2013), and estimating wheat yield (Reeves, Zhao, and Running 2005). Although used frequently, the global MOD17 products have certain limitations. For example, the input data for NPP may be influenced by cloud (Zhao et al. 2005; Propastin et al. 2012), particularly because the average cloud cover in the LMB region reaches approximately 85–90% during the wet season (Leinenkugel, Kuenzer, and Dech 2013). Similarly, smoke from forest fires may also have some influence on the quality of the NPP product.

2.2.3. *Climate data*

We used monthly precipitation and temperature data from the Modern-Era Retrospective Analysis for Research and Applications (MERRA) dataset (Rienecker et al. 2011) for 2000–2011 to detect meteorological anomalies during the study period. These data are provided by the Global Modeling and Assimilation Office (GMAO) and cover the period from 1970 to the present with a spatial resolution of 0.500° × 0.667°. MERRA uses data derived from NASA's Earth Observation System satellites; this dataset has achieved significant improvements in reducing the uncertainty in precipitation and water vapour climatology through the representation of the atmospheric branch of the hydrological cycle in the reanalysis products (Rienecker et al. 2011).

2.2.4. *Mekong LC2010 product*

We used the Mekong LC2010 product (Leinenkugel et al. 2013) at a spatial resolution of 500 m to identify different vegetation types in LMB. This product is developed through a multi-step unsupervised classification approach based on MODIS spectral reflectance in bands 1–7 and information from an 11 year MODIS enhanced vegetation index (EVI) time series (2000–2011), including a series of phenological metrics for 2010. The accuracy of the Mekong LC2010 product was validated through comparison with numerous data, including Google Earth, Landsat TM, and auxiliary data products, with an overall accuracy of 74% (Leinenkugel et al. 2013). In fact, the quality of the Mekong LC2010 product has been shown to be superior to the 2009 GlobCover and 2009 MODIS land-cover (MCD12Q2) products, with overall accuracy approximately 20–25% greater than that of the other products (Leinenkugel et al. 2013).

2.3. ***Data analysis***

2.3.1. *Drought identification*

We used PDSI data to characterize drought conditions across the basin for 2000–2011. In particular, we detected the impact of drought on productivity for mild drought areas with PDSI between –2 and –1 and severe drought areas with PDSI less than –2. The areal proportion affected by each of these levels of drought was calculated by dividing the area affected by drought by the total area of the entire LMB.

2.3.2. Drought impact on vegetation productivity

The MODIS NPP product was used to detect annual NPP anomalies for 2000–2011. We used the standardized anomalies index (SAI) to derive the spatial distribution of NPP anomalies and analysed the corresponding distribution of drought anomalies during the study period. In previous studies, SAI was applied effectively to detect anomalies in different variables (Giuffrida and Conte 1989; Peters et al. 2002). For example, Pei et al. (2013) applied SAI to assess the temporal dynamics of NPP anomalies in China and demonstrated the effectiveness of the index through its good correlation with the vegetation health index. In the present study, we defined SAI as follows:

$$\mathrm{SAI_{NPP}} = \frac{\mathrm{NPP}(i) - \overline{\mathrm{NPP}}}{\sigma_{\mathrm{NPP}}}. \tag{1}$$

Here, $\mathrm{SAI_{NPP}}$ represents the NPP anomalies, NPP(i) is the annual NPP in the ith year, $\overline{\mathrm{NPP}}$ is the value of mean NPP for period 2000–2011, and σ_{NPP} is the standard deviation of the 12 year NPP.

To investigate the impact of drought on NPP, we calculated the percentage of two levels of drought-affected areas ($-2 < \mathrm{PDSI} < -1$ and $\mathrm{PDSI} < -2$) and then analysed their correlations with the regional mean NPP for the study period. To provide a common resolution for NPP and GPP, we re-sampled the PDSI and climate data to a spatial resolution of 1 km. Then, we calculated the annual mean NPP for each of the dominant vegetation types and calculated relative changes in NPP (i.e. the difference between annual NPP and 12 year mean NPP, divided by the 12 year mean) under different levels of drought to analyse the responses of different vegetation types to different drought levels during 2000−2011.

To further explore the seasonal characteristics of the impact of drought on productivity during drought years, we calculated monthly mean GPP, mean temperature, and total precipitation in 2005 and 2010 and compared them with the 12 year means to identify meteorological anomalies and their impact on productivity in different seasons. We also selected the most drought-affected areas (Cambodia and Vietnam) to detect monthly GPP reductions for different vegetation types in 2005 and 2010.

3. Results and discussion

3.1. Droughts in the LMB over the last decade

During 2000–2011, the LMB experienced several drought events. Figure 2 illustrates the spatial distribution of PDSI, which characterizes the intensity and extent of drought for each year in the LMB during 2000–2011. These data demonstrate clearly that droughts occurred during 2003–2007 and in 2010. This observation is in accordance with the findings of Son et al. (2012), who used the NDVI and LST data to identify the 2003–2006 droughts (particularly that in 2005) that affected the majority of the LMB. Drought periods between 2003 and 2006 were also indicated by the MRC report (MRC 2005), whereas Naeimi et al. (2013) demonstrated recently that 2010 was also a drought year for the LMB. Thus, our observed results based on PDSI (Figure 2) are in accord with reported

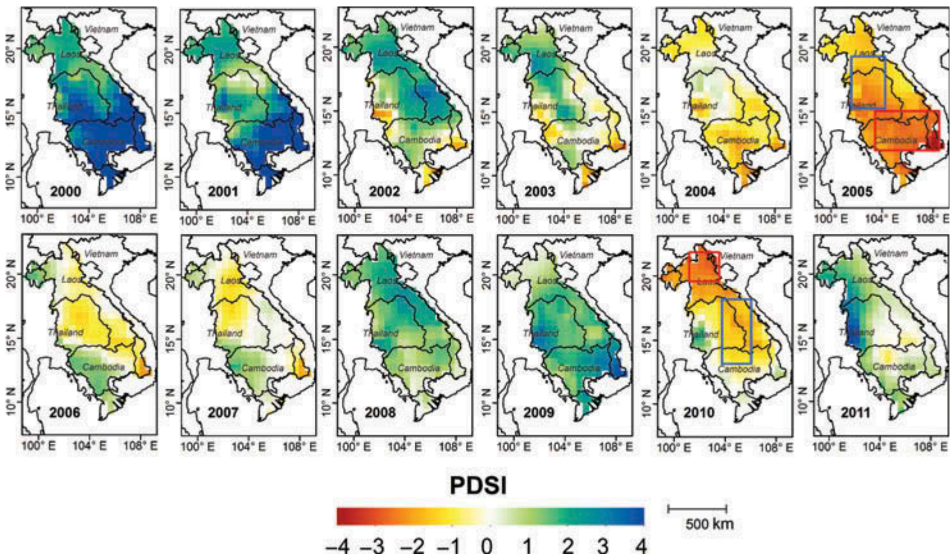

Figure 2. Spatial distribution of PDSI over the period 2000−2011 over the Lower Mekong Basin. Blue and red boxes indicate examples of mild and severe drought, respectively.

drought events from other sources, demonstrating that PDSI can be considered an effective index for monitoring droughts in the LMB.

During 2003–2007 and 2010, mild drought hit 11.2%, 29.6%, 45.1%, 17.5%, 15.5%, and 38.3% of the LMB, respectively, whereas severe droughts typically affected only small portions of the LMB (2.9%, 6.3%, 2.4%, and 0.5% in 2003, 2004, 2006, and 2007, respectively) (Figure 6). Regionally, the drought in 2003 affected the Vietnam Mekong Delta and southwest Thailand, whereas that in 2004 affected primarily Cambodia and Vietnam. In 2006 and 2007, drought was observed in parts of Thailand and Lao PDR. In general, our results indicate that Cambodia has been affected by frequent droughts over the past decade, which is in accordance with the study of Son et al. (2012).

Relatively extensive and severe droughts occurred during 2005 and 2010 and affected almost the entire LMB. The regional mean values of PDSI during 2005 and 2010 were −2.1 and −1.1, respectively; these are the lowest values obtained throughout the study period (i.e. over 12 years) and are much lower than the long-term mean of 0.6 (Figure 3). In terms of both extent and intensity, the drought in 2005 was much more extensive and severe than that in 2010: the total area affected by drought in 2005 accounted for 98.1% of the LMB (52.9% for severe drought and 45.1% for mild drought), whereas that in 2010 accounted for only 58.7% of the LMB (20.2% for severe drought and 37.0% for mild drought). Furthermore, the regional mean PDSI in 2005 (–2.1) was much lower than that in 2010 (–1.1). The most severely affected region in 2005 was located in Cambodia, with an average PDSI of –2.5; this is much lower than the 12 year mean for Cambodia (0.8). Conversely, in 2010, the most severely affected region was Lao PDR, where the average PDSI was –1.9; this is considerably lower than the 12 year mean for Lao PDR (0.6).

Droughts in the LMB were induced primarily by high temperatures concurrent with shortages of precipitation (Figure 3). In the data for the LMB, precipitation shortages can be observed during 2003–2005 and 2009–2010, whereas relatively high temperatures can be observed for most of 2004–2006 and 2009–2010 (Figure 3). In 2005 and 2010, the

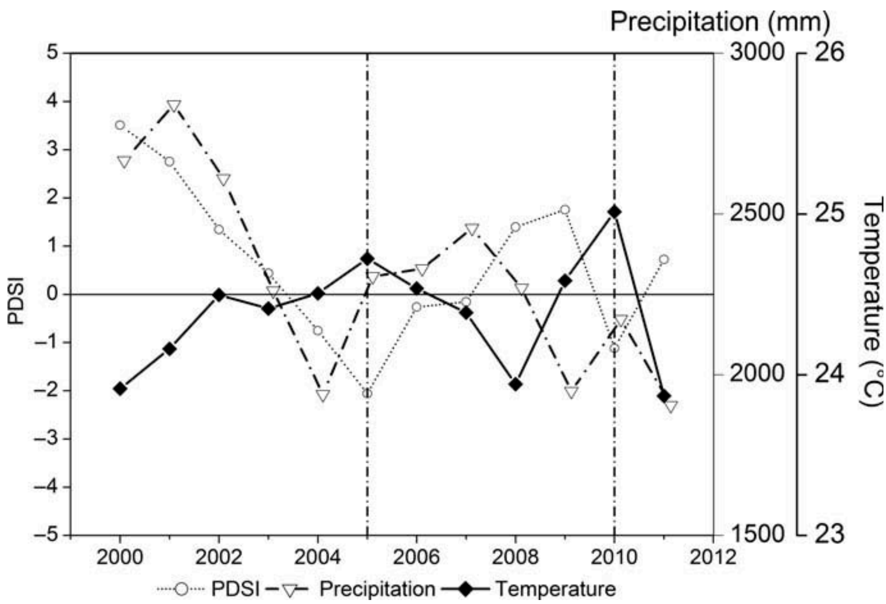

Figure 3. Inter-annual variations in regional mean PDSI, temperature, and precipitation over the period 2000−2011.

annual mean temperatures were 0.3°C and 0.6°C higher than the 2000−2011 mean, respectively. Moreover, annual total precipitation in 2010 was 5.9% lower than the 12 year mean. Although total precipitation in 2005 was close to the long-term mean, the shortage of water in the region can be traced back to October−December 2004, when the mean regional rainfall in LMB was only 57.2% of the 12 year mean and just 47% of the 1985–2000 normal rainfall (Te 2007).

3.2. *Drought impacts on annual NPP*

Figure 4 illustrates the annual NPP for the LMB during 2000–2011, which varied from nearly 142 g C m^{-2} $year^{-1}$ in the Vietnam Mekong Delta to over 1521 g C m^{-2} $year^{-1}$ in northern Lao PDR. Lower NPP was found along Tonle Sap Lake in Cambodia and the Vietnam Mekong Delta, where cropland types are dominant. In contrast, the dominant vegetation in Lao PDR is forests, which accounts for over 40% of the country's land area (Southavilay and Castrén 1999) and contributes to the high annul NPP in Lao PDR.

Figure 5 illustrates the annual NPP anomaly relative to the mean for the period 2000–2011. As can be seen from Figures 2 and 5, the spatial distribution of the PDSI is generally consistent with the distribution of the NPP anomalies in most years and areas. We found apparent negative anomalies in NPP for 2005 and 2010 for the entire region, with basin-averaged NPP values that were 14.7% and 8.4% less, respectively, than the 12 year mean. Moreover, the drought-affected areas were more extensive in these 2 years than in any other years studied (Figure 6). As we identified based on the PDSI (Figure 2), the NPP data indicate that the drought in 2005 was more severe and extensive than that in 2010. In particular, large areas of negative NPP anomalies were found in all of the countries studied in 2005 but were concentrated notably in Lao PDR and the east of Cambodia in 2010.

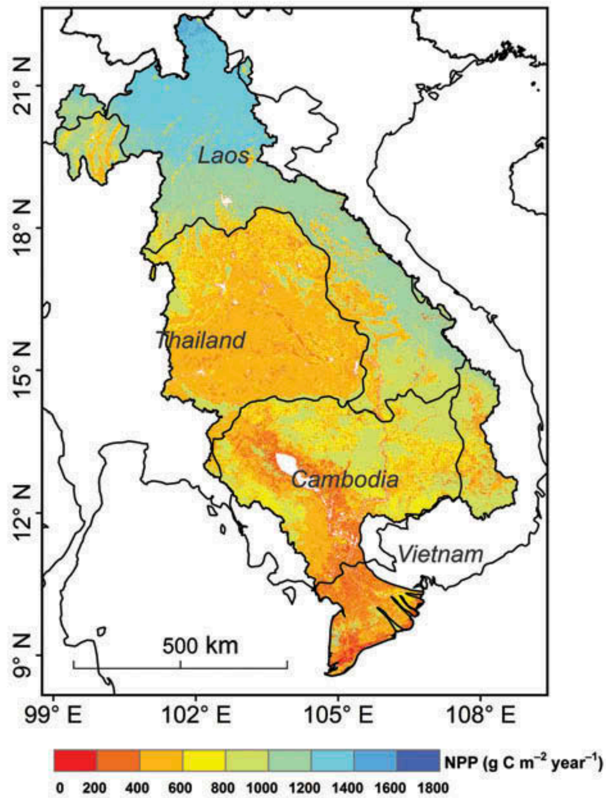

Figure 4. Spatial distribution of mean annual NPP over the period 2000–2011.

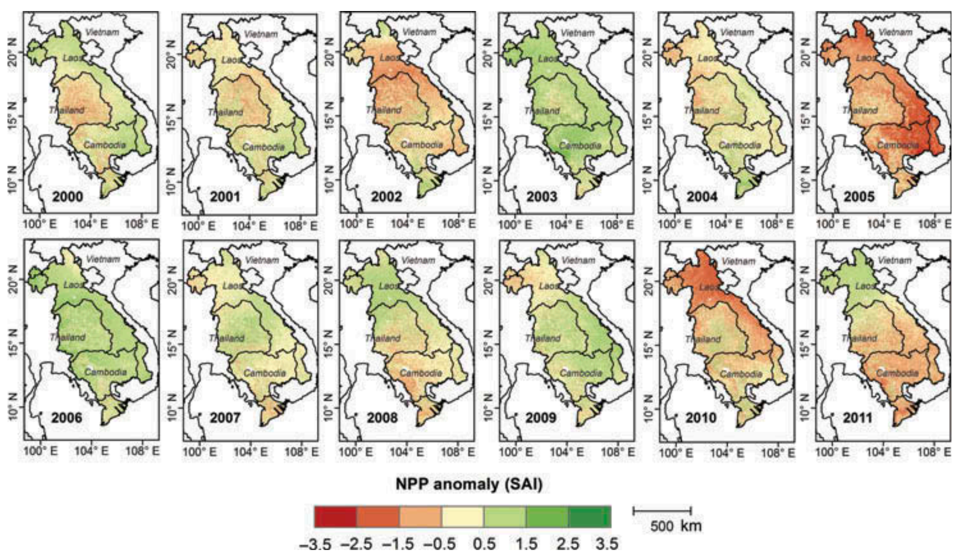

Figure 5. The 2000–2011 NPP anomalies relative to the mean (2000–2011).

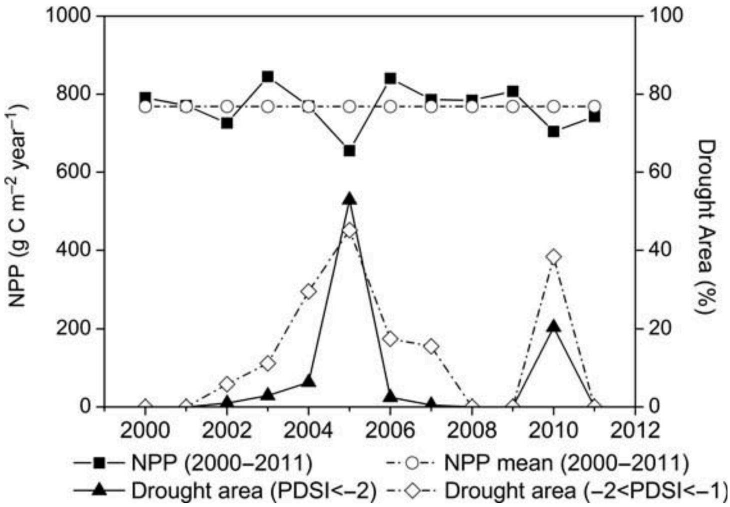

Figure 6. Inter-annual variations in regional mean NPP and areal percentage of drought-affected areas in the LMB from 2000 to 2011.

Compared with NPP in 2005 and 2010, the NPP data for other drought years (including 2003, 2004, 2006, and 2007) are not indicative of large reductions in NPP, which can be explained partly by the effects of different levels of drought. During 2003–2004 and 2006–2007, the percentages of areas experiencing severe drought (PDSI < –2) were relatively low (2.9%, 6.3%, 2.4%, and 0.5%, respectively) compared to those in 2005 and 2010; this could explain the relatively low NPP anomaly in these years. During the study period, the severe drought areas (PDSI < –2) exhibited a higher correlation with NPP (R^2 = 0.55) than did the mild drought areas (–2 < PDSI < –1; R^2 = 0.31) (Figure 6), indicating that severe drought had a much greater impact on regional NPP than mild drought. This has been demonstrated previously for China by Pei et al. (2013), who showed that a stronger correlation between droughts and NPP anomalies occurred during or after the time at which drought intensities reached their peak values.

In years for which no drought impact was identified by PDSI (e.g. 2002 and 2011), the negative NPP anomalies in the region (Figure 5) may be attributable to factors other than drought, such as the severe floods observed in the central LMB in 2002 and in the central and southern parts of the LMB in 2011 (MRC 2011). Several reasons for flooding-induced NPP reductions have been presented previously in the literature. For example, floods can have a significant impact on forests by inhibiting the growth of trees and suppressing respiration and on croplands through destruction of large areas of rice fields (Masumoto, Hai, and Shimizu 2008).

3.3. Drought impact on different vegetation ecosystems of the LMB

Figure 7 illustrates changes in NPP for the dominant vegetation types relative to the 12 year mean NPP during the study period. Drought (i.e. PDSI < –1) could not be observed in the LMB for 2000–2001, 2008–2009, or 2011; therefore, the relative NPP changes for these years were not considered. Large reductions in NPP were observed during 2005 and 2010 for all vegetation types, and severe droughts (PDSI < –2) had a greater impact on the NPP of different vegetation types (i.e. relative changes of 9.1–27.1% in 2005 and 4.0–

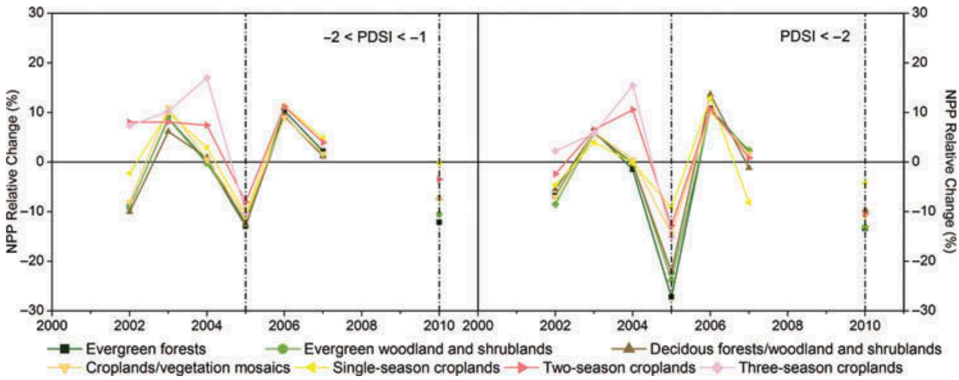

Figure 7. Relative NPP changes for different land-cover types for drought-affected areas where –2 < PDSI < –1 and PDSI < –2.0 during 2000–2011.

13.4% in 2010) than mild droughts (–2 < PDSI < –1; relative changes of 8.0–12.9% in 2005 and 0.2–12.1% in 2010).

Under the mild drought conditions of 2005, the relative change in NPP was small for forests, woodlands, and shrublands (12.9%, 11.8%, and 12.6% for evergreen forests, evergreen woodland and shrublands, and deciduous forests/woodland and shrublands, respectively), and croplands (11.0%, 10.6%, 8.0%, and 10.3% for croplands/vegetation mosaics, single-season croplands, two-season croplands, and three-season croplands, respectively). Conversely, under severe drought conditions, the impact of drought varied considerably for different vegetation types. For the four types of croplands, severe drought had a similar effect to that of mild drought: NPP declined by 14.5%, 9.2%, 12.8%, and 15.1% for croplands/vegetation mosaics, single-season croplands, two-season croplands, and three-season croplands, respectively, whereas the NPP reduction for forests, woodlands, and shrublands were much larger (declines of 27.2%, 23.8%, and 22.1% for evergreen forests, evergreen woodland and shrublands, and deciduous forests/woodland and shrublands, respectively). This demonstrates that, while mild drought exerts relatively homogeneous effects regardless of vegetation type in LMB, the impact of severe droughts on forests, woodlands, and shrublands is much more pronounced than that on croplands. This lower impact for croplands may be attributable to the presence of irrigation systems that can mitigate the impact of droughts. Furthermore, severe droughts can be a potential factor in inducing forest fires (Taylor et al. 1999). In Vietnam, about 9000–12,000 ha of forests were burned during the 2002–2005 droughts (FAO 2007; ADB 2009), producing tree mortality over large areas (Allen et al. 2010) and reducing NPP. Moreover, smoke from forest fires reduces the amount of photosynthetically active radiation (PAR) available for plants, leading to further reductions in NPP (Kobayashi, Matsunaga, and Hoyano 2005). Our findings regarding the more significant impact of drought on forests than on croplands have also been observed in Amazonian forests: during the same years investigated in the present study (i.e. 2005 and 2010), Amazonian forests suffered severe drought that led to a large decline in productivity (Samanta et al. 2010; Lewis et al. 2011), which was particularly evident for closed broadleaf forests (Potter et al. 2011).

The relatively small reduction in NPP for croplands in the LMB can likely be ascribed to human factors. Rice is one of the most important agricultural products in the basin and accounts for more than 10 million ha of cultivated land (MRC 2010). In the Vietnam

Mekong Delta, about 60% of rice is irrigated (MRC 2010), and local people store water during the flood season and use it to irrigate rice during the drought period. In addition, improvements to irrigation systems (e.g. the addition of canal sluices to block sea water inflow) have also likely helped mitigate the effects of drought on irrigated rice (Sakamoto et al. 2009). Rain-fed rice is also important in the region investigated in the present study and is distributed primarily in Lao PDR, the central highlands of Vietnam, northeast and parts of northern Thailand, and Cambodia (Nesbitt, Johnston, and Solieng 2003). However, rain-fed rice is not typically affected seriously by drought, except for extreme drought, because water supplied through small ponds in and around the rain-fed fields can be used for irrigation during drought periods (Shimizu, Masumoto, and Pham 2006). Therefore, drought may not reduce crop production immediately for crop-intensive areas in LMB, where farmers can implement a series of adaptation strategies in case of insufficient precipitation. Consequently, NPP rates for croplands can be expected to be affected to a lesser degree than natural vegetation types (e.g. forests) by precipitation shortage and droughts.

3.4. *Seasonal characterization of drought impact on productivity*

To further investigate the seasonal characteristics of drought impact on vegetation productivity, we used monthly GPP data from the most severe drought years (2005 and 2010) to compare differences in seasonal reactions of vegetation during the 2 years. Figure 8 illustrates the variation in monthly GPP (along with temperature and precipitation) in the two severe drought years and previous years. Drought in 2005 was caused primarily by delayed monsoon rainfall and 2005 has been characterized as an El Niño year (Räsänen and Kummu 2012), which may contribute to the weather anomaly during this period. The water shortage in 2005 can be traced back to June 2004 and lasted until May 2005; precipitation was reduced by 19.9% during this period. In addition to this lower precipitation, higher temperatures occurred during the winter (January–February) of 2005; in particular, the monthly mean temperature for February 2005 was 2.4°C higher than the 12 year mean. The lack of precipitation associated with the 2010 drought can be traced

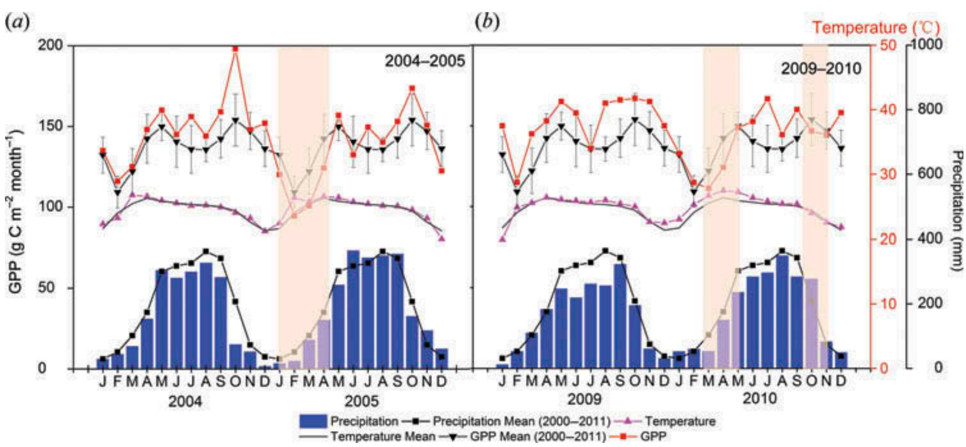

Figure 8. Monthly GPP, temperature, and precipitation averaged over the LMB in (*a*) 2004−2005 and (*b*) 2009−2010. The orange box denotes the period experiencing GPP reduction. For the 2000 −2011 GPP mean, the error bars denote mean ± standard error.

back to May 2009, and the annual total precipitation in 2009 was about 15.6% lower than the 12 year mean. Although precipitation increased in January and February 2010, the monthly total precipitation between March and December was 14.6% lower than the 12 year mean. Moreover, the monthly mean temperatures from January to May 2010 were higher than the 12 year mean (1.3°C, 1.2°C, 1.1°C, 1.1°C, and 1.3°C higher in January, February, March, April, and May, respectively). The regional drought in 2009 and 2010 has been attributed to the weakness of the 2009 southwest monsoon and its early withdrawal (MRC 2010). Zhou et al. (2011) found that the upper reaches of the Mekong River Basin experienced a lack of precipitation from November 2009 to January 2010, which caused most rivers to fall to their lowest levels on record (MRC 2010); this relative lack of available water affected groundwater, soil moisture, and the growth of plants in the LMB.

The meteorological differences between the two years likely contributed to the observed differences in the reduction of GPP. The decrease of GPP in 2005 was more severe than that in 2010 in terms of both intensity and duration. The reduction of GPP in both 2005 and 2010 occurred primarily in winter and spring. In 2005, GPP decreased by 9.1%, 13.6%, 17.5%, and 12.8% in January, February, March, and April, respectively. Conversely, in 2010, GPP reduction occurred during March and April, with decreases of 8.9% and 12.7%, respectively. The shorter duration and intensity of these GPP changes in 2010 can be explained by the fact that the stress conditions in 2010 were alleviated considerably by the exceptionally high precipitation in January and February, when precipitation increased by 68.4% and 12.9%, respectively. Our result is in accordance with other studies that have demonstrated that winter and spring droughts can affect productivity by shortening the length of the growing season and suppressing canopy development and peak leaf area, thus leading to a decline in annual net carbon uptake (Noormets et al. 2009).

As Cambodia was affected most severely by drought, we selected Cambodia as an example to further analyse the seasonal characteristics of the droughts during 2005 and 2010 (Figure 9). In 2005, 92.3% (7.7%) of Cambodia was hit by severe drought (mild drought); conversely, in 2010, 69.2% of Cambodia suffered from mild drought, with no severe drought recorded. Because drought in both years was either predominantly severe (i.e. in 2005) or entirely mild (i.e. in 2010), we simply calculated mean GPP for drought conditions (PDSI < –1) and did not separate our results into two levels of drought in the following analysis. Our results demonstrate that the drought in 2005 caused larger reductions in GPP than that in 2010 for all vegetation types. In 2005 (2010), drought occurred primarily in winter and early spring (spring and summer). However, the drought in 2005 can be traced back to 2004 and even to 2003 in some regions, when drought lowered the normal water levels and river flows (Te 2007). For all vegetation types, the reduction in GPP in 2005 began from January to July and lasted for 7 months; thus, these reductions persisted for a longer period than those in 2010 (January–June; 6 months). During January–April 2005, the decline of evergreen woodland and shrublands was the greatest (215.4 g C m^{-2}), followed by evergreen forests (211.9 g C m^{-2}), deciduous forests/woodland and shrublands (154.1 g C m^{-2}), croplands/vegetation mosaics (126.4 g C m^{-2}), and single-season croplands (64.0 g C m^{-2}). During March and May in 2010, GPP declined by 68.9, 62.4, 44.7, and 33.9 g C m^{-2} in croplands/vegetation mosaics, deciduous forests/woodland and shrublands, evergreen woodland and shrublands, and single-season croplands, respectively. In contrast to other vegetation types, the variation in GPP in 2010 for single-season croplands was very close to the 12 year mean; we attribute the less-pronounced effects of drought in this instance to human intervention (such as irrigation). The 2010 drought was

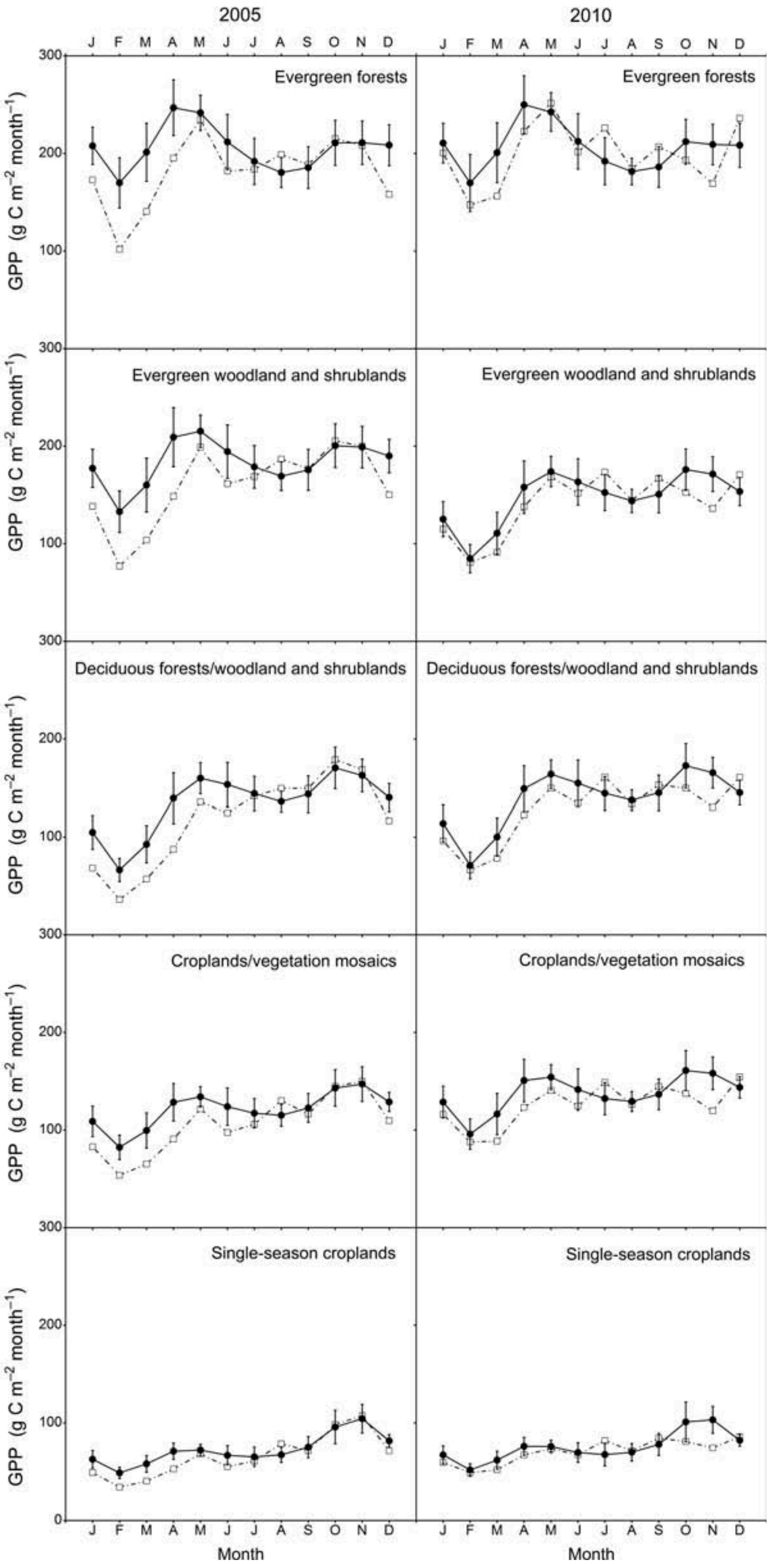

Figure 9. Monthly variations in regional mean GPP under drought condition (PDSI < –1) for 2005, 2010, and 2000–2011 average in Cambodia. The dashed and solid lines denote the 12 year mean and monthly GPP, respectively. For the 2000–2011 mean, the error bars denote mean ± standard error.

characterized primarily by mild drought, with no areas affected by severe drought. However, severe drought affected 92.3% of the study area in 2005, inducing larger reductions in GPP for one-season croplands in 2005 relative to 2010. Our results imply that, although human practices may mitigate the effects of drought on croplands to some degree, drought mitigation measures cannot prevent reductions in plant yield when drought becomes extreme (Shimizu, Masumoto, and Pham 2006).

To detect the impact of drought on different types of crops, we further analysed the variation in GPP between different vegetation types in the LMB within Vietnam (including the majority of the Mekong Delta) (Figure 10). The Mekong Delta is a large rural area, dominated by aquaculture and rice paddy cultivation. A dense and complex hydrologic network of man-made canals, dikes, and sluices used for transport and irrigation (Leinenkugel, Esch, and Kuenzer 2011) allows the cultivation of two-season (19.2%) and even three-season (7.8%) croplands. Only a small area of Vietnam within the LMB experienced drought (PDSI < –1) in 2010; therefore, we focused our analysis for this region in 2005. Large differences in the reduction of NPP can be observed between forests, woodlands and shrublands, and croplands in response to the 2005 drought (Figure 10). The GPP variations obtained for two-season and three-season croplands are approximately within the 12 year standard deviation, whereas evergreen forests and evergreen woodland and shrublands experienced large GPP reductions during January–July. Compared to croplands/vegetation mosaics in Vietnam and single-season croplands in Cambodia in 2005, two-season and three-season croplands in Vietnam were impacted less by the drought in 2005. In January, the GPP values of two-season and three-season croplands were 152.1 and 159.2 g C m^{-2} $month^{-1}$, respectively; these values are 18.6 and 20.9 g C m^{-2} $month^{-1}$ higher than the 12 year mean. It appears that farming practices can reduce the impact of drought, particularly through the use of different rice varieties in different harvest cycles. Most paddy fields in the Mekong Delta are planted with double irrigated-rice crops, double rain-fed rice crops, or triple irrigated-rice crops growing in different seasons (Sakamoto et al. 2006); therefore, the

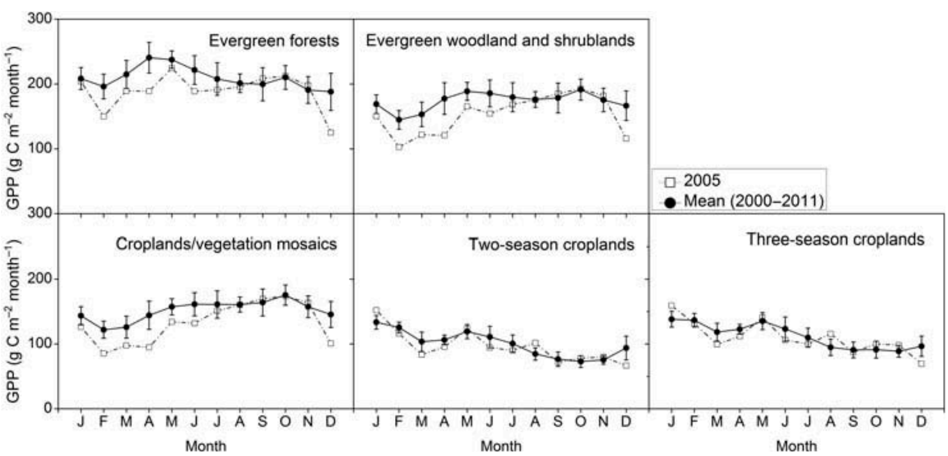

Figure 10. Monthly variations in regional mean GPP under drought conditions (PDSI < –1) for 2005, and the 2000–2011 average in the part of Vietnam within the LMB (including the majority of the Mekong Delta). The dashed and solid lines denote the 12 year mean and monthly GPP, respectively. For the 2000–2011 mean, the error bars denote mean ± standard error.

winter and spring drought in 2005 likely influenced only a short part of the total growing period for these croplands types.

4. Conclusions

In the present study, we investigated the impact of droughts on vegetation productivities in the LMB during 2000–2011. Several drought events occurred in the LMB during 2000–2011: mild droughts were observed in 2003, 2004, 2006, and 2007, whereas two severe drought events occurred in 2005 and 2010. Cambodia and Lao PDR were the countries affected most severely in 2005 and 2010, with PDSI values of –2.5 and –1.8, respectively. In terms of drought intensity, the drought in 2005 was more severe than that in 2010 and had a more significant impact on vegetation productivity in the LMB. For the entire study region, large reductions in NPP were found during both 2005 (14.7%) and 2010 (8.4%). The lack of precipitation during June 2004 and May 2005 resulted in GPP reduction (66.5 g C m^{-2}) during January–April 2005. Similarly, in 2010, the reduction in GPP (29.1 g C m^{-2}) between March and May could be traced back to a lack of precipitation that commenced in May 2009 and lasted until September 2010 (excluding January and February in 2010). The longer duration and larger deficit of precipitation in 2005 resulted in more severe drought in this year; thus, larger GPP reductions were observed in 2005 than in 2010.

Variations in NPP differed between vegetation types, and severe drought (PDSI < –2) exerted a greater impact on NPP than mild drought (–2 < PDSI < –1). In the LMB, the NPP of forests, woodlands, and shrublands exhibited larger reductions than that of croplands, which we attribute to the wider adoption of irrigation and other water-control measures in croplands, such as those in Cambodia and the Vietnam Mekong Delta. Furthermore, during the 2005 drought, two-season and three-season croplands in the Mekong Delta were impacted less by drought than single-season croplands in Cambodia and croplands/vegetation mosaics in Vietnam, likely owing to the more extensive irrigation and adoption of multiple harvest cycles in these two-and three-season croplands.

Although there are some limitations imposed by the quality of the MODIS productivity product, our study still provides an insight into how extreme climate may affect tropical and subtropical vegetation ecosystems in the LMB, a region that is critical to global bioecology. Our results suggest that, in regions in which conditions are appropriate for multi-season harvest (e.g. sufficient water supplies), local farmers could change rice varieties (i.e. cultivate two-season and three-season croplands) and adapt their harvesting and sowing cycles where applicable to reduce the effects of short periods of drought. Furthermore, improvements in irrigation technology may contribute to the mitigation of drought impacts in regions where irrigation is possible.

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