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Basin-wide Impacts of Climate Change on Ecosystem Services in the Lower Mekong Basin

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Abstract

Water resources support more than 60 million people in the Lower Mekong Basin (LMB) and are important for food security—especially rice production—and economic security. This study aims to quantify water yield under near- and long-term climate scenarios and assess the potential impacts on rice cultivation. The InVEST model (Integrated Valuation of Ecosystem Services and Tradeoffs) forecasted water yield, and land evaluation was used to delineate suitability classes. Pattern-downscaled climate data were specially generated for the LMB. Predicted annual water yields for 2030 and 2060, derived from a drier overall scenario in combination with medium and high greenhouse gas emissions, indicated a reduction of 9–24% from baseline (average 1986–2005) runoff. In contrast, increased seasonality and wetter rainfall scenarios increased annual runoff by 6–26%. Extreme drought decreased suitability of transplanted rice cultivation by 3%, and rice production would be reduced by 4.2 and 4%, with and without irrigation projects, relative to baseline. Greatest rice reduction was predicted for Thailand, followed by Lao PDR and Cambodia, and was stable for Vietnam. Rice production in the LMB appears sufficient to feed the LMB population in 2030, while rice production in Lao PDR and Cambodia are not expected to be sufficient for domestic consumption, largely due to steep topography and sandy soils as well as drought. Four adaptation measures to minimize climate impacts (i.e., irrigation, changing the planting calendar, new rice varieties, and alternative crops) are discussed.

Keywords

Lower Mekong Basin; Climate Change; Water Yield; Rice Cultivation; Adaptation

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Introduction

Water resource availability is recognized as crucial for agriculture, national economies and sustainable development in the Lower Mekong Basin (LMB) to secure food productivity and livelihoods for more than 80% of its population (Mekong River Commission, MRC 2011a). Further agricultural development is also important to support a rapidly increasing population and to improve human well-being in the region. Thailand and Vietnam are the world's top rice-exporting countries, and rice production in the LMB is sufficient to feed nearly five times the LMB's population. Demand for agricultural products from the LMB is expected to increase 20–50% in the next 30 years to support world population growth (MRC 2015). Besides the provision of food and water, the LMB has become one of the most active regions for hydropower development. The total installed power capacity of 26 existing medium and large dams on tributaries of the Mekong River is approximately 2700 MW but could potentially rise to 29,700 MW if all planned dams are completed (MRC 2011b).

The overall amount of water is not limited in the LMB, but some areas would be affected by altered rainfall patterns, particularly during the dry season from November through May (Linke 2014). Water shortages in the dry season have been observed and will be the major constraints to rice cultivation. Shrinking rice production in the LMB is a concern because it will affect the food security of an increasing world population and the livelihood of local communities (Jalota et al. 2012). Furthermore, the water distribution system is limited and varies greatly across the LMB (Phengphaengsy and Okudaira 2008). The most recent land use map shows that paddy fields cover approximately 28% of the region, or 15 million ha (MRC 2011b), but total irrigation areas encompass about 4 million ha, or 25% of paddy fields. In the dry season, less than 10% of paddy fields are irrigated.

Extensive studies on climate change impact on water resources in the LMB have been conducted in recent years (Mainuddin and Kirby 2009; TKK and SEA START RC 2009, unpublished data; Keskinen et al. 2010; Katzfey et al. 2013; Linke 2014; Parajuli and Kang 2014; Räsänen et al. 2016); however, the consequences of climate change on rice cultivation has received less attention. Furthermore, the studies were conducted at local or national scales (Chivannoand Snidvongs 2005, unpublished data; SEA START RC 2006, unpublished data; Sawano et al. 2008). The few basin-wide assessments (Mainuddin et al. 2011, 2013; Yamauchi 2014) were not spatially explicit and had contradictory results. Yamauchi (2014) indicated that baseline and future development scenarios will delay the transplant date for rain-fed rice due to drought risk, which may cause decreasing rice production across the LMB. Mainuddin et al. (2011, 2013) revealed that rain-fed rice yield may increase significantly in the upper part of the basin but decrease in the lower part, mainly due to less rainfall derived from the IPCC SRES A2 and B2 scenarios as simulated by ECHAM4 global climate model from 2030 to 2050.

To minimize unforeseen climate impacts at the basin level, the MRC established the Climate Change and Adaptation Initiative (CCAI) in 2009 as a basin-wide initiative to assist member countries in adapting to the impacts of climate change (MRC 2011c). A number of models have been developed in recent years to quantify and evaluate ecosystem services for decision making (Bagstad et al. 2013). Based on workshops with international, regional and national experts held in the LMB, InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs, Kareiva et al. 2011; Tallis et al. 2013) was selected because it is well documented and applied worldwide at multiple scales. InVEST has been used to evaluate impacts of land use and climate change in the LMB, including Thailand (Trisurat 2013; Trisurat et al. 2016), Cambodia (Hean 2014) and Vietnam (Ministry of Natural Resources and Environment 2013; Tue et al. 2014). InVEST also requires moderate data inputs (Bagstad et al. 2013), and most basin-wide data are available (MRC 2011b).

This study aimed to quantify the baseline distribution of water yield in the LMB (as of 2010), assess potential changes in spatial distribution of rainfall under climate change scenarios in near-term (2030) and long-term (2060), and evaluate potential impacts to paddy field suitability for rice production. Although InVEST is capable of predicting additional ecosystem services under climate change not presented in this study (e.g., carbon sequestration and timber harvest), our goal was to use the model to address water-related ecosystem services. However, the effect of altered river flow from hydropower projects situated in the upper basin were not included in the study, with flows typically manipulated in the mainstream (Kubiszewski et al. 2013).

Materials and Methods

Study area

The Mekong has a catchment area of 795,000 km^2, covering China (Yunnan Province), Myanmar, Lao PDR, Thailand, Cambodia and Vietnam. The Upper Mekong Basin located in China is known as the Lancang Jiang. It covers 24% of the total basin area and contributes 15–20% of the water flowing into the Mekong River (Food and Agriculture Organization of the United Nations, FAO 2011). The LMB includes the majority land area of Lao PDR and Cambodia, the northeast and part of northern regions of Thailand, and the Mekong Delta and Central Highland regions of Vietnam. The LMB covers 76% of the entire Mekong River Basin (Fig. 1). The LMB excludes the river and contributing watersheds north of Lao PDR, which are located in Yunnan province, China. The population in the LMB was 60.7 million in 2005 and is projected to be 78 million by 2030 (MRC 2011b).

Steep topography is predominant in Lao PDR, while flat terrain is common on the plateau in northeast Thailand. Landscape features in Cambodia and the delta in Vietnam are generally flat. The 2010 land cover map indicated that natural forests account for 41%, paddy fields for 28%, field crops for 8%, and miscellaneous for 23%. Thailand and Vietnam account for 56 and 11%, respectively, of total paddy fields (MRC 2011b). Approximately 60% of the area of the LMB is Acrisol defined as clay rich soil with high acidity and low fertility developed in areas of intense weathering and rapid leaching of nutrients that become a major problem in cultivation (Fukai et al. 1998; Suif et al. 2013). These soils are commonly forested, although acid-tolerant cash crops such as tea, coffee, rubber and pineapples can be grown with some success (MRC 2011b). Cambisol soils occur along river valleys in Lao PDR and Cambodia. Fertile soils derived from parent materials and alluvium deposits (Luvisol) are found in the Mekong Delta, northern Lao PDR, and northern Thailand. Gleysols found in wetlands and inundated areas are dominant in Mekong Delta and surrounding Tonle Sap. Other soil types include Luvisol, Leptosol, Ferralsol, Arenosol, and Fluvisol.

Mean annual rainfall ranges from less than 1000 mm in northeast Thailand to more than 3500 mm in north-central Lao PDR, due to the effects of topography and the southwest monsoon and cyclones from the South-China Sea (MRC 2011b). Previous studies have also found that mean annual rainfall in the LMB is affected by El Niño–Southern Oscillation (or ENSO events) on an approximately 10-year cycle (Räsänen et al. 2016). The rainy season is generally from May to October. The planting date for transplanting rice in the LMB typically begins in late May or early June and the growing period takes approximately 120–130 days.

Methodology

There are five main steps in the assessment: (1) gather future climate scenarios, (2) calculate water yields, (3) evaluate land suitability for paddy, (4) integrate irrigation scheme, and (5) assess changes in suitability classes (Fig. 2).

Gathering climate scenarios

There is a broad range of future climate scenarios projected by Global Climate Models (GCMs) and different GCMs provide different projections. In this research we used three GCM scenarios generated by CMIP3 and CMIP5 based on the MRC selection criteria. The selected scenarios include (1) drier overall (GISS-E2-R-CC or GS) as the lower bound from CMIP5, (2) wetter overall (GFDL-CM3 or GF) from CMIP3 as the upper bound, and (3) increased seasonality (IPSL-CM5A-MR or IS from CMIP5, drier dry season and wetter wet season combined). More information about SimCLIM and the original reference (Warrick 2009) are provided (http://www.climsystems.com/resources/publications/).

In addition, three different greenhouse gases emission scenarios (low emissions (RCP2.6), medium emissions (RCP4.5) and high emissions (RCP8.5) emerged from the IPCC AR5 report were added to provide nine plausible climate projections across the LMB (CCAI 2015). These nine scenarios were aligned with temporal scales of baseline (average during 1986–2005), near-term future centered on 2030 (2021–2040), and long-term future centered on 2060 (2051–2070).

The original GCM outputs contain very coarse resolution (grid size varies from 64–640 km × 64–640 km), which are not suitable for the LMB. Therefore, they were downscaled to 1-km resolution using SimCLIM tool SimCLIM is an open-framework software package designed by CLIMsystem. A preliminary case was conducted to assess the effects of low rainfall conditions on household water tank systems in Australia (Warrick 2009). This software tool becomes popular and has been used for a variety of projects in many different locations around the world (http://www.climsystems.com/resources/publications/). SimCLIM was selected because it offers the broadest set of information in terms of coverage of nearly the full set of GCMs and all the greenhouse gas emission scenarios, as well as RCPs used in the IPCC's reports (ESM 1). The derived data are easily updateable and affordable in terms of time and finances required to extract and to analyze the climate change projection information. In addition, it is able to be stored, accessed and transferred across the MRC, its member countries and other stakeholders (CCAI 2015). We used Nash–Sutcliffe efficiency (NSE) to quantitatively describe the performance of SimCLIM rainfall output. The observed average annual rainfall at weather stations across the LMB during 1986–2005 was compared with pattern-downscaled output. The results indicated that the NSE was 0.87, the root-mean-square error (RMSE) was 0.89, which are acceptable (Benaman et al. 2005; Moriasi et al. 2007). Please see Table S1 for details.

The downscaled climate data derived from SimCLIM indicated that annual rainfall in the LMB is expected to increase from 1697 mm at the baseline to 1831 mm in 2030, and to 1968 mm in 2060 under the wetter overall GCM forecast (Table 1). The maximum increment of 344 mm, or 20% from the baseline, is predicted in Vietnam in 2060. In contrast, substantial loss of annual rainfall is expected in northeast Thailand in 2030 under the combined drier condition and medium emissions (RCP4.5), and in 2060 under the drier condition and high emissions (RCP8.5). Low emissions (RCP2.6) would also increase temperature about 0.4°C across the LMB. Rising temperatures (by 1.5 and 3°C) are expected for the medium emissions (RCP4.5) and medium climate sensitivity, and for high emissions (RCP8.5) and high climate sensitivity, respectively.

Calculating water yield

The InVEST Reservoir Hydropower Production model (also “Water Yield” model) (Tallis et al. 2013) was employed to estimate annual surface water yield. The InVEST model utilizes a gridded map of the study area to forecast annual average water quantity from each subwatershed. InVEST calculates the amount of water from each pixel as precipitation minus evapotranspiration, then sums and averages water yield for each subwatershed and watershed subsequently as annual runoff. The InVEST water yield model hydrologic input is annual average precipitation at each pixel (1 km^2 is this study) and is based on the Budyko curve (Zhang et al. 2001). InVEST does not differentiate between surface runoff, subsurface flow and base flow. Required input data in the InVEST model included land use/land cover (LULC), annual precipitation, soil depth, annual reference evapotranspiration (ETo), plant available water content (PAWC), watershed and subwatershed boundaries, maximum root depth and the evapotranspiration coefficient (K_c).

The ETo was derived from the modified Hargreaves equation (Subburayan et al. 2011) based on maximum and minimum monthly temperature and monthly precipitation. In addition, PAWC values from 0 to 1 were generated from soil texture and organic matter (Saxton and Rawls 2006). Soil texture and effective soil depth was obtained from the Harmonized World Soil Database v1.2 from IIASA (FAO/IIASA/ISRIC/ISSCAS/JRC 2012). Grid resolution of 1 km was used for all spatial analyses because it was appropriate for landscape scale (basin-wide) and consistent with climatic data, soil map and LULC map. The generic maximum root depth (mm) was obtained from Canadell et al. (1996). The K_c value for each land use type was gathered from previous studies (Allen et al. 1998; Pukngam 2001; Tanaka et al. 2008; Guardiola-Claramonte et al. 2010). Seasonality factor or Zhang value (Z) representing rainfall distribution and rainfall depths was assigned at 4 because the LMB region is influenced by monsoons and the wet and dry seasons are distinct (Tallis et al. 2013; Trisurat

2013). Accuracy of the predicted water yields was validated with measurement data from selected reservoirs using the NSE and RMSE.

Evaluating land suitability for paddy

This research employed the Land Evaluation Framework developed by FAO (1976) and the Land Development Department of Thailand (Tansiri and Saifak 1999) to determine suitability classes for transplanting paddy for both present and year 2030. Combined drier overall (GS) and medium emissions (RCP4.5) in 2030 was selected because this scenario generates less annual rainfall in comparison to the combined drier condition and high emissions (RCP8.5) in 2060, while other scenarios provide more rainfall (Table 2). In addition, drought is considered a major constraint to crop production in the LMB. Importantly, this timeframe (2030) is relevant to the ongoing Basin Development Plan (MRC 2011a) to be implemented by all member countries. The MRC was evaluating food security under climate change resulting from reduced water yield and was selected as the near-term date for comparison to baseline as opposed to 2060 (MRC 2012).

The FAO framework used a matching approach between crop growth requirements and land conditions which consists of four steps: (1) selecting land quality factors, (2) class-determining score rating, (3) calculation of suitability scores, and (4) determining overall suitability class. Generally, there are 13 land quality factors of crop requirements, land management and conservation practices (FAO 1976; Tansiri and Saifak 1999), but our research used five factors highly related to climate and important factors for rice production (Table 2).

Rating scores of 1.0, 0.8, 0.5 and 0.0 were assigned to each land quality unit (LQC) according to suitability class—high (S1), moderate (S2), low (S3) and not suitable (N) (FAO 1976). They were rated according to land performance or average yield productivity obtained from each factor if other factors were stable. Four land quality factor ratings for crop requirement (LQC1-4) were then multiplied to obtain a tentative suitability class (Eq. 1), and later multiplied with land management and conservation unit (Eq. 2), as shown below.

$$\text{Crop requirement suitability scores (CRS)} = (\text{LQC1} \times \text{LQC2} \times \text{LQC3} \times \text{LQC4})$$

$$\text{Overall land suitability} = \text{CRS class} \times \text{management class}$$

where LQC1 is for temperature, LQC2 for water availability, LQC3 for aeration, and LQC4 for rooting (see Table 2 for details). The accumulated scores (Eqs. 1 and 2) were reclassified into overall suitability classes: 0.8–1.0 as S1, 0.4–0.8 as S2, 02.2–0.4 as S3, and < 0.2 as N (FAO 1976).

Integrating irrigation scheme

The existing irrigation areas in the LMB were gathered from the Atlas of LMB report (MRC 2011b). The irrigation areas were assigned as the current adaptation strategy. If any paddy patch was located in an area with an irrigation system, the previous class (e.g., S2) was upgraded to the next suitable class (e.g., S1); otherwise, it remained the same.

Assessing changes in suitability classes

The predicted suitability class maps for paddy at baseline and future conditions under drier overall (GS) scenario combined with medium emission—namely, without and with irrigation scheme were assessed in terms of change in total extent among classes.

Results

Predicted water yields

The estimated amount of annual water runoff in the entire LMB derived from InVEST at the baseline was 635 million m^3 and the average rainfall depth per pixel was 1024 mm, or approximately 59% of total rainfall. Contributions of annual flow from Thailand, Lao PDR, Vietnam and Cambodia were 154, 251, 78.1 and 151.8 million m^3, respectively. The highest runoff depth of 1314 mm, 65% of annual precipitation, was found in Vietnam, followed by Lao PDR (1097 mm), Cambodia (953 mm) and Thailand (887 mm). The minimum runoff depth of 366 mm (only 25% of annual precipitation) was located at the Nam Mae Kham subwatershed in northern Thailand (subwatershed 8 in Fig. 1). In contrast, Nam Hinboun subwatershed (subwatershed 47 in Fig. 1), situated in the central-west part of Lao PDR, generated the highest runoff depth of 82% of annual precipitation and five additional subwatersheds drained more than 70% of annual precipitation.

Landscape features are important to surface runoff. The tributary situated in Thailand contributes approximately 24% of the total annual water runoff while covering about 30% of the entire LMB. By contrast, Lao PDR contributes nearly 40% of the annual flow, although it covers only about 33% of the basin. This is due to the fact that most areas of the subwatershed in Thailand (Khorat plateau) have sandy soil with low water retention. Also, a number of areas in Lao PDR are classified as mountainous, and surface water reaches outlets faster due to the elevation gradient.

The predicted annual water yields in 2030 and 2060 were derived from drier overall projections, in combination with medium and high emissions in short- and medium-terms, which indicated a substantial reduction of predicted water yields by 9–24% from baseline runoff. It should be noted that runoff percent change from baseline was reduced 25% for 2030 and 10% for 2060 (with medium emissions). Note in Table 1 average annual rainfall is 1421 mm (2030) and 1587 mm (2060) for GS and RCP4.5. With high emissions RCP8.5 the precipitation values approximately reverse to 1592 mm (2030) and 1454 (2060). This is the reason for the pattern of runoff reduction for the GS scenarios in 2030 and 2060 in Fig. 3. Greater impact was predicted in the north (subwatershed 1) in Fig. 1 and in the central part of Lao PDR (subwatersheds 26, 28, 322, 36 and 37) and in parts of subwatersheds 42 and 47 situated along Thailand and Lao PDR borders, as shown in Figs. 1 and 4. Moderate water yield reduction was predicted in western Cambodia (subwatersheds 80, 84, 85, 92, 96, 100 and 102) and partial areas of subwatersheds 71, 77, 86 and 103 (Mekong Delta) (Figs. 1, 4). A similar amount of annual rainfall as the baseline was predicted under low emissions in both near- and long-term. A greater water yield loss (39%) was predicted in Lao PDR under the long-term, drier scenario due to decreased rainfall that affects that country more than others in the LMB. The regions of greatest water yield reduction of north and central Lao PDR correspond to regions of substantially reduced average annual precipitation in the GCM (Fig. 4). Increased seasonality and wetter climate (increased annual rainfall by 10–20% from the baseline) in connection with greater emissions would result in an amplification of 6–26% runoff basinwide relative to baseline.

Predicted water yield (635 million m^3) derived from the InVEST model was approximately 13% greater than the mean annual Mekong River flow that reached the South China Sea from 1960 to 2004 (MRC 2012). The NSE value calculated from 15 subwatersheds (4 for Thailand, 7 for Lao PDR, 2 for Vietnam, and 2 for Cambodia) ranging from 300–28,678 km^2 was 0.94. RMSE was 0.95 (Table S2). These values were acceptable among hydrological scientists (Moriasi et al. 2007). In general, NSE values are relatively high in small catchments situated in intact ecosystems that are not dominated by human activities; for example, the NSE value of 0.81 was obtained from the Thadee catchment in southern Thailand (Trisurat et al. 2016).

High reduction of annual flow from the baseline was predicted in central and northern parts of Lao PDR in 2030 under the drier climate with medium emissions, especially at Nam Ou subwatershed (40%) (subwatershed 1 in Fig. 4). Moderate loss was predicted along the tri-national borders of Thailand, Lao PDR and Cambodia.

Land suitability for paddy

Although the growing season varies within the LMB and changes from year to year, the rainy season spans approximately late May to November. The LMB was divided into four classes for transplanting paddy based on mean temperature in growing season, water requirement in growing season, slope, effective root depth, and soil drainage (Table 2). Results for baseline and 2030 under drier overall projection combined with medium emissions is shown in Table 3 (and Figs. 5, 6).

The suitability assessment showed that almost 36% of the LMB was classified as highly suitable for rice and 20% was moderately suitable. In addition, 10.4% of the LMB was low or marginally suitable due to severe limitations of slope, water availability and soil texture (Fig. 5). Furthermore, 34% of all paddy areas at the baseline was not suitable (Table 3), meaning less than 20% of average yield productivity would be obtained from the high suitability class (FAO 1976). Under the predicted drier overall climate in combination with medium emissions in 2030, highly suitable (S1) relatively declines to 33%, and approximately 14% of the existing highly suitable class will be downgraded to moderately suitable (S2), mainly due to a lack of available water in the growing season. Although the total extent of moderately suitable (S2) and low or marginally suitable classes (S3) now and in the future are similar, the spatial distribution would be significantly altered from class to class and place to place. For instance, approximately 25% of the current moderately suitable class was predicted to become low suitable (S3; 13%) and not suitable for paddy (N; 12%) in 2030 under the drier overall climate combined with medium emissions scenario.

The most affected areas were in northeast Thailand and northwest of Tonle Sap in Cambodia where large patches of the moderately suitable class were predicted to become not suitable (Fig. 6). Paddy fields situated in central and northern Lao PDR and western Cambodia remain not suitable due to predicted severe drought, steep slope, shallow soil and coarse soil texture. The reduction of annual rainfall of 200–300 mm in the Mekong Delta of Vietnam (Fig. 4) does not affect the suitability class due to the current and future rainfall in a growing season that already exceeds 900 mm; this area is therefore still classified as highly suitable for paddy (Table 2).

Existing total irrigated area in the LMB is estimated at 4 million ha of which Vietnam accounts for 56%, Thailand 36%, Cambodia 7% and Lao PDR 2% (MRC 2011a). Irrigation projects improve paddy from moderately suitable to highly suitable, that is, from 33.29% of total paddy area to 35.49%. However, irrigation only marginally improves low and not suitable classes due to limitations of erosion hazard and soil texture.

Discussion

Water yield and model performance

The substantial difference between observed and predicted water yields in the entire LMB may be related to agricultural withdrawals and hydropower diversion, such that substantial water withdrawal occurs along the mainstream before it reaches the South China Sea. MRC (2012) and FAO (2011) reported that total water withdrawal was estimated at 62 million m^3 and withdrawal for irrigation accounts for 90% of the total. Of the amount withdrawn for crop irrigation, surface water diversion accounts for 97% (rather than groundwater extraction). In the last decade, total paddy field in the LMB (MRC 2011b) increased from 138,700 km^2 in 2003 to 162,700 km in 2010. Thus, a significant amount of surface water is expected to be diverted from river channels because less than 10% of the total paddy fields are irrigated in the dry season (MRC 2011b). For example, about 47 million m^3 was pumped from the Mekong River into the Huai Luang River of Nong Khai province, Thailand (http://www.abc.net.au/news/2016-03-18). In addition, a number of hydropower plants have been constructed along the mainstream, especially in China and Lao PDR. In fact, Article 5 of the Mekong Agreement of 1995 stated that projects on the tributaries of the Mekong River are subject to ‘notification’ to the MRC’s Joint Committee, especially water diversion from the mainstream in the dry season. The amount of total water diverted is not officially recorded though.

Altered paddy suitability and food security

We focused on transplanting rice in the wet season, because this accounts for more than 90% of the total annual rice production in the LMB (Mainuddin et al. 2011; MRC 2011c; Yamauchi 2014). Variation in rainfall amount and distribution due to climate change is important for rice production and the overall livelihood of the LMB population (MRC 2012; Furuya et al. 2014). Model results indicated that drier climate in combination with the medium emission scenario would decrease water yield by 25% from the baseline in 2030. The mechanism responsible for the pattern of runoff reduction shown in Fig. 3 is largely related to average annual rainfall differences between 2030 and 2060. Trisurat et al. (2016) indicated that rainfall is a strong factor to explain the predicted reduction of the runoff.

The changes of runoff reduction (Fig. 3) would subsequently lessen the area of high suitability for transplanting rice production by approximately 3% from the baseline, but increase the moderately suitable class by 1% (Table 3). The International Rice Research Institute (IRRI) reported that the average yield of rice production in 2000 ranked from 1.99 ton/ha in northeast Thailand to 4.19 ton/ha in Vietnam (http://www.irru.org/science/ricestat/data/). Using these statistics and the expected average yield from each suitability class (FAO 1976), the estimated rice production in the LMB would decline 4.2% from the baseline, 4.0% if existing irrigation projects were taken into account (FAO 1976; Tansiri and Saifak 1999). The highest reduction rate of 8.2% was predicted for Thailand, with reductions of 3.7% for Lao PDR and 1.0% for Cambodia which is due to soil fertility and sandy soil (Fukai et al. 1998). Rice production is predicted to be stable in Vietnam since there is no substantial reduction of annual rainfall predicted in 2030 (Table 2 and Fig. 4).

Thailand and Vietnam are ranked in the top five of the world’s rice exporters. In 2010, they exported 8.9 and 6.9 million metric tons, respectively, while rice production in Lao PDR and Cambodia was generally sufficient for domestic consumption (http://ricestat.irri.org/mistig/demos/php/global.php). Using average rice consumption per capita, annual population growth rate, and effects of climate change on land suitability mentioned above, it is expected that rice production will be enough to feed the population of 78 million predicted in the LMB in 2030 (MRC 2011b). Thailand and Vietnam will still have higher production than domestic consumption, but production in Lao PDR and Cambodia is not expected to be enough to support their additional populations of 4 and 5 million, respectively, in 2030 (http://www.esa/un.org/undp). Results of this study are similar to findings of Mainuddin et al. (2011) and Yamauchi (2014), although derived from different crop models and climate scenarios (A2 and B2 climate projections) which indicated that agriculture in Lao PDR, particularly rice cultivation, will be vulnerable.

The predicted impact on paddy suitability area (potential rice production) is different from Chinvanno S and Snidvongs A (2005, unpublished data), SEA START RC (2006, unpublished data), Yamauchi (2014) and Mainuddin et al. (2011). Previous studies indicated that rain-fed rice production would increase in the upper LMB and decrease in the lower part which is largely due to different climate data and crop modeling techniques (Aggarwal and Mall 2002; Schipper et al. 2010; IPBES 2016). The current study used high resolution (1 km^2) climatic data provided by the SimClim database for the LMB (CCAI 2015). The future scenario was also based on the drier overall lower bound in combination with medium emissions (RCP4.5) projected for 2030, while other studies used IPCC SRES A2 and B2 scenarios. SRES climate data have a coarse resolution of 0.1° (about 10 km × 10 km) or 0.2° (about 20 km × 20 km) and do not match the scale of paddy field in the LMB, which are relatively small due to steep topography. Paddy fields are largely hand cultivated and therefore labor intensive, which also tends to result in smaller fields.

Predicted climate data used in this study indicated that annual rainfall in 2030 would decrease by 250 mm from the baseline (Table 1) although the IPCC SRES A2 and B2 scenarios predict greater annual precipitation in sub-catchments of the LMB from 0–25% per year (Chinvanno S and Snidvongs A 2005, unpublished data) and 12–32% (Mainuddin et al. (2011) from the baseline, with the greatest increases projected for Lao PDR. These values are similar to a wetter overall projection (Table 1). It is widely recognized that rainfall in the growing season is the most important factor for rice production (FAO 1976; Tansiri and Saifak 1999), with a positive correlation between increased rainfall and rice yield (Mainuddin et al. 2011; Yamauchi 2014). The predicted increased mean temperature ranging from 0.5–1.5°C derived from SimClim and SRES A2 and B2 scenarios were similar. In addition, all studies predicted the maximum temperature would not be greater than 35°C during the growing season and thus it would not have direct impact on rain-fed rice production (Table 2; Tansiri and Saifak 1999).

Mainuddin et al. (2011) used the AquaCrop model (Raes et al. 2009) in which rice yield depends on planting date, fertilizer application, pesticide and herbicide application, and crop management (analysis was done at the provincial level). Yamauchi (2014) used the Integrated Water Quantity and Quality Model (IQQM) and similar data inputs to ours but conducted the assessment at site scale. Our analysis used InVEST and the land evaluation method, which are spatially explicit (cell-based) across the entire LMB. Based on different climate data input and crop models, uncertainties and dissimilarities between this and previous studies were observed.

Adaptation measures

Adaptation measures to minimize climate change impacts on agriculture include changing the planting calendar, managing the water supply, and using new crop varieties or alternative crops (e.g., Hasegawa et al. 2008; MRC 2012; Mainuddin et al. 2013; Bastakoti et al. 2014). The effectiveness of adaptation practices varies with location, and this study deals only with the irrigation system as a means of managing supply. Approximately 11,420 irrigation projects are currently in operation, and irrigated areas cover 4 million ha, with 87% is irrigated for wet season rice, 31% for dry season rice, and 37% for rice cropping between wet and dry seasons mainly found in Vietnam and Cambodia (MRC 2015). The Basin Development Plan (BDP) also aims to increase irrigation to 6 million ha total by 2030 (MRC 2011b).

Mainuddin et al. (2011) revealed that supplementary irrigation during the growing season would increase rice yield by 30% from the baseline for A2 and B2 scenarios in selected sub-catchments of the LMB because water availability is the limiting factor (Tansiri and Saifak 1999). Our basin-wide results indicated that irrigation projects improve the moderately suitable class to highly suitable (Table 3), largely due to other environmental constraints such as erosion hazard and soil texture (FAO 1976; Fukai et al. 1998; Tansiri and Saifak 1999; Suif et al. 2013). It is questionable whether new irrigation projects can improve rice production because the limiting factors are likely permanent and cannot be addressed by irrigation.

Among the four tributary countries, Vietnam has the largest irrigation areas but expansion of irrigated rice in the delta is restricted by unavailable land, acid sulfate soils and salt water intrusion (MRC 2011b). Thailand has the most irrigation projects, located along river channels and in the floodplain surrounding large reservoirs; however, saline soils, high groundwater tables, and accessibility to surface water runoff are major constraints for planned irrigation. Further projects will therefore be predominantly related to water diversion from the Mekong and likely located near mainstream channels. Paddy fields are widely distributed across northeast Thailand; however, planned projects would not significantly mitigate drought (Figs. 5, 6).

Lao PDR has relatively few irrigation areas compared to the other tributary countries, but it has ambitious plans to increase irrigated areas by 240 and 460% for upland crops and dry-season rice, respectively, by 2030 (MRC 2011b). Low suitability and not suitable areas for paddy are mainly limited by steep terrain and soil texture (Fukai et al. 1998; Suif et al. 2013). Cambodia plans to develop 32 new projects to cover an additional 6000 ha of irrigated area by 2030. Because most irrigation increases will likely be expansions to existing projects (MRC 2011b), new irrigated areas will maintain high suitability for rice cultivation and will upgrade existing classes around Tonle Sap (Fig. 6).

Previous studies (Hasegawa et al. 2008; Mainuddin et al. 2011, 2013) indicated that changing planting dates by 2 weeks earlier or later would increase or decrease rice yield from the baseline in certain areas for A2 and B2 scenarios. This is because changing the planting date directly affects distribution of water during the growing period. There are also extensive studies involving drought tolerance in rice varieties (Sawatdikarn and Kansomtob 2012; Kumar et al. 2014). Sawatdikarn and Kansomtob (2012) indicated that Hom Thung, Chainat 1 and Suphan Buri 3 rice varieties had the greatest drought tolerance index among 15 varieties commonly planted in Thailand, making them suitable for predicted drought areas.

Although this study did not conduct cost–benefit and economic return analyses, these are important factors to consider. Rice prices in the world market rapidly declined from US$600 per ton in 2012 to US$360 per ton in 2015, while the average investment cost for that period was US$470 per ha (Office of Agricultural Economics 2015). A likely alternative crop is sugar cane because it requires less water and grows well in loamy sand (Tansiri and Saifak 1999). Sugar cane prices have been mostly stable for the last 5 years at US$25–27 per ton. The average production of sugar cane is 76 ton/ha and the average investment is US$741 per ha (Office of Agricultural Economics 2015). The net economic return for sugar cane is US $1260 per ha per year, while the range for rice is US$556–1240. The alternative crop may not be suitable for areas that can grow a second and third crop, as in the Mekong Delta; nevertheless, adaptation measures need to recognize hydroclimatic variability resulting from ENSO events. Adaptation practices must also consider social perceptions and should not be restricted to model predictions (Räsänen et al. 2016).

Conclusions

This study demonstrated that future climate change scenarios specifically developed for the LMB (i.e., drier, wetter and increased seasonality) will affect water yield and rice cultivation in the tributary countries. Previous studies used coarse global climate data and focused on more rainfall derived from A2 and B2 scenarios. Effects of drier climate overall in combination with medium emissions were substantial and would reduce annual water yield by approximately 24% from the baseline runoff. Although the overall impact at the entire LMB is not large, it was unequally distributed across the LMB landscape. The largest reduction of suitable areas for rice cultivation was predicted for Thailand, followed by Lao PDR and Cambodia, but was minimal for Vietnam. Thailand and Vietnam can produce more rice than is consumed, but Lao PDR and Cambodia are expected to face food security shortage problems and will likely need to import rice for larger populations by 2030. Although this study broadly considered irrigation as an adaptation, we also discussed other options including changing planting dates, trying new rice varieties and/or new crops, particularly sugar cane. These are both simpler and more cost-effective than altering irrigation systems. The above adaptation measures must recognize hydroclimatic uncertainty as the result of ENSO events in the region. Our results advance and demonstrate scientific understanding of climate change and the utility of spatially-explicit models that forecast water yield to evaluate consequences for rice cultivation for the entire LMB as well as individual tributary countries. The results also aid the MRC and its member countries by supporting them in basin-wide climate change adaptation strategies.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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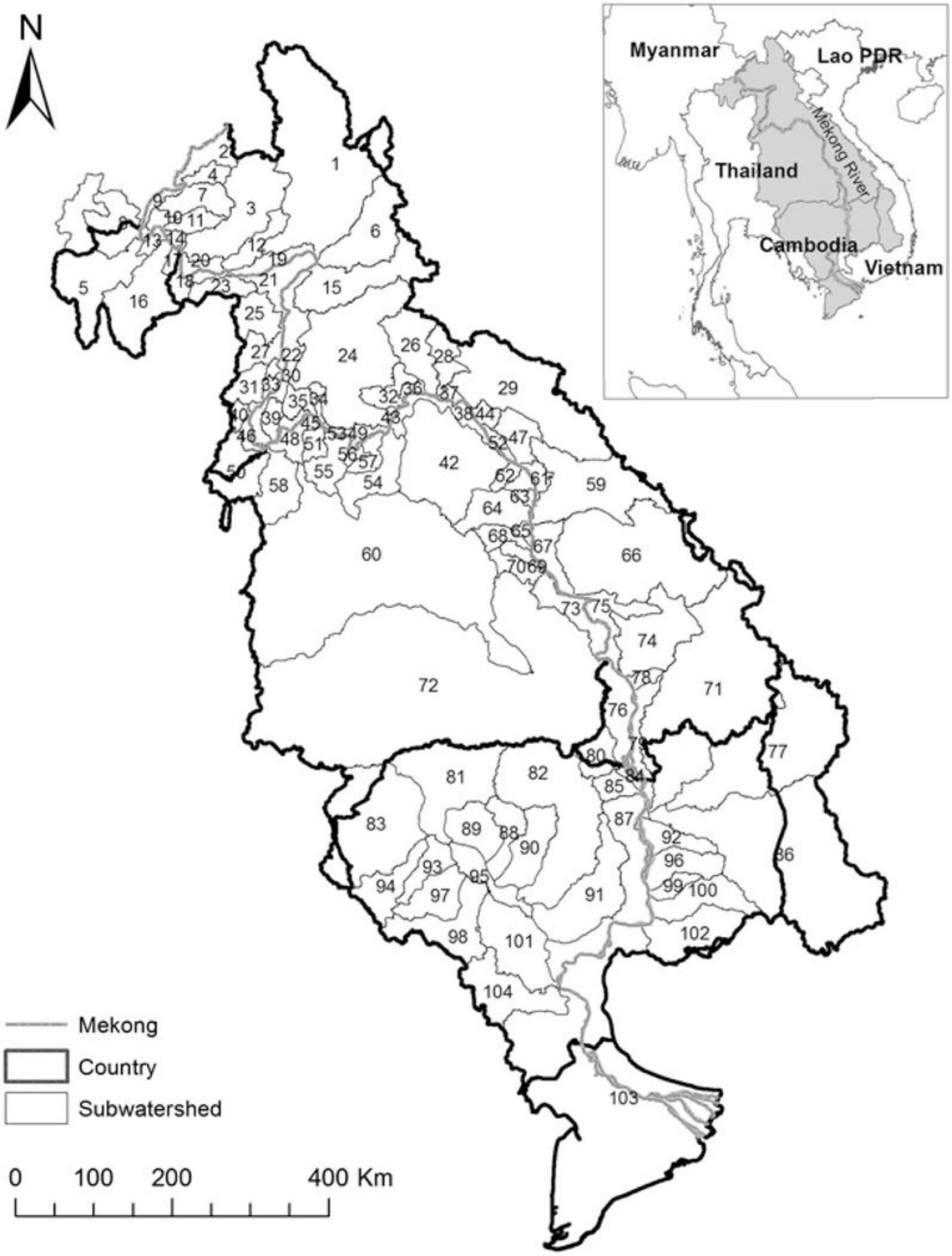

Fig. 1.

Location of subwatersheds in the Lower Mekong Basin

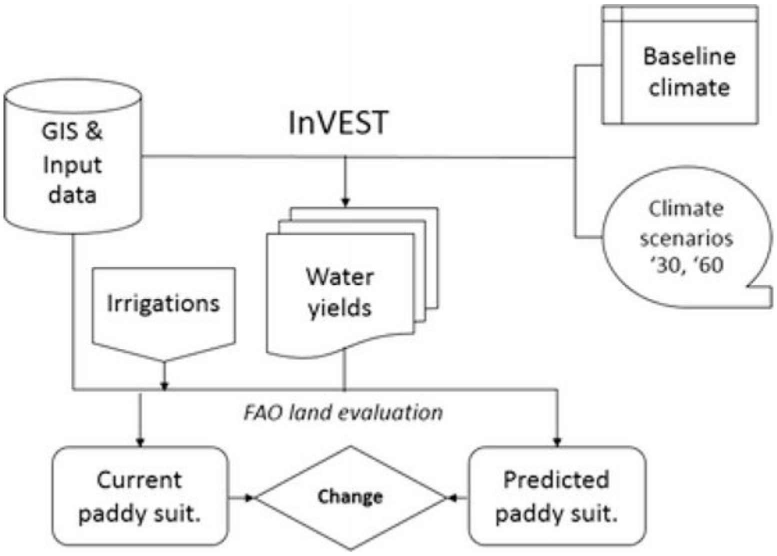

Fig. 2.

Flowchart illustrating study methodology. *FAO* Food and Agriculture Organization of the United Nations, *InVEST* Integrated Valuation of Ecosystem Services and Tradeoffs Model

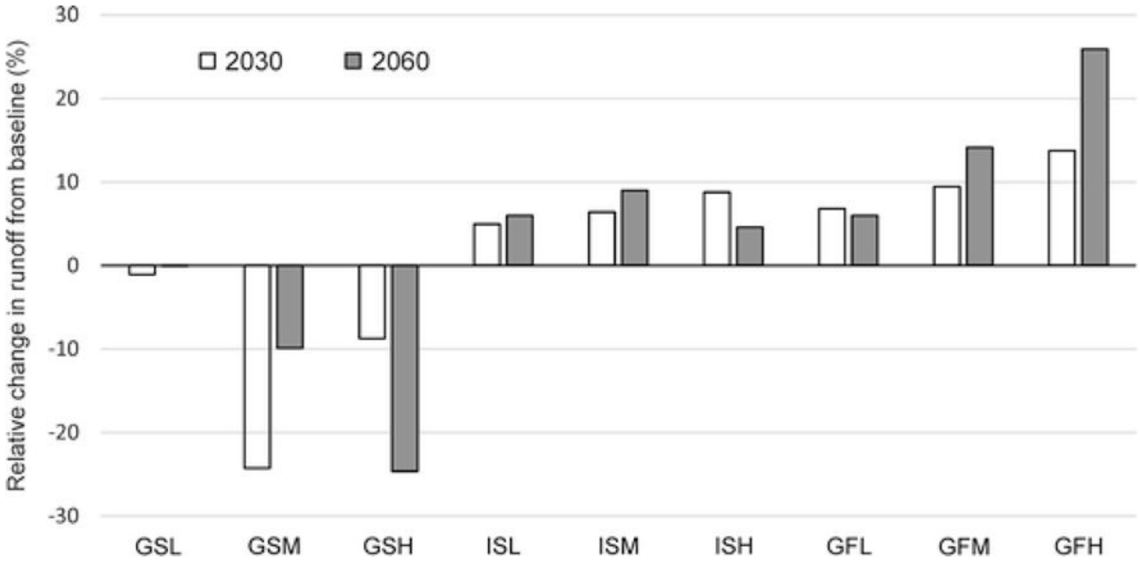

Fig. 3.

Relative changes of predicted water yields from the baseline (%) average (1986–2005). *GSL* Drier overall climate and low emissions scenario, *GSM* drier overall climate and medium emissions scenario, *GSH* drier overall climate and high emissions scenario, *ISL* increased seasonality and low emissions scenario, *ISM* increased seasonality and medium emissions scenario, *ISH* increased seasonality and high emissions scenario, *GFL* wetter overall climate and low emissions scenario, *GFM* wetter overall climate and medium emissions scenario, *GFH* wetter overall climate and high emissions scenario

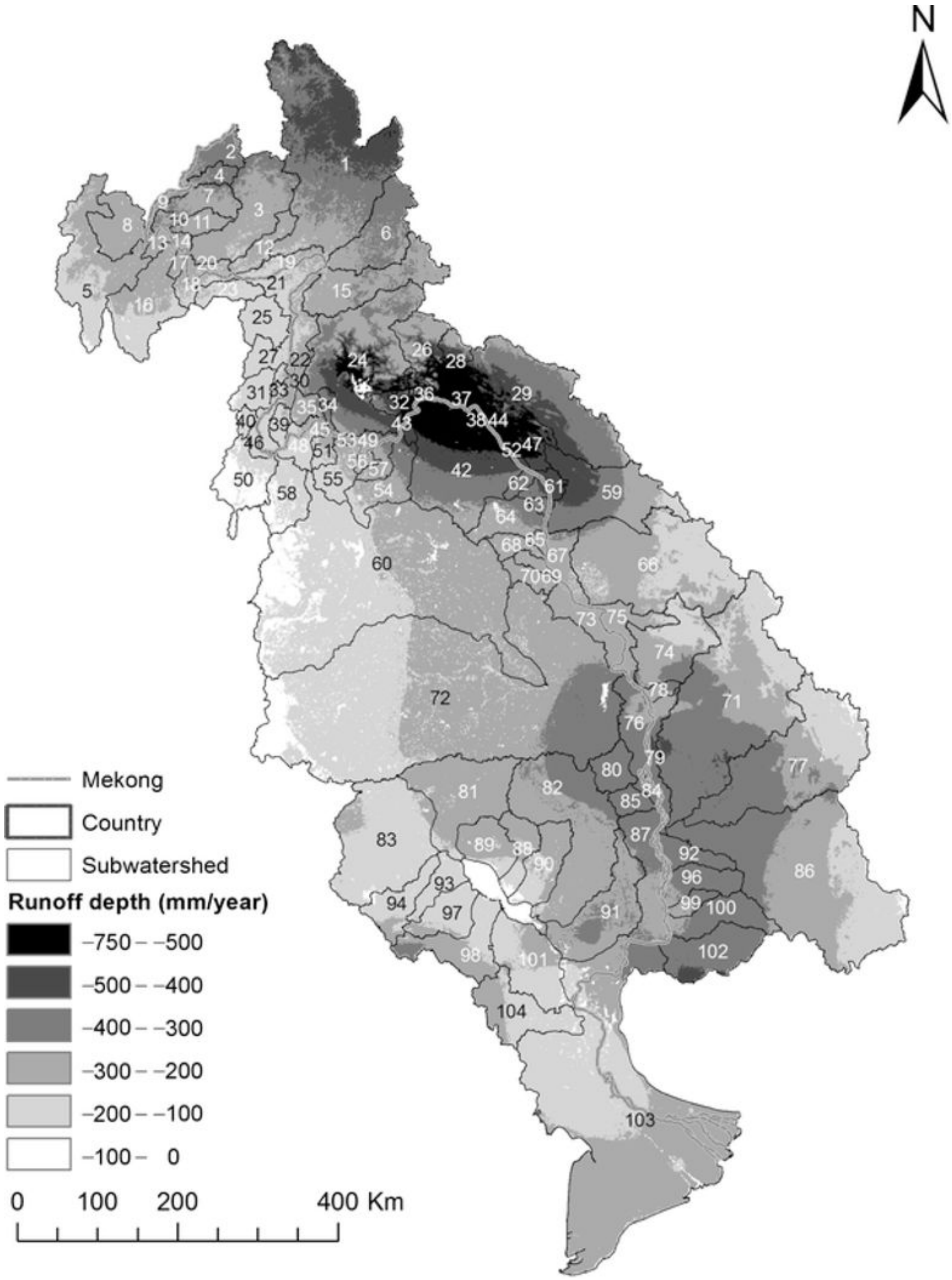

Fig. 4.

Change in annual runoff depth (mm/year) between baseline (average 1986–2005) and a drier overall climate in combination with medium emissions in year 2030 (negative values indicate decreased water yields)

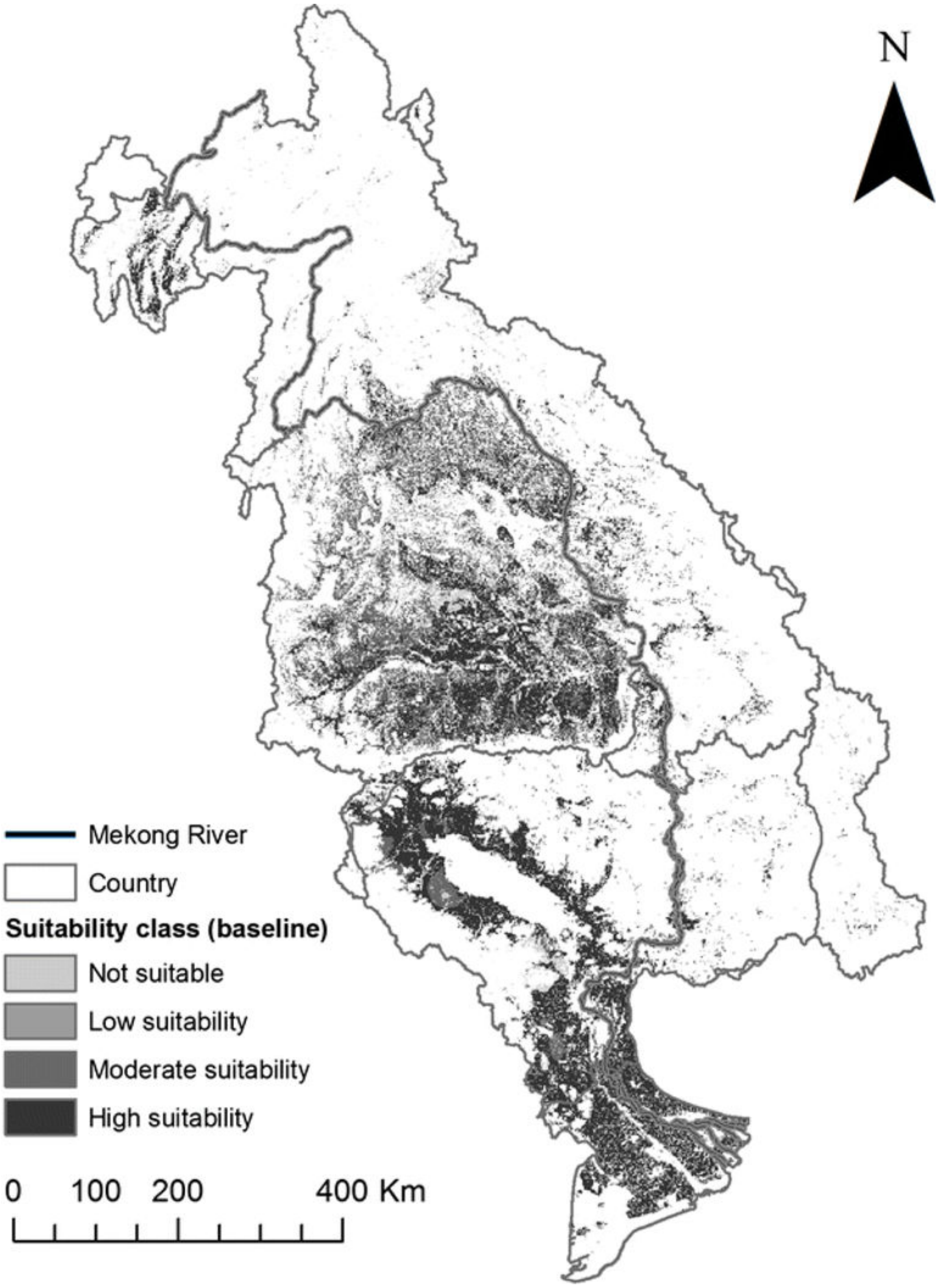

Fig. 5.

Land suitability for paddy at baseline year (average during 1986–2005)

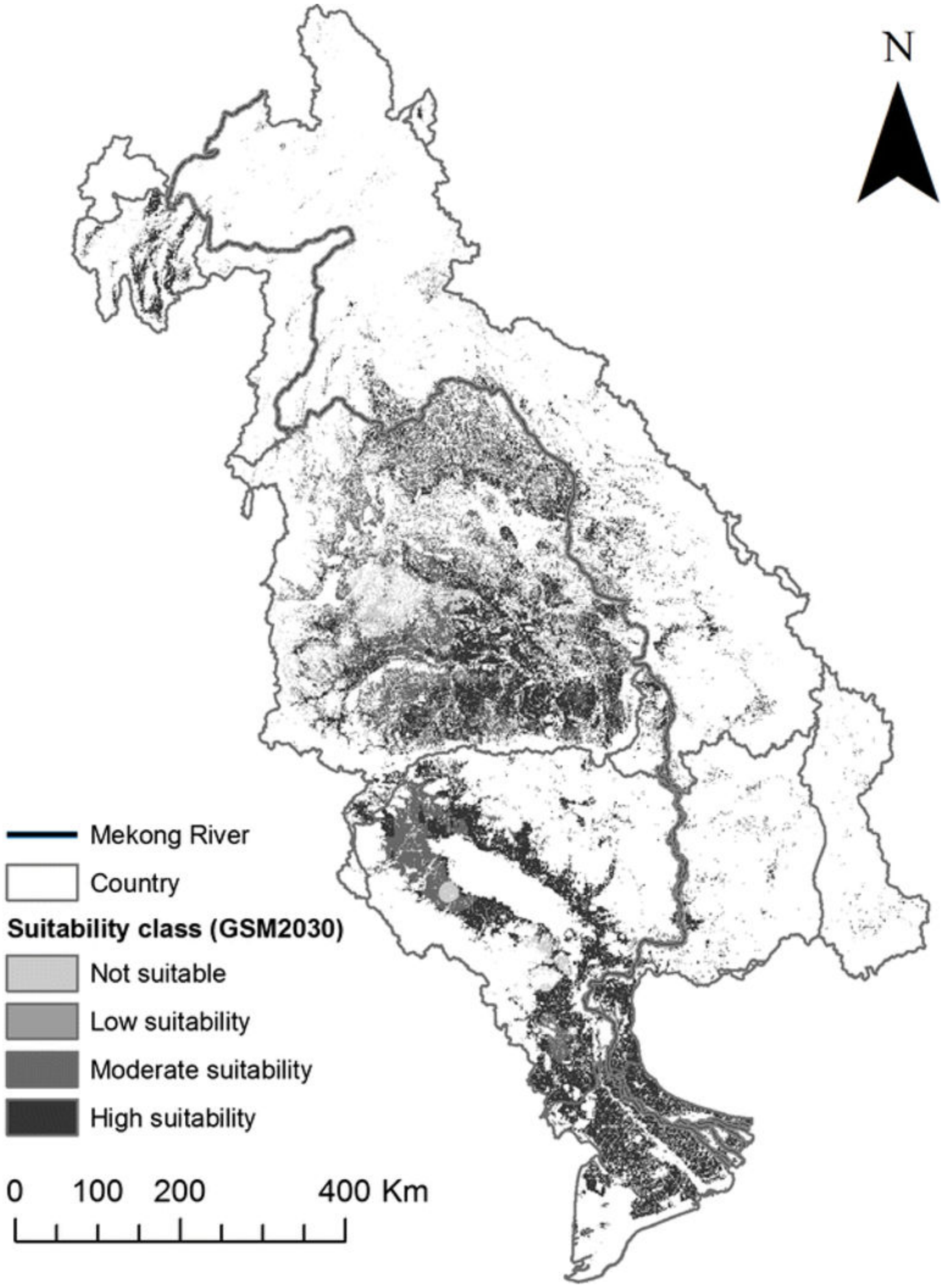

Fig. 6.

Land suitability for paddy under the predicted drier overall climate in combination with medium emissions in year 2030

Table 1

Future climate scenarios in the Lower Mekong Basin in 2030 and 2060

	Emission scenario					
	Low emissions (RCP2.6)		**Medium emissions (RCP4.5)**		**High emissions (RCP8.5)**	
	2030	**2060**	**2030**	**2060**	**2030**	**2060**
GCMs						
Drier overall (GS)						
Rainfall (mm)	1671 (985–3805)[b]	1680 (992–3806)	1421 (875–3384)	1587 (918–3849)	1592 (921–3846)	1454 (779–4158)
Temp. (°C)[a]	25.7 (122.3–28.4)[c]	25.6 (12.2–28.3)	26.0 (12.6–28.8)	26.7 (13.2–29.4)	26.7 (13.2–29.4)	28.3 (14.7–29.4)
Increased seasonality (IS)						
Rainfall (mm)	1739 (1029–3833)	1742 (1032–3856)	1759 (1030–3833)	1794 (1016–3882)	1791 (1017–3880)	1882 (982–3882)
Temp. (°C)	25.6 (12.3–28.3)	25.5 (12.2–28.2)	26.0 (12.6–28.6)	26.5 (13.2–29.2)	26.5 (13.2–29.2)	28.0 (14.8–30.6)
Wetter overall (GF)						
Rainfall (mm)	1752 (1036–3870)	1742 (1032–3856)	1782 (1051–3915)	1835 (1077–3994)	1831 (1075–3987)	1968 (1041–4192)
Temp. (°C)	25.6 (12.3–28.3)	25.5 (12.2–28.2)	26.0 (12.6–28.7)	26.7 (13.2–29.2)	26.5 (13.2–29.2)	26.5 (14.8–30.7)

GCMs global climate models, *GS* drier overall climate scenario, *IS* increased seasonality scenario, *GF* wetter overall climate scenario, average annual rainfall (mm)

[a] Mean temperature (°C)

[b] Minimum–maximum annual rainfall (mm)

[c] Minimum–maximum mean temperature (°C)

Table 2

Land quality factors and suitability classes for transplanting paddy.

Land attribute	Quantity	Suitability class			
		High	Moderate	Low	Not
Crop requirements					
Temperature	Mean temp. in growing season (°C)	22–30	31–33 21–20	34–35 19–18	> 35 < 18
Water availability	Water content in growing season (mm)	700–900	550–700	400–500	< 400
Aeration/oxygen	Soil drainage (class)	Poor	Moderate	Well	Excessive
Rooting	Effective root depth (cm)	> 50	25–50	15–25	< 15
Management and conservation					
Erosion hazard	Slope (%)	< 2	2–5	5–12	> 12

Source: Tansiri and Saifak (1999)

Table 3

Probability of transition among suitability classes for paddy at baseline (average 1985–2006) and under a drier overall climate in combination with medium emissions in 2030

	2030				**% Suitable area**	
	N	**S3**	**S2**	**S1**	**Without irrigation**	**With irrigation**
Baseline						
N	86.86	9.25	2.47	1.47	33.61	33.25
S3	32.46	40.44	22.31	4.80	10.43	10.69
S2	11.56	12.97	64.35	11.12	19.57	17.87
S1	1.47	1.82	13.90	82.81	36.39	38.41
% Suitable area						
Without irrigation	35.37	10.53	20.81	33.29	100.00	100.00
With irrigation	34.80	10.92	18.79	35.49	100.00	

High suitability (S1), moderate suitability (S2), low suitability (S3), not suitable (N)