Regional Environmental Change (2023) 23:117
https://doi.org/10.1007/s10113-023-02111-5

ORIGINAL ARTICLE

Climate change impacts on tree crop suitability in Southeast Asia

Jonas L. Appelt[1] · **Thatheva Saphangthong**[2] · **Žiga Malek**[1] · **Peter H. Verburg**[1,3] · **Jasper van Vliet**[1]

Received: 25 March 2023 / Accepted: 12 August 2023 / Published online: 31 August 2023

Abstract

Cultivation of tree crops such as coconut, oil palm and rubber are an important source of income in Southeast Asia, both for the national economies and for the local population. Climate change has the potential to drastically affect the suitability for growing these crops, but until now the impacts thereof on existing production areas have not been considered. This study combines climate change projections with data on crop cultivation to analyze how suitability for coconut, oil palm and rubber will change under different scenarios in Southeast Asia. We find that projected increases in total precipitation and longer dry periods in the insular part of Southeast Asia will result in 127,000 ha of current coconut and 1.17 Mha of current oil palm area will no longer be highly suitable under the most severe climate scenario. Conversely, increasing temperature in the mainland part of the region will cause 97,000 ha of current rubber cultivation area to become highly suitable. Increasing temperatures will also allow for potential expansion of rubber and coconut cultivation in the northern mainland part of the region, while the potential highly suitable area for oil palm cultivation will decrease. These changes in crop suitability may result in impacts on local farmers, including fall in yields and displacement of cultivation areas. This, in turn, may add pressure to biodiversity conservation in the region since areas that become highly suitable are disproportionally located within Key Biodiversity Areas.

Keywords Crop suitability · EcoCrop · Land use change · Plantations · Smallholder agriculture

Introduction

Southeast Asia is a major region for cultivation for tree crops. Countries in the region are responsible for 88% of global palm oil production, 75% of global natural rubber production and 56% of global coconut production (FAO 2021). This has implications for the region's agricultural landscapes, large areas of which are dominated by plantations with coconut, oil palm and rubber. Cultivation of these three crops takes up more than 37 Mha, covering 31% of the cropland area in Southeast Asia (FAO 2021). There has been a substantial increase in the area of large-scale plantations over the past couple of decades, primarily due to an increase in commercial oil palm growing in Indonesia and Malaysia (Xu et al. 2020). The area of rubber cultivation has also increased considerably in mainland Southeast Asia, primarily in Cambodia, Lao PDR, Thailand and Vietnam (Hurni and Fox 2018; Kenney-Lazar and Ishikawa 2019), while the size of the coconut area, primarily in Indonesia and the Philippines, has remained relatively stable in recent decades (FAO 2021). These developments have resulted in a decline in forest area, with an annual forest loss of 3.2 Mha between 2001 and 2019 in the region (Feng et al. 2021), making Southeast Asia one of the global deforestation hotspots (Hoang and Kanemoto 2021). With continued increases expected in the demands for both coconuts (Alouw and Wulandari 2020), palm oil (Corley 2009; Khatiwada et al. 2021) and natural rubber (Laroche et al. 2022; Warren-Thomas et al. 2022), it is important to assess how climate change affects the suitability of the existing crop areas as well as in potential future cultivation areas.

The agricultural landscapes of Southeast Asia are dominated by a mixture of smallholder farmers and large-scale

Communicated by George Zittis

✉ Jonas L. Appelt
j.l.appelt@vu.nl

Thatheva Saphangthong
thatheva@gmail.com

Žiga Malek
ziga.malek@vu.nl

Peter H. Verburg
p.h.verburg@vu.nl

Jasper van Vliet
jasper.van.vliet@vu.nl

1 Institute for Environmental Studies, Vrije Universiteit Amsterdam, De Boelelaan 1111, 1081, HV, Amsterdam, The Netherlands

2 Department of Agricultural Land Management, Ministry of Agriculture and Forestry, Vientiane, Lao People's Democratic Republic

3 Swiss Federal Research Institute WSL, Zürcherstrasse 111, 8903 Birmensdorf, Switzerland

holdings. Smallholder farmers range from traditional subsistence-oriented farming households engaged in shifting cultivation to intensive, market-integrated small-scale farmers (Mertz et al. 2009; Rigg et al. 2016; Schreinemachers et al. 2017), while large-scale holdings are mainly export oriented and managed as industrial plantations (Miettinen et al. 2012; Kenney-Lazar and Ishikawa 2019). Development in smallholder agriculture is often associated with positive impacts on income and mixed to positive impacts on employment, food security and health for local communities (Appelt et al. 2022), but can in some cases also result in negative impacts on local farmers, for instance due to price volatility of newly introduced crops (i.e. 'crop booms') (Ornetsmüller et al. 2018; Kallio et al. 2019). Large-scale plantations can often impact local communities negatively across a range of livelihood dimension (Appelt et al. 2022), including potentially increasing levels of conflict between companies and local communities (Obidzinski et al. 2012), and causing harm to income generation and food security of local smallholder farmers (Andrianto et al. 2019). Coconut is primarily grown in non-intensive smallholder systems, where farmers rely heavily on the crop income for their livelihood (Andriesse 2018; Alouw and Wulandari 2020; Davila 2020). For example, 79% of Filipino coconut farmers have farms sizes below two hectare (PCA 2019). In contrast, oil palm growing in Southeast Asia consists of a mixture between both smallholders and large-scale production (Bissonnette and De Koninck 2017). Smallholders are responsible for 27% of the oil palm area in the region, with national levels ranging from 15% in Malaysia to 71% in Thailand (Descals et al. 2021). Oil palm can be attractive to smallholders due to the large potential for income generation, but requires considerable capital investment and access to processing infrastructure (Feintrenie et al. 2010a; Rist et al. 2010). As a result, it exists in various configurations of contract farming and out-grower schemes connected to large-scale industrial style plantations (Gatto et al. 2017). Similarly, rubber production in the region is a mixture of smallholder farmers and large-scale plantations. Smallholder farmers' share of the rubber production ranges from 23% in Lao PDR to 93% in Malaysia (Fox and Castella 2013). It is an attractive crop for smallholders due to the income generation potential (Simien and Penot 2011), but a specialization in rubber can increase the vulnerability of households due to price fluctuations and market dependence (Jin et al. 2021).

Coconut, oil palm and rubber all require tropical conditions to grow, which are found in most of the countries in Southeast Asia. They need high average temperatures and are, when grown without irrigation, dependent on medium to high levels of precipitation (Sys et al. 1993). Therefore, cultivation of these crops is centered in areas around the equator (Gunn et al. 2011; Corley and Tinker 2015; Priyadarshan 2017), although development of rubber clones resistant to low temperatures and wind has spread rubber cultivation to some historically 'sub-optimal' areas including parts of mainland Southeast Asia, southern China and northern India (Priyadarshan et al. 2005; Ahrends et al. 2015; Priyadarshan 2017). Previous studies of suitability for coconut (FAO and IIASA 2021), oil palm (Pirker et al. 2016; Paterson et al. 2017) and rubber (Ahrends et al. 2015; Golbon et al. 2018) show Southeast Asia as one of the globally best suited areas for these crops. Yet, these studies also indicate that the area available for expansion is limited (Ahrends et al. 2015; Pirker et al. 2016).

Climate change is likely to affect the suitability for cultivating coconut, oil palm and rubber. Impacts include direct limitations for plant growth (Paterson et al. 2015; Golbon et al. 2018), as well as impacts on flowering and fruit development (Kumar and Aggarwal 2013; Corley and Tinker 2015), increasing climate induced stress and susceptibility to diseases like stem rot and mildew (Paterson et al. 2013; Liyanage et al. 2016) and directly impacting harvest and productions, for instance through changing latex flow rates in rubber trees (Ismail and Gohet 2021). Previous projections indicate that suitability for oil palm could decrease in Indonesia and Malaysia due to heat and dry stress (Paterson et al. 2015; Sarkar et al. 2020). Similarly, the suitability for rubber cultivation is expected to decrease due to heat stress in the southern parts of mainland Southeast Asia, while it could increase in the northern parts of the region (Golbon et al. 2018). These climate-induced changes can have serious impacts on smallholder farmers in the region. Yet, they may also create opportunities for crop expansion in other areas, potentially leading to deforestation, harming natural habitat in biodiversity-rich and valuable ecosystem (Ahrends et al. 2015; Vijay et al. 2016). Despite previous studies on general land suitability for oil palm and rubber (Paterson et al. 2015, 2017; Golbon et al. 2018; Sarkar et al. 2020), we do not yet have an assessment of how climate change will impact specifically in the existing crop production areas. With the construction of high-resolution crop maps for oil palm (Descals et al. 2021) and rubber (Hurni and Fox 2018), we have the possibility for projecting suitability change in the exact areas where existing crop production is taking place. Furthermore, while coconut is an important export and smallholder crop in the Southeast Asia, with demand expected to increase, there has not been any regionwide studies on projected climate impacts on coconut suitable area or impact on existing crop area.

In this paper, we analyze the impact of climate change on the suitability for coconut, oil palm and rubber in Southeast Asia, and compare these with the current crop extents, to see how climate change may impact existing production areas and how the area for potential expansion in the region is projected to change.

Materials and methods

This study uses a range of data sources to map the current and future suitability for coconut, oil palm and rubber in Southeast Asia, under different climate scenarios, and compare the suitability with the current crop extent and total suitable area (Fig. 1). To that effect, we use historical and projected future climate data under different scenarios from general circulation models (GCMs) (Climate data) and process them as input to the EcoCrop suitability model (Modelling crop suitability). Subsequently, we compare our results with the current extent of each of the three crops (Impact of climate change on existing crop area) to see how the total suitable crop area changes under different climate scenarios (Suitability of area for future potential crop expansion). Southeast Asia is in this study defined as the area of the ten member states of the Association of Southeast Asian Nations (ASEAN). The data sources and modelling approach are described below, while a complete overview of all model parameters is provided in the supplementary material.

Climate data

To assess how climate will change in Southeast Asia, we compared two future scenarios for 2041–2070 following the Shared Socioeconomic Pathways (SSP) 1 and 5, and the respective Representative Concentration Pathways 2.6 and 8.5 (SSP1-2.6 and SSP5-8.5). SSP1-2.6 represents a development characterized by sustainable policies with low climate change and low levels of mitigation and adaptation challenges, while SSP5-8.5 represents a future with fossil-fuelled development and larger climate changes, with high levels of mitigation challenges, but low levels of adaptation challenges (O'Neill et al. 2017). These two scenarios are selected as they present a representative range of possible future climate change scenarios, thus showing the range of potential impacts on crop suitability.

Climate change projections are based on data from 5 GCMs available from the Climatologies at High resolution for the Earth's Land Surface Areas (CHELSA) v2 database (Karger et al. 2017). CHELSA provides high resolution (30

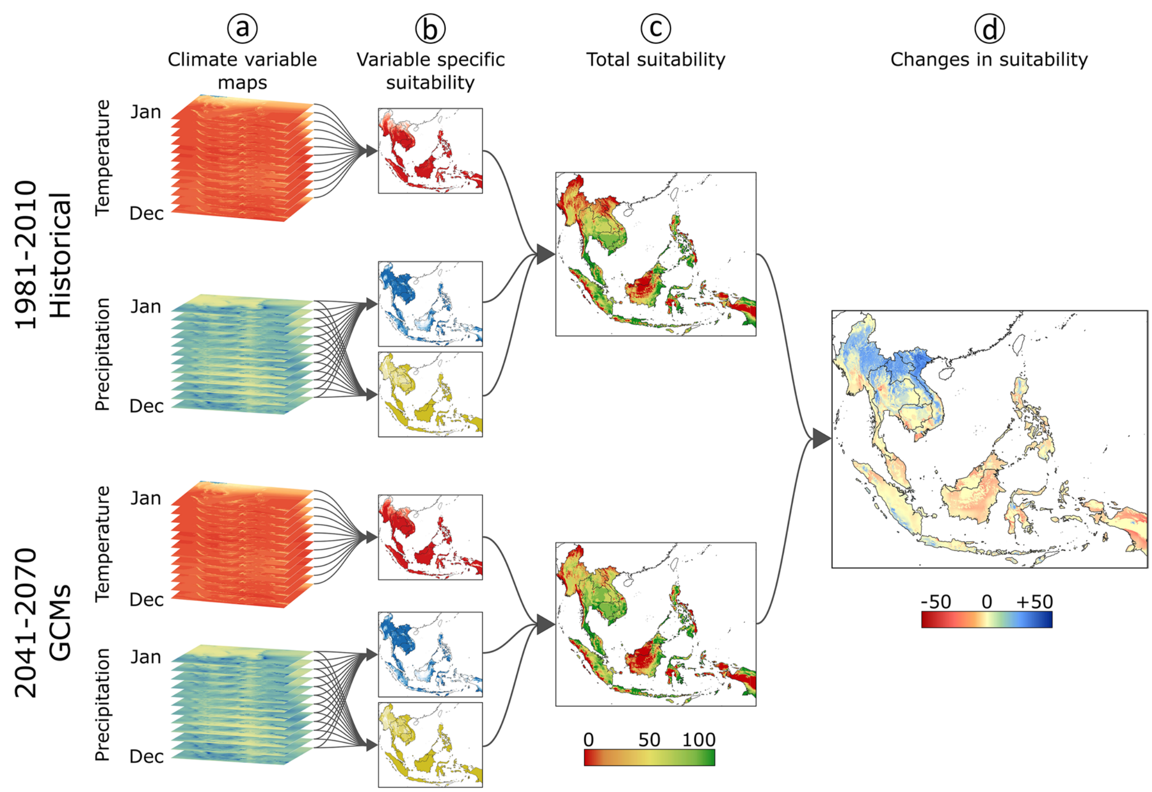

Fig. 1 Methodology for modelling of crop suitability (example for coconut under SSP1-2.6). Historical and projected climate data on monthly average temperature and monthly total precipitation (**a**) was used to produce temperature (red), precipitation (blue) and precipitation seasonality (yellow) suitability maps (**b**). These were then combined to produce total suitability maps for both the historical and projected scenarios (**c**), which were then combined to show changes in suitability (**d**). This was done individually for each included General Circulation Model (GCM) and results then combined across models

arc seconds) historical climate data (1981–2010) as well as down-scaled data for a range of GCMs and SSPs from the 6th phase of the Coupled Model Intercomparison Project (CMIP6). We included climate change projections from multiple different GCMs to explore the uncertainty within these scenarios. The range of GCMs included in our study reflects the data availability from CHELSA.

Modelling crop suitability

Crop suitability was assessed using the EcoCrop model (Hijmans et al. 2001), building upon Ramirez-Villegas et al. (2013). EcoCrop is a niche-based mechanistic model that evaluates the crop specific suitability of an area based on climate conditions as a score ranging between not suitable and optimally suitable. The model establishes crop suitability based on monthly average minimum temperature, monthly average temperature and total precipitation in the growth period. The crops investigated in this study are all perennial crops, and we therefore treated the full year as the growing period (i.e. 12 months).

In the model, suitability is determined independently for temperature and precipitation variables, based on a set of crop-specific thresholds values describing optimal (100), sub-optimal (between 0 and 100) and non-suitable (0) growing conditions. Sub-optimal suitability scores are calculated by linear interpolation between the marginal values for non-suitable and optimal conditions. The model multiplies these variable scores to get a total suitability score ranging from 0 to 100. Threshold values used are based on reviewed literature on the crop-climate relationship for coconut (Peiris et al. 1995; Thomas et al. 2018), oil palm (Corley and Tinker 2015; Pirker et al. 2016) and rubber (Ahrends et al. 2015; Priyadarshan 2017), as well as the original EcoCrop database (FAO 2022). In addition, we considered values used by the Global Agro-Ecological Zones model (Fischer et al. 2021). Table 1 includes the crop-specific thresholds parameters used.

In addition to total annual precipitation, the included crops are also sensitive to precipitation seasonality. To account for this, we included the number of dry months as a separate input variable to the EcoCrop model, to capture the effect of precipitation seasonality. This seasonality was implemented as another suitability score, with crop specific threshold values for non-suitable and optimal conditions from the literature on the included crops (Corley and Tinker 2015; Golbon et al. 2018; Nampoothiri et al. 2019), using linear interpolation in a similar matter as for temperature and total precipitation suitability (Table 1). More details on the implementation of EcoCrop in this study is included in the supplementary material (S1).

Impact of climate change on existing crop area

To investigate the impact on climate change for local farmers and production areas, we compared suitability changes for the respective crops with the current extent of each crop.

Table 1 Parameters used for modelling crop suitability. Climatic parameters were used to differentiate between unsuitable, sub-optimal and optimal conditions

Crop type	Climate condition	Suitability		
		Unsuitable: 0	Sub-optimal suitability: 1–99	Optimal suitability: 100
Coconut	Monthly average temperature	< 14 °C > 38 °C	14–22 °C 34–38 °C	22–34 °C
	Monthly average minimum temperature	< − 1 °C	> − 1 °C	
	Annual precipitation	< 650 mm > 4000 mm	650–1200 mm 2400–4000 mm	1200 - 2400 mm
	No. of dry months (precipitation < 50 mm)	> 7	4 - 7	< 4
Oil palm	Monthly average temperature	< 12 °C > 38 °C	12–21 °C 32–38 °C	21–32 °C
	Monthly average minimum temperature	< 0 °C	> 0 °C	
	Annual precipitation	< 1000 mm > 8000 mm	1000–1500 mm 3000–8000 mm	1500–3000 mm
	No. of dry months (precipitation < 50 mm)	> 5	2–5	< 2
Rubber	Monthly average temperature	< 10 °C > 45 °C	10–24 °C 30–45 °C	24–30 °C
	Monthly average minimum temperature	< 0 °C	> 0 °C	
	Annual precipitation	< 1200 mm > 6000 mm	1200–2000 mm 4000–6000 mm	2000–4000 mm
	No. of dry months (precipitation < 50 mm)	> 5	4–5	< 4

High resolution, remotely sensed data on crop areas is available for the extent of oil palm for the natural production range (whole region of Southeast Asia, except above 18° North; Descals et al. 2021) and for the primary production areas for rubber in mainland Southeast Asia (Hurni and Fox 2018). Additional data on rubber extent for Indonesia and Malaysia was added from the Global Forest Watch data on planted trees (Harris et al. 2019). The extent of coconut was based on information on modelled harvested crop area from the SPAM model (IFPRI 2019). Table 2 provides an overview of the data sources for crop area. We assumed that the included crops were not cultivated in areas for which no such data was available. For oil palm, this misses a small amount of existing cultivated area falling outside the historical suitable range (Descals et al. 2021), for instance in northern Thailand (Jaroenkietkajorn et al. 2021), while for rubber a minor part of the existing cultivation area in eastern Thailand and the Philippines is not included (FAO 2021). Yet, the available data covers the majority of all areas on which oil palm, rubber and coconut are grown in Southeast Asia.

To facilitate analysis of change in suitable area, the suitability scores were reclassified into areas that are unsuitable (0), and low (1–50), medium (50–80) and high suitability (80–100).

Suitability of area for future potential crop expansion

To assess potential future land use changes, we analyzed the impact of climate change on the suitability of potential future expansion areas for the three crops. To do this, we looked at the change in the total area with high crop suitability (> 80 in EcoCrop), but excluded areas that are unsuitable for other reasons than climate conditions, such as due to topography, soil characteristics or existing land use (Table 3).

Threshold values for topography and soil were obtained based on Sys et al. (1993) and Fischer et al. (2021). Data on slopes was derived from the NASA SRTM elevation data set (Farr et al. 2007), and information on soil characteristics was obtained from the Harmonized World Soil Database (Nachtergaele et al. 2012) and from SoilGrids (de Sousa et al. 2020).

Over the past decades, new tree crop cultivation has mostly been developed in areas not yet in use for crop production or as built-up land (Hurni and Fox 2018; Xin et al. 2021). We therefore also excluded areas that are currently under other land uses and are therefore not suitable for expansion of tree crop cultivation, including built-up area (Corbane et al. 2018, 2019) and cropland area (Fritz et al. 2015). To get an indication of the potential environmental impact of the climate induced changes in crop suitability, we further overlayed the modelling results with data on Key Biodiversity Areas (KBAs) (BirdLife International 2022).

Results

Future changes in crop suitability for oil palm, rubber and coconut

Areas that are currently highly suitable for coconut are primarily found in the southern part of mainland Southeast Asia, mostly in Cambodia and Thailand, and in some of the insular parts of the region, while some areas along the equator currently have low suitability due to high levels of annual precipitation. We find that the suitability for coconut is projected to increase in the northern, mainland parts of Southeast Asia, but decrease in the insular parts of the region, along the equator, and to a smaller degree in the Philippines (Fig. 2b and c). The largest decreases in suitability are projected on Borneo and New Guinea, as well as along the eastern coast of Sumatra. The decrease in suitability is primarily due to increasing total precipitation (Fig. S2).

For oil palm, highly suitable areas are currently found in the insular parts of Southeast Asia around the equator, while areas in the mainland are largely unsuitable (Fig. 2d). Projections show little area with increasing suitability, while projected decreases are largest in the

Table 2 Data on existing crop extent used in the study

Tree crop	Coverage	Resolution	Year	Unit and collection method	Source
Coconut	Whole study area	10 km	2010	% harvested area; modelled from production statistics	MapSPAM (IFPRI 2019)
Oil Palm	Whole study area, except for northern Lao PDR, northern Thailand, northern Vietnam and most of Myanmar	10 m	2019	Observed area; remote sensing	Descals et al. (2021)
Rubber	Cambodia, Lao PDR and parts of Myanmar, Thailand and Vietnam	231 m	2014	Observed area; remote sensing	Hurni and Fox (2018)
	Indonesia, Malaysia	Polygons	2013–2015	Observed area; manual polygon delineation/supervised classification	Spatial database of planted trees (Harris et al. 2019)

Table 3 Parameters used for defining suitable areas based on topographical and soil conditions

Suitable conditions		Coconut	Oil palm	Rubber
Topography	Slope	< 25°	< 25°	< 30°
Soil characteristics	Texture	All classes except heavy clay	All classes except heavy clay, loamy sand and sand	All classes except heavy clay and sand
	Coarse fragments	< 65 vol%	< 65 vol%	< 65 vol%
	Soil depth	> 40 cm	> 40 cm	> 50 cm
	pH	4.5–8.5	3.5–7.5	3.5–7
	Base saturation	n.a.	> 0%	< 80%
	$CaCO_3$	< 75%	< 10%	< 1%
	$CaSO_4$	< 25%	< 3%	< 0.2%
	Cation exchange capacity	> 2 cmol/kg	> 2 cmol/kg	> 2 cmol/kg
	Electric conductivity	< 20 dS/m	< 4 dS/m	< 2 dS/m
	Exchangeable sodium	< 45%	< 12%	< 2%

southern parts of Sumatra and southern Borneo (Fig. 2e and f). This decrease is mainly due to an increase in total precipitation and in precipitation seasonality (increased number of dry months) (Fig. S2).

Areas with high suitability for rubber cultivations are currently found in insular Southeast Asia around the equator, while areas in the mainland are less suitable (Fig. 2g). High suitability is projected to continue in most of the insular parts of Southeast Asia (Fig. 2h and i), while some lower suitability areas in the northern mainland parts are projected to see an increase in suitability. This increase is driven by increasing temperatures, in particular in the valleys and lowland areas of northern Lao PDR and northern Vietnam (Fig. S2). In central mainland Southeast Asia, the increasing precipitation is projected to increase suitability, but precipitation seasonality as well as increasing temperatures will continue to be limiting factors in this area.

The changes in suitability for the tree crops in the included climate change scenarios are highly consistent in direction but differ in the magnitude of the changes. As a result, the trends described above are expected under both SSP1-2.6 and SSP5-8.5, but generally with more pronounced changes under SSP5-8.5.

Climate change impacts on existing crop areas

Climate change impacts on the suitability of currently cultivated areas yield both improvements and deteriorations (Fig. 3). For coconut and rubber, gains and losses in the three suitability categories are somewhat similar, resulting in only small net changes in the cultivated areas in each category. For oil palm, changes in the low suitability category are small, while both climate change scenarios show a net increase in medium suitable land and a comparable net decrease in high suitable land. For all three crops, gross changes are larger under SSP5-8.5 than under SSP1-2.6.

Just over half of the land cultivated with coconut is characterized as highly suitable, while the rest is characterized as medium suitable, low suitable and unsuitable, respectively (Fig. 3a). We find a projected average net loss of existing crop area located in high suitable areas of 180,000 ha and 127,000 ha under SSP1-2.6 and SSP5-8.5, respectively. The range of results from the included GCMs is quite large, in particular under SSP5-8.5, where four of the models show a net loss of crop in high suitable areas, ranging from 20,000 to 430,000 ha, while one model (MRI-ESM2-0) predicts a gain of 170,000 ha. This disagreement is primarily due to differences in the projected annual precipitation in the crop area in central Sumatra.

A large majority of existing oil palm production is in areas which are currently highly suitable (Fig. 3b). We find an average net loss of 607,000 ha and 1.17 Mha of crop area located in high suitable areas under SSP1-2.6 and SSP5-8.5, respectively (Fig. 3e). All five GCMs show a decrease in crop in high suitable areas under SSP5-8.5, ranging from 0.55 Mha to 1.72 Mha, but three of the included models (MPI-ESM1-2-HR, MRI-ESM2-0, UKESM1-0-LL) project a particular large loss in southern Sumatra under SSP5-8.5, due to increase in precipitation seasonality in that area.

Rubber is currently primarily cultivated in areas with high climate suitability (Fig. 3c). We find an average net increase of existing crop area located in high suitable areas of 115,000 ha under SSP1-2.6 and a slightly smaller increase of 97,000 ha under SSP5-8.5. The included GCMs show a large range in the net gain and loss of crop in high suitable areas, with four models showing an increase and one model (MRI-ESM2-0) showing a net loss of crop in high suitable areas (of 268,000 ha) under SSP5-8.5.

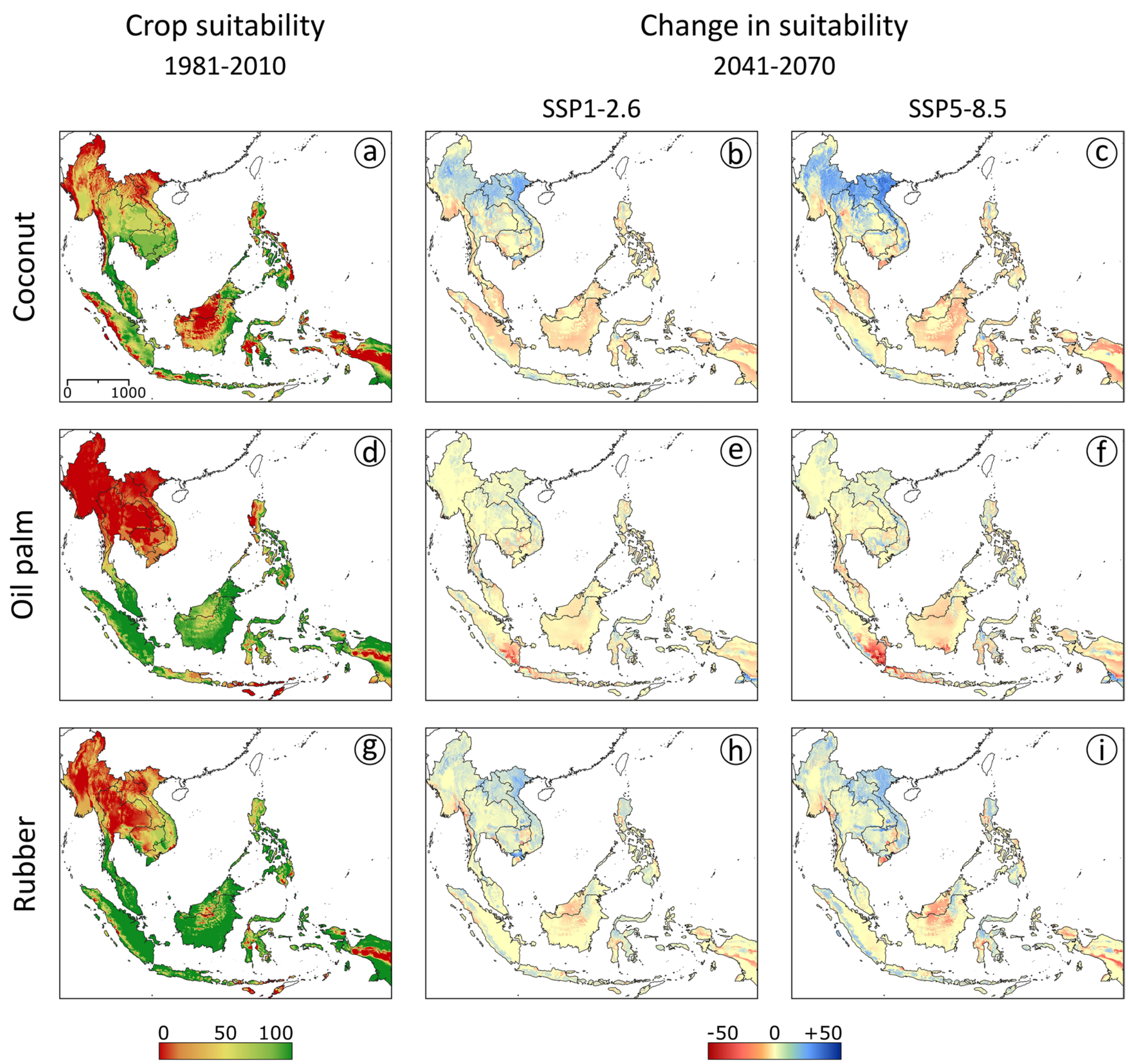

Fig. 2 Current crop suitability score (**a**, **d**, **g**) (on a scale of 0–100) and climate induced changes in suitability score in 2041–2070 under SSP1-2.6 (**b**, **e**, **h**) and SSP5-8.5 (**c**, **f**, **i**) for coconut, oil palm and rubber in Southeast Asia

Change in suitability for potential crop expansion area

The high suitable potential expansion area for coconut in Southeast Asia is projected to an average net decrease of 4.8% (3.5 Mha) under SSP1-2.6, but a net increase with 4.5% (3.3 Mha) under SSP5-8.5 (Fig. 4a). Four of the five included models agree on a net increase in the high suitable potential expansion area under SSP5-8.5 (ranging from 5 to 20%). The gross changes in all suitability categories are much larger than the net changes, with, e.g. the gain in high suitability potential expansion area under SSP5-8.5 projected to 14–26% and the loss of high suitability area to 6–26% across the included GCMs. This indicates the models projecting larger local changes in suitability, with increase in some locations generally being accompanied by deterioration of suitability in other locations.

For oil palm, we find that the high suitable potential expansion area is projected to an average net decrease of 5.3% (6.1 Mha) and 9.9% (11.3 Mha) under SSP1-2.6 and SSP5-8.5, respectively (Fig. 4b). The net decrease in high suitable area is consistent across the include GCMs, but with three of the models (MPI-ESM1-2-HR, MRI-ESM2-0, UKESM1-0-LL) projecting a particular a large decrease in high suitable areas (11 to 15%), with much of the loss due to increased precipitation seasonality in southern Sumatra. The difference between gross and net changes for oil palm is smaller than for coconut, with, e.g. projected gain in high suitability potential expansion area under SSP5-8.5 of 2–4% and projected loss of 6–14% across the included GCMs. This indicates a more consistent projection of generally less favourable conditions for oil palms in a number of areas in Southeast Asia.

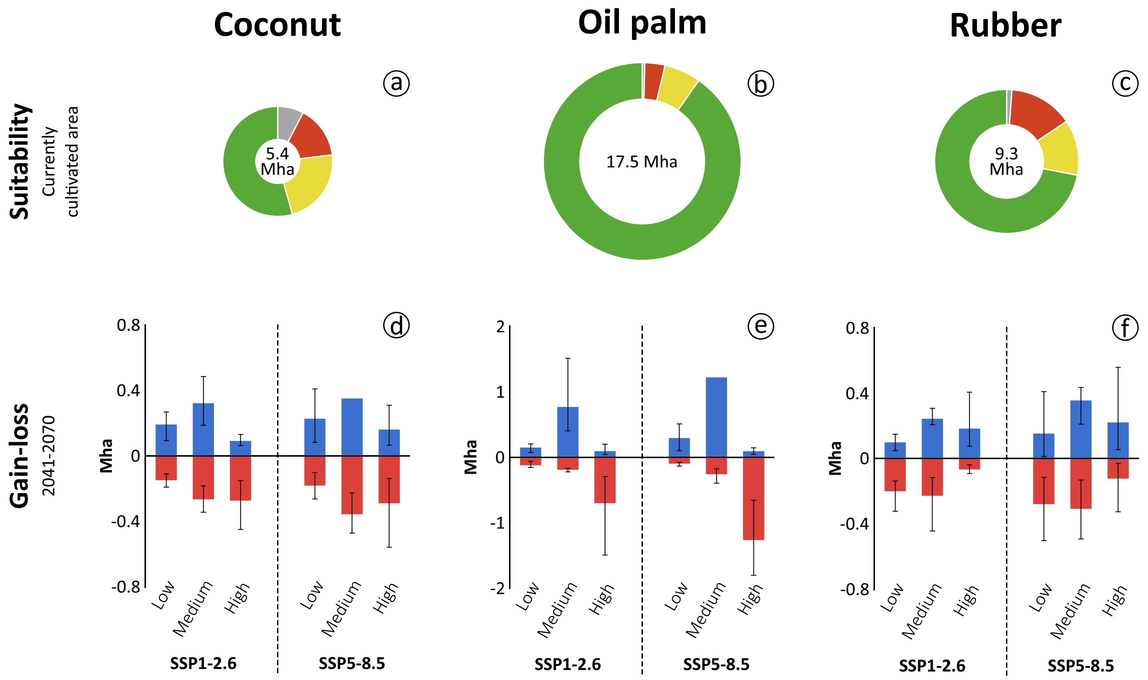

Fig. 3 Changes in suitability for existing crop areas. Top part of the figure (**a**, **b**, **c**) shows the suitability of area currently cultivated with coconut, oil palm and rubber. Bottom part (**d**, **e**, **f**) shows the gains and losses in low (1–50), medium (50–80) and high (80–100) suitable areas in 2041–2070 for the existing crop area under SSP1-2.6 and SSP5-8.5. Results show the average over included GCMs included, while whiskers indicate the range of gains and loss of area across these GCMs. Numerical results for gain and loss in of potential expansion area can be found in Table S1

The high suitable potential expansion area for rubber is on average projected to a net increase of 3.8% (4.7 Mha) under SSP1-2.6 and 5.2% (6.4 Mha) under SSP5-8.5 (Fig. 4c). The patterns of change in high suitable area are different between models, but all of them show increasing high suitable area along the southern coast of Vietnam and in the highland areas of Indonesia and Malaysia, due to increasing temperatures, and two models (GFDL-ESM4, MPI-ESM1-2-HR) show a large increase in high suitable area in eastern Cambodia under SSP5-8.5, due to increase in precipitation and fewer dry months (Fig. S2). All models show increase in the amount of medium suitable area in highland areas

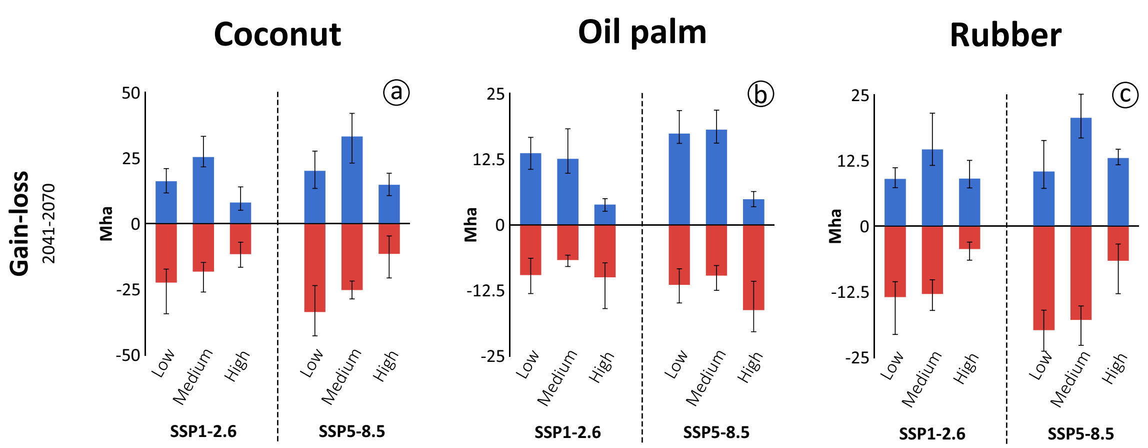

Fig. 4 Average gain and loss in of potential expansion area for different suitability categories in 2041–2070 under SSP1-2.6 and SSP5-8.5 across Southeast Asia for coconut (**a**), oil palm (**b**) and rubber (**c**). Whiskers show range of gains and loss of area across included GCMs. Areas that are unsuitable due to soil conditions or slope, as well as areas that are currently built-up, cropland or permanent water, have been excluded. Numerical results for gain and loss in of potential expansion area can be found in Table S2

in central and northern Lao PDR and in northern Vietnam under both SSP1-2.6 and SSP5-8.5. The gross changes in potential expansion area for rubber are considerable, in particular for medium suitable area, where the net change under SSP5-8.5 is an increase of 6.7%, but this covers projected gains of 29–51% and projected loss of 24–38% across the included GCMs.

Key Biodiversity Areas (KBAs) cover approximately 18.4% of terrestrial Southeast Asia. We find that areas that become highly suitable under both climate change scenarios are disproportionally included in these areas (Table S3). For coconut, only 16.7% of the loss of high suitable potential expansion area happens in KBAs under SSP1-2.6, while 24.0% of the gain happens in these areas in the same scenario. Similarly, the loss of high suitability area for oil palm is relatively smaller in KBAs, constituting 12.7% and 12.4% under SSP1-2.6 and SSP5-8.5 respectively, while 27.6% and 30.6% of the gains in high suitability areas are within KBAs. For rubber, 20.6% and 18.0% of the losses in high suitability areas are found within KBAs, for SSP1-2.6 and SSP 585 respectively, and 36.2% and 37.7% of the gains. Hence, for all three tree crops, we find that climate change leverages additional pressure on KBAs.

Discussion

Impacts of climate change on tree crops and producers in Southeast Asia

Climate change will have both positive and negative impacts on the suitability to grow coconut, oil palm and rubber in Southeast Asia, depending on the location within the region. We find overall improvements for coconut and rubber in the mainland part of Southeast Asia, while we also find a decrease in suitability for all three crops in the insular part of the region. These findings are consistent with previous studies, which have found that the global area suitable for production of major food and energy crops will shift towards higher elevation and areas further away from equator (Zabel et al. 2014; King et al. 2018; Hannah et al. 2020), but with some exceptions due to the specific climate requirements of the individual crops, as we discuss below. Our study provides new insights on these impacts for coconut cultivation, while it is consistent with previously reported increase in areas suitable for cultivating palm oil (Pirker et al. 2016) and rubber (Ahrends et al. 2015).

Net change in the area with high and medium suitability for coconut is low for both SSP1-2.6 and SSP5-8.5 but the underlying gross changes are considerable. As coconut is mainly produced by smallholders, these developments indicate a threat for the livelihoods of these smallholders. This is pertinent especially as these farmers often lack the capacity to adapt to climate change in areas where negative climate change impacts are expected, including in parts of the Philippines and on Sumatra (Landicho et al. 2015; Davila 2020). At the same time, the expected increasing demand for coconuts (Alouw and Wulandari 2020) could result in increase in prices and thus profits for smallholders, potentially compensating decreases in suitability. There are few areas where improved climate conditions offer potential for expansion of coconut production, the most significant one being parts of central and northern Vietnam, where increasing temperatures are projected to improve suitability. Our results show a large share of existing coconut cultivation located in areas with medium or low suitability (Fig. 3a). This could be due to inaccuracy in the data and model used, i.e. the data for coconut cultivation being on a coarse (10 km) resolution, but might also be an indication that coconut is frequently grown in lower suitable areas because it is often used as a non-primary income source or is grown in systems with other crops, e.g. as intercropping (Feintrenie et al. 2010b).

We project that between 0.6 and 1.2 Mha of oil palm currently cultivated in areas that are highly suitable will experience worsening climate conditions. As oil palm is grown mainly on large-scale plantations (Descals et al. 2021), these changes are likely to mainly affect large-scale industrial growers, potentially lowering yields and making the plantations less profitable. At the same time, the area under cultivation with oil palm has increased considerably in recent year, and this is expected to continue due to increased demand (Corley 2009; Wicke et al. 2011). This development is already causing pressure for conversion of natural areas into plantations, with deforestation and loss of ecosystem functions as a result (Savilaakso et al. 2014; Vijay et al. 2016). In addition to the worsening conditions for parts of the existing production area, we find that future climate change will decrease the potential highly suitable areas not yet cultivated for palm, thus limiting possible areas to replace loss from existing plantations and creating further pressure on natural frontier areas for oil palm expansion, such as on Borneo and New Guinea (Descals et al. 2021; Runtuboi et al. 2021). Climate change is also likely to be detrimental to smallholder producers in the existing areas where suitability is projected to decrease (southern Sumatra and parts of Borneo). Smallholders often lack the capacity for relocating production or adapting to changing climate conditions. Increasing expansion in frontier areas is similarly likely to have detrimental impacts on local population in those areas, who often experience loss of land rights and decrease in livelihoods and welfare as a consequences of large-scale oil palm development (Andrianto et al. 2019; Runtuboi et al. 2021). Since the main limiting factor for oil palm suitability in mainland Southeast Asia is the length of dry season, irrigation may be a viable option for expansion of oil palm cultivation in this area (Carr 2011), but the needed investment would favour large-scale growers, who have the capacity for large capital investments, over smallholders.

On average, existing rubber productions areas will see a small net improvement in suitability in both included climate scenarios. This can partly be explained by a large amount of the existing rubber area being located in the mainland parts of Southeast Asia, in areas that have historically not had optimal climate conditions for the crop (Priyadarshan et al. 2005; Ahrends et al. 2015). The area used to grow rubber has increased considerably in recent years, and this trend is expected to continue (Warren-Thomas et al. 2022), further increasing the pressure on remaining ecosystems (Grogan et al. 2019). Our results show that rubber will become more suitable in several regions in mainland Southeast Asia, notably in southern Lao PDR, Vietnam and along the coast of Cambodia, and natural areas in these regions may therefore become under threat of land conversion to rubber cultivation. Furthermore, rubber clones have been developed, like the ones used in parts of southern China (Priyadarshan 2017), that are more resistant to cold temperatures than is reflected in the modelling in this study. If such clones are introduced in mainland Southeast Asia, the area of suitability could increase further which can result in additional conversion pressure on natural areas in the region.

Expansion of tree crops, most notably oil palm, have caused a loss in natural areas in recent years (Hoang and Kanemoto 2021; Fagan et al. 2022). As a result, researchers, international organizations and national policies responded in order to prevent further deterioration of especially the biodiversity rich tropical forests in the region, in particular in the insular parts of Southeast Asia (Carlson et al. 2018; Leijten et al. 2020). Our findings show that, especially for oil palm, the locations of the most suitable areas are not expected to change much. In addition, the changes in potential expansion area are disproportionally impacting important natural areas, with smaller losses (coconut and oil palm) in larger gains (all crops) in high suitable area in KBAs, thus confirming the need to focus protection measures particular on vulnerable frontier areas, possibly by strategically expanding the protected area network in these regions and ensuring connectivity between protected areas (Scriven et al. 2015; Laurance 2016). At the same time, it is important to identify alternative livelihood options for smallholders in these areas, to decrease conversion pressures while ensuring improvement in human wellbeing. Furthermore, the crop suitability for production will worsen considerably for coconut on Sumatra and in parts of the Philippines, and for oil palm in southern Sumatra, highlighting a particular need for climate adaptive measures for farmers in these areas.

Increased suitability can also result in areas becoming attractive for development of agro-industrial plantations for the included tree crops, which can be a considerable risk for the livelihoods of existing smallholders in these areas. Development of large-scale agricultural plantations in Southeast Asia is known to previously have caused displacement of existing farmers (Kenney-Lazar and Ishikawa 2019) and resulting in undermining the natural resource base and local livelihoods for communities in impacted areas (Obidzinski et al. 2012; Andrianto et al. 2019). So while improvement in suitability can potentially be beneficial to some smallholder farmers engaged in tree crop production, this can also constitute a risk to local communities due to potential loss of land and resources from development of agro-industrial production.

Limitations

The results of the five GCMs included in this study vary widely, suggesting a significant uncertainty in the future climate conditions in the study region. Consistently, the projected changes in the suitability for different tree crops, as well as the location of potential future changes, are also equally uncertain. While there is a general uncertainty in modelling of climate change in Southeast Asia (Kamworapan and Surussavadee 2019), for our study of crop suitability, this uncertainty pertains especially to the exact location of the changes, as directions of change over the entire area are generally more consistent across the included GCMs. In other words, the uncertainty mainly affects the allocation of climate change impacts, while the overall trends remain valid regardless of the specific GCM scenario.

We added seasonality of precipitation to the EcoCrop model to better represent climate conditions affecting the suitability for growing coconut, oil palm and rubber. This methodological innovation is especially relevant for the perennial crops due to their sensitivity of the number of dry months, which would otherwise have not been accounted for in the model (Ramirez-Villegas et al. 2013). In addition to precipitation seasonality, there are other climate change aspects that could affect the suitability for these crops. These include the occurrence of extreme weather events, such as prolonged droughts (Carr 2011; Wang 2014; Corley et al. 2018), heavy winds storms (Stromberg et al. 2011; Qi et al. 2021) and extreme precipitation events (Corley and Tinker 2015). It is expected that extreme weather events will increase in Southeast Asia as a result of climate change and that this will affect tree crops in locally variable ways (Ahrends et al. 2015; Corley and Tinker 2015; Almazroui et al. 2021; Malek et al. 2022). Flooding can both directly impact plant growth in oil palm and rubber, by reducing transpiration rates, impacting stomatal closure and photosynthesis, but long-term flooding can also cause rotting of roots (Corley and Tinker 2015; Hardanto et al. 2017). Droughts affect both photosynthesis and stomatal closing in oil palms and rubber, but can in oil palms also impact the ratio of female-to-male flowers and abortion ratio (Corley and Tinker 2015). Rubber can be impacted by cold spells and high winds in parts of the existing production areas, but breeding for specific varieties can increase wind resistance (Priyadarshan 2017; Sterling et al. 2020). For all three crops, increasing occurrence of extreme weather events will decrease suitability, and it is therefore likely both that climate change impacts on existing production will be worse and that that it will impact a larger area than our results indicate. Yet, in the absence of data on such events, partly due to their probabilistic nature, we could not include these in the present study. As a result, we might have overestimated the suitability in future time periods and underestimated suitability loss due to impacts of climate change.

In addition, our study does not take into account differences in varieties of the crops or differences in production methods, which both impact the general climate suitability of the crops and the yield loss under extreme weather events (Jayasooryan et al. 2015; Woittiez et al. 2017). Irrigation may in particular be an option for maintaining oil palm production in case of increased precipitation seasonality and for expanding production into parts of mainland Southeast Asia that are currently unsuitable for oil palm cultivation (Silalertruksa et al. 2017). Different varieties might also be more adapted to climate variations outside the parameters used in this study and is already used in some areas (Priyadarshan et al. 2005; Corley et al. 2018), including the use of cold resistant rubber clones in southern China and northern India (Priyadarshan 2017). Though considering the rotation rates of the included crops, even if farmers have access to more climate resilient varieties, replacement in already existing crop areas could take years or decades.

Conclusion

Our results show that the insular parts of Southeast Asia will continue to be highly suitable for cultivation of coconut, oil palm and rubber, and that it is likely that the region as a whole will continue to be a major production area for these tree crops under future climate scenarios. But we also find that increased precipitation and longer dry seasons will in the future impacts existing crop areas negatively for coconut and oil palm in Indonesia, Malaysia and the Philippines. This, combined with improving conditions for coconut in the mainland parts of Southeast Asia is likely to cause coconut production to increasingly shift northward, while oil palm production is more likely to move to other high suitable areas in the insular parts of the region, causing increasing conversion pressures on existing frontier areas in Indonesia and Malaysia. For rubber, increasing temperatures in the mainland part of Southeast Asia is likely to cause a continued pressure for opening of new areas for cultivation in the already existing production areas in Cambodia, Lao PDR, Malaysia and Thailand. Areas that become highly suitable are disproportionally included in Key Biodiversity Areas, indicating the need to protecting these areas as well as the need for ensuring adaptation measures and alternative livelihood options for smallholder farmers in areas where climate change will have negative impacts on cultivation conditions.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10113-023-02111-5.

Funding This study is part of the project 'Reducing trade-offs and increasing synergies associated with improved food security in Lao PDR and Myanmar', which has been funded by Netherlands Organization for Scientific Research (NWO) under the NWO-WOTRO Science for Global Development (Grant no. W07.303.108).

Data availability Script used for suitability modelling and data on historical and average projected future suitability for the included crops is available for download at Dataverse (https://dataverse.nl/dataverse/BETA): https://doi.org/10.34894/FUL0QK

References

Ahrends A, Hollingsworth PM, Ziegler AD, Fox JM, Chen H, Su Y, Xu J (2015) Current trends of rubber plantation expansion may threaten biodiversity and livelihoods. Glob Environ Chang 34:48–58. https://doi.org/10.1016/j.gloenvcha.2015.06.002

Almazroui M, Saeed F, Saeed S, Ismail M, Ehsan MA et al (2021) Projected changes in climate extremes using CMIP6 simulations over SREX regions. Earth Syst Environ 5:481–497. https://doi.org/10.1007/s41748-021-00250-5

Alouw JC, Wulandari S (2020) Present status and outlook of coconut development in Indonesia. IOP Conf Ser Earth Environ Sci 418:012035. https://doi.org/10.1088/1755-1315/418/1/012035

Andrianto A, Komarudin H, Pacheco P (2019) Expansion of oil palm plantations in Indonesia's frontier: problems of externalities and the future of local and indigenous communities. Land 8:56. https://doi.org/10.3390/land8040056

Andriesse E (2018) Primary sector value chains, poverty reduction, and rural development challenges in the Philippines. Geogr Rev 108:345–366. https://doi.org/10.1111/gere.12287

Appelt JL, Garcia Rojas DC, Verburg PH, van Vliet J (2022) Socioeconomic outcomes of agricultural land use change in

Southeast Asia. Ambio 51:1094–1109. https://doi.org/10.1007/s13280-022-01712-4

BirdLife International (2022) World Database of Key Biodiversity Areas. Developed by the KBA Partnership: BirdLife International, International Union for the Conservation of Nature, American Bird Conservancy, Amphibian Survival Alliance, Conservation International,. Critical Ecosystem Partnership Fund, Global Environment Facility, Re:wild, NatureServe, Rainforest Trust, Royal Society for the Protection of Birds, Wildlife Conservation Society and World Wildlife Fund. September 2022 version. http://keybiodiversityareas.org/kba-data/request

Bissonnette JF, De Koninck R (2017) The return of the plantation? Historical and contemporary trends in the relation between plantations and smallholdings in Southeast Asia. J Peasant Stud 44:918–938. https://doi.org/10.1080/03066150.2017.1311867

Carlson KM, Heilmayr R, Gibbs HK, Noojipady P, Burns DN et al (2018) Effect of oil palm sustainability certification on deforestation and fire in Indonesia. Proc Natl Acad Sci U S A 115:121–126. https://doi.org/10.1073/pnas.1704728114

Carr MKV (2011) The water relations and irrigation requirements of coconut (Cocos nucifera): a review. Exp Agric 47:27–51. https://doi.org/10.1017/S0014479710000931

Corbane C, Florczyk A, Pesaresi M, Politis P, Syrris V (2018) GHS built-up grid, derived from Landsat, multitemporal (1975-1990-2000-2014), R2018A. European Commission, Joint Research Centre (JRC) [Dataset]. https://doi.org/10.2905/jrc-ghsl-10007

Corbane C, Pesaresi M, Kemper T, Politis P, Florczyk AJ et al (2019) Automated global delineation of human settlements from 40 years of Landsat satellite data archives. Big Earth Data 3:140–169. https://doi.org/10.1080/20964471.2019.1625528

Corley RHV (2009) How much palm oil do we need? Environ Sci Pol 12:134–139. https://doi.org/10.1016/j.envsci.2008.10.011

Corley RHV, Rao V, Palat T, Praiwan T (2018) Breeding for drought tolerance in oil palm. J Oil Palm Res 30:26–35. https://doi.org/10.21894/jopr.2017.00011

Corley RHV, Tinker PB (2015) The oil palm, Fifth Edition. Wiley-Blackwell. https://doi.org/10.1002/9781118953297

Davila F (2020) Human ecology and food discourses in a smallholder agricultural system in Leyte, The Philippines. Agric Hum Values 37:719–741. https://doi.org/10.1007/s10460-019-10007-6

de Sousa L, Poggio L, Batjes N, Heuvelink G, Kempen B, et al (2020) SoilGrids 2.0: producing quality-assessed soil information for the globe. SOIL Discuss 1–37. https://doi.org/10.5194/soil-2020-65

Descals A, Wich S, Meijaard E, Gaveau DLA, Peedell S et al (2021) High-resolution global map of smallholder and industrial closed-canopy oil palm plantations. Earth Syst Sci Data 12:1211–1231. https://doi.org/10.5194/essd-13-1211-2021

Fagan ME, Kim D-H, Settle W, Ferry L, Drew J et al (2022) The expansion of tree plantations across tropical biomes. Nat Sustain 5:681–688. https://doi.org/10.1038/s41893-022-00904-w

FAO (2021) FAOSTAT statistical database. https://www.fao.org/faostat/. Accessed 29 Sep 2021

FAO (2022) Database of Crop Constraints and Characteristics (ECOCROP). https://gaez.fao.org/pages/ecocrop. Accessed 16 May 2022

FAO and IIASA (2021) Global Agro Ecological Zones version 4 (GAEZ v4). https://gaez.fao.org/. Accessed 12 Oct 2021

Farr TG, Rosen PA, Caro E, Crippen R, Duren R, et al (2007) The shuttle radar topography mission. Rev Geophys 45:. https://doi.org/10.1029/2005RG000183

Feintrenie L, Chong WK, Levang P (2010a) Why do farmers prefer oil palm? Lessons learnt from Bungo District, Indonesia. Small-scale For 9:379–396. https://doi.org/10.1007/s11842-010-9122-2

Feintrenie L, Ollivier J, Enjalric F (2010b) How to take advantage of a new crop? The experience of Melanesian smallholders. Agrofor Syst 79:145–155. https://doi.org/10.1007/s10457-010-9285-z

Feng Y, Ziegler AD, Elsen PR, Liu Y, He X et al (2021) Upward expansion and acceleration of forest clearance in the mountains of Southeast Asia. Nat Sustain 4:892–899. https://doi.org/10.1038/s41893-021-00738-y

Fischer G, Nachtergaele FO, van Velthuizen HT, Chiozza F, Franceschini G et al (2021) Global Agro-Ecological Zones v4 – Model documentation. FAO, Rome. https://doi.org/10.4060/cb4744en

Fox J, Castella JC (2013) Expansion of rubber (Hevea brasiliensis) in Mainland Southeast Asia: what are the prospects for smallholders? J Peasant Stud 40:155–170. https://doi.org/10.1080/03066150.2012.750605

Fritz S, See L, Mccallum I, You L, Bun A et al (2015) Mapping global cropland and field size. Glob Chang Biol 21:1980–1992. https://doi.org/10.1111/gcb.12838

Gatto M, Wollni M, Asnawi R, Qaim M (2017) Oil palm boom, contract farming, and rural economic development: village-level evidence from Indonesia. World Dev 95:127–140. https://doi.org/10.1016/j.worlddev.2017.02.013

Golbon R, Cotter M, Sauerborn J (2018) Climate change impact assessment on the potential rubber cultivating area in the Greater Mekong Subregion. Environ Res Lett 13:084002. https://doi.org/10.1088/1748-9326/aad1d1

Grogan K, Pflugmacher D, Hostert P, Mertz O, Fensholt R (2019) Unravelling the link between global rubber price and tropical deforestation in Cambodia. Nat Plants 5:47–53. https://doi.org/10.1038/s41477-018-0325-4

Gunn BF, Baudouin L, Olsen KM (2011) Independent origins of cultivated coconut (Cocos nucifera L.) in the old world tropics. PLoS One 6:e21143. https://doi.org/10.1371/journal.pone.0021143

Hannah L, Roehrdanz PR, Krishna Bahadur KC, Fraser EDG, Donatti CI et al (2020) The environmental consequences of climate-driven agricultural frontiers. PLoS One 15:e0228305. https://doi.org/10.1371/journal.pone.0228305

Hardanto A, Röll A, Niu F, Meijide A, Hendrayanto et al (2017) Oil palm and rubber tree water use patterns: effects of topography and flooding. Front Plant Sci 8:452. https://doi.org/10.3389/fpls.2017.00452

Harris N, Goldman ED, Gibbes S (2019) Spatial database of planted trees (SDPT Version 1.0). Technical Note. World Resources Institute. https://www.wri.org/research/spatial-database-planted-trees-sdpt-version-10. Accessed 16 Sept 2021

Hijmans RJ, Guarino L, Cruz M, Rojas E (2001) Computer tools for spatial analysis of plant genetic resources data : 1. DIVA-GIS Plant Genet Resour Newsl 127:15–19

Hoang NT, Kanemoto K (2021) Mapping the deforestation footprint of nations reveals growing threat to tropical forests. Nat Ecol Evol 5:845–853. https://doi.org/10.1038/s41559-021-01417-z

Hurni K, Fox J (2018) The expansion of tree-based boom crops in mainland Southeast Asia: 2001 to 2014. J Land Use Sci 13:198–219. https://doi.org/10.1080/1747423X.2018.1499830

IFPRI (2019) Global spatially-disaggregated crop production statistics data for 2010 Version 2.0. https://doi.org/10.7910/DVN/PRFF8V

Ismail T, Gohet E (2021) Impact of climate change on latex harvesting. In: Pinizzotto S, Aziz A, Gitz V et al (eds) Natural rubber systems and climate change: proceedings and extended abstracts from the online workshop, 23–25 June 2020. The CGIAR Research Program on Forests, Trees and Agroforestry, Bogor, Indonesia

Jaroenkietkajorn U, Gheewala SH, Scherer L (2021) Species loss from land use of oil palm plantations in Thailand. Ecol Indic 133:108444. https://doi.org/10.1016/j.ecolind.2021.108444

Jayasooryan KK, Satheesh PR, Krishnakumar R, Jacob J (2015) Occurrence of extreme temperature events – a probable risk on natural

rubber cultivation. J Plant Crop 43:218–224. https://doi.org/10.19071/jpc.2015.v43.i3.2856
Jin S, Min S, Huang J, Waibel H (2021) Falling price induced diversification strategies and rural inequality: evidence of smallholder rubber farmers. World Dev 146:105604. https://doi.org/10.1016/j.worlddev.2021.105604
Kallio MH, Hogarth NJ, Moeliono M, Brockhaus M, Cole R et al (2019) The colour of maize: Visions of green growth and farmers perceptions in northern Laos. Land Use Policy 80:185–194. https://doi.org/10.1016/j.landusepol.2018.10.006
Kamworapan S, Surussavadee C (2019) Evaluation of CMIP5 global climate models for simulating climatological temperature and precipitation for southeast Asia. Adv Meteorol 2019:1–18. https://doi.org/10.1155/2019/1067365
Karger DN, Conrad O, Böhner J, Kawohl T, Kreft H et al (2017) Climatologies at high resolution for the earth's land surface areas. Sci Data 4:1–20. https://doi.org/10.1038/sdata.2017.122
Kenney-Lazar M, Ishikawa N (2019) Mega-plantations in Southeast Asia. Environ Soc 10:63–82. https://doi.org/10.3167/ares.2019.100105
Khatiwada D, Palmén C, Silveira S (2021) Evaluating the palm oil demand in Indonesia: production trends, yields, and emerging issues. Biofuels 12:135–147. https://doi.org/10.1080/17597269.2018.1461520
King M, Altdorff D, Li P, Galagedara L, Holden J et al (2018) Northward shift of the agricultural climate zone under 21st-century global climate change. Sci Rep 8:7904. https://doi.org/10.1038/s41598-018-26321-8
Kumar SN, Aggarwal PK (2013) Climate change and coconut plantations in India: Impacts and potential adaptation gains. Agric Syst 117:45–54. https://doi.org/10.1016/j.agsy.2013.01.001
Landicho LD, Paelmo RF, Baliton RS, Lasco RD, Visco RG et al (2015) Field-level evidences of climate change and coping strategies of smallholder farmers in Molawin-Dampalit Sub-Watershed, Makiling forest reserve, Philippines. Asian J Agric Dev 12:81–94
Laroche PCSJ, Schulp CJE, Kastner T, Verburg PH (2022) Assessing the contribution of mobility in the European Union to rubber expansion. Ambio 51:770–783. https://doi.org/10.1007/s13280-021-01579-x
Laurance WF (2016) Lessons from research for sustainable development and conservation in Borneo. Forests 7:314. https://doi.org/10.3390/f7120314
Leijten F, Sim S, King H, Verburg PH (2020) Which forests could be protected by corporate zero deforestation commitments? A spatial assessment Environ Res Lett 15:064021. https://doi.org/10.1088/1748-9326/ab8158
Liyanage KK, Khan S, Mortimer PE, Hyde KD, Xu J et al (2016) Powdery mildew disease of rubber tree. For Pathol 46:90–103. https://doi.org/10.1111/efp.12271
Malek Ž, Loeffen M, Feurer M, Verburg PH (2022) Regional disparities in impacts of climate extremes require targeted adaptation of Fairtrade supply chains. One Earth 5:917–931. https://doi.org/10.1016/j.oneear.2022.07.008
Mertz O, Padoch C, Fox J, Cramb RA, Leisz SJ et al (2009) Swidden change in southeast Asia: understanding causes and consequences. Hum Ecol 37:259–264. https://doi.org/10.1007/s10745-009-9245-2
Miettinen J, Hooijer A, Shi C, Tollenaar D, Vernimmen R et al (2012) Extent of industrial plantations on Southeast Asian peatlands in 2010 with analysis of historical expansion and future projections. GCB Bioenergy 4:908–918. https://doi.org/10.1111/j.1757-1707.2012.01172.x
Nachtergaele F, van Velthuizen H, Verelst L, Batjes N, Dijkshoorn K et al (2012) Harmonized world soil database, version 1.2. FAO, IIASA, ISRIC, ISSCAS, JRC. https://data.isric.org/geonetwork/srv/eng/catalog.search?uuid=bda461b1-2f35-4d0c-bb16-44297068e10d. Accessed 7 Oct 2020
Nampoothiri KUK, Krishnakumar V, Thampan PK, Achuthan Nair M (2019) The coconut palm (Cocos nucifera L.) - research and development perspectives. Springer, Singapore. https://doi.org/10.1007/978-981-13-2754-4
O'Neill BC, Kriegler E, Ebi KL, Kemp-Benedict E, Riahi K et al (2017) The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. Glob Environ Chang 42:169–180. https://doi.org/10.1016/j.gloenvcha.2015.01.004
Obidzinski K, Andriani R, Komarudin H, Andrianto A (2012) Environmental and social impacts of oil palm plantations and their implications for biofuel production in Indonesia. Ecol Soc 17:25. https://doi.org/10.5751/ES-04775-170125 http://www.ecologyandsociety.org/vol17/iss1/art25/
Ornetsmüller C, Castella JC, Verburg PH (2018) A multiscale gaming approach to understand farmer's decision making in the boom of maize cultivation in Laos. Ecol Soc 23:25. https://doi.org/10.5751/ES-10104-230235
Paterson RRM, Kumar L, Shabani F, Lima N (2017) World climate suitability projections to 2050 and 2100 for growing oil palm. J Agric Sci 155:689–702. https://doi.org/10.1017/S0021859616000605
Paterson RRM, Kumar L, Taylor S, Lima N (2015) Future climate effects on suitability for growth of oil palms in Malaysia and Indonesia. Sci Rep 5:14457. https://doi.org/10.1038/srep14457
Paterson RRM, Sariah M, Lima N (2013) How will climate change affect oil palm fungal diseases? Crop Prot 46:113–120. https://doi.org/10.1016/j.cropro.2012.12.023
PCA (2019) Annual Report 2019. Philippine Coconut Authority, Department of Agriculture, Manila, Phillipines, https://pca.gov.ph/images/pdf/annualreport/PCA_2019_Annual_Report.pdf
Peiris TSG, Thattil RO, Mahindapala R (1995) An analysis of the effect of climate and weather on coconut (Cocos nucifera). Exp Agric 31:451–460. https://doi.org/10.1017/S0014479700026430
Pirker J, Mosnier A, Kraxner F, Havlík P, Obersteiner M (2016) What are the limits to oil palm expansion? Glob Environ Chang 40:73–81. https://doi.org/10.1016/j.gloenvcha.2016.06.007
Priyadarshan PM (2017) Biology of Hevea rubber. Springer, https://doi.org/10.1007/978-3-319-54506-6
Priyadarshan PM, Hoa TTT, Huasun H, Gonçalves PDS (2005) Yielding potential of rubber (Hevea brasiliensis) in sub-optimal environments. J Crop Improv 14:221–247. https://doi.org/10.1300/J411v14n01_10
Qi D, Wu Z, Yang C, Xie G, Li Z et al (2021) Can intercropping with native trees enhance structural stability in young rubber (Hevea brasiliensis) agroforestry system? Eur J Agron 130:126353. https://doi.org/10.1016/j.eja.2021.126353
Ramirez-Villegas J, Jarvis A, Läderach P (2013) Empirical approaches for assessing impacts of climate change on agriculture: the EcoCrop model and a case study with grain sorghum. Agric For Meteorol 170:67–78. https://doi.org/10.1016/j.agrformet.2011.09.005
Rigg J, Salamanca A, Thompson EC (2016) The puzzle of East and Southeast Asia's persistent smallholder. J Rural Stud 43:118–133. https://doi.org/10.1016/j.jrurstud.2015.11.003
Rist L, Feintrenie L, Levang P (2010) The livelihood impacts of oil palm: smallholders in Indonesia. Biodivers Conserv 19:1009–1024. https://doi.org/10.1007/s10531-010-9815-z
Runtuboi YY, Permadi DB, Sahide MAK, Maryudi A (2021) Oil palm plantations, forest conservation and indigenous peoples in west papua province: what lies ahead? For Soc 5:23–31. https://doi.org/10.24259/fs.v5i1.11343
Sarkar MSK, Begum RA, Pereira JJ (2020) Impacts of climate change on oil palm production in Malaysia. Environ Sci Pollut Res 27:9760–9770. https://doi.org/10.1007/s11356-020-07601-1

Savilaakso S, Garcia C, Garcia-Ulloa J, Ghazoul J, Groom M et al (2014) Systematic review of effects on biodiversity from oil palm production. Environ Evid 3:1–21. https://doi.org/10.1186/2047-2382-3-4
Schreinemachers P, Chen H, Pu NTTL, Buntong B, Bouapao L et al (2017) Too much to handle? Pesticide dependence of smallholder vegetable farmers in Southeast Asia. Sci Total Environ 593:470–477. https://doi.org/10.1016/j.scitotenv.2017.03.181
Scriven SA, Hodgson JA, McClean CJ, Hill JK (2015) Protected areas in Borneo may fail to conserve tropical forest biodiversity under climate change. Biol Conserv 184:414–423. https://doi.org/10.1016/j.biocon.2015.02.018
Silalertruksa T, Gheewala SH, Pongpat P, Kaenchan P, Permpool N et al (2017) Environmental sustainability of oil palm cultivation in different regions of Thailand: greenhouse gases and water use impact. J Clean Prod 167:1009–1019. https://doi.org/10.1016/j.jclepro.2016.11.069
Simien A, Penot E (2011) Current evolution of smallholder rubber-based farming systems in southern Thailand. J Sustain For 30:247–260. https://doi.org/10.1080/10549811.2011.530936
Sterling EJ, Pascua P, Sigouin A, Gazit N, Mandle L et al (2020) Creating a space for place and multidimensional well-being: lessons learned from localizing the SDGs. Sustain Sci 15:1129–1147. https://doi.org/10.1007/s11625-020-00822-w
Stromberg PM, Esteban M, Gasparatos A (2011) Climate change effects on mitigation measures: the case of extreme wind events and Philippines' biofuel plan. Environ Sci Pol 14:1079–1090. https://doi.org/10.1016/j.envsci.2011.06.004
Sys C, van Ranst E, Debayeye J, Beernaert F (1993) Land evaluation. Part III: crop requirements. Agricultural Publications no. 7. General Administration for Development Cooperation, Brussels, Belgium
Thomas GV, Krishnakumar V, Dhanapal R, Reddy DVS (2018) Agro-management practices for sustainable coconut production. In: Nampoothiri KUK, Krishnakumar V, Thampan P, Nair M (eds) The coconut palm (Cocos nucifera L.) - research and development perspectives. Springer, Singapore. https://doi.org/10.1007/978-981-13-2754-4_7
Vijay V, Pimm SL, Jenkins CN, Smith SJ (2016) The impacts of oil palm on recent deforestation and biodiversity loss. PLoS One 11:e0159668. https://doi.org/10.1371/journal.pone.0159668
Wang L (2014) Physiological and molecular responses to drought stress in rubber tree (Hevea brasiliensis Muell. Arg.). Plant Physiol Biochem 83:243–249. https://doi.org/10.1016/j.plaphy.2014.08.012
Warren-Thomas E, Ahrends A, Wang Y, Wang MMH, Jones JPG (2022) Rubber needs to be included in deforestation-free commodity legislation. bioRxiv 2022.10.14.510134. https://doi.org/10.1101/2022.10.14.510134
Wicke B, Sikkema R, Dornburg V, Faaij A (2011) Exploring land use changes and the role of palm oil production in Indonesia and Malaysia. Land Use Policy 28:193–206. https://doi.org/10.1016/j.landusepol.2010.06.001
Woittiez LS, van Wijk MT, Slingerland M, van Noordwijk M, Giller KE (2017) Yield gaps in oil palm: a quantitative review of contributing factors. Eur J Agron 83:57–77. https://doi.org/10.1016/j.eja.2016.11.002
Xin Y, Sun L, Hansen MC (2021) Biophysical and socioeconomic drivers of oil palm expansion in Indonesia. Environ Res Lett 16:034048. https://doi.org/10.1088/1748-9326/abce83
Xu Y, Yu L, Li W, Ciais P, Cheng Y et al (2020) Annual oil palm plantation maps in Malaysia and Indonesia from 2001 to 2016. Earth Syst Sci Data 12:847–867. https://doi.org/10.5194/essd-12-847-2020
Zabel F, Putzenlechner B, Mauser W (2014) Global agricultural land resources - a high resolution suitability evaluation and its perspectives until 2100 under climate change conditions. PLoS One 9:e107522. https://doi.org/10.1371/journal.pone.0107522