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Climate change impact on medicinal plants in Indonesia

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ABSTRACT

Indonesia is a global hotspot of plant diversity. The country contains medicinal plants that have immense value to the people and worldwide. However, climate change is affecting the distribution of medicinal plants in Indonesia. In this study, the future greenhouse gas emission scenarios of RCP4.5 and RCP8.5 for a mid-term future projection to 2050 and a long-term future projection to 2080 were used to simulate the effect of climate change upon medicinal plants distribution within Indonesia. In 2050 and 2080, under both RCP scenarios species richness is expected to decrease over more than half the current distribution area of medicinal plant species. Over half of the medicinal plant species populations will lose up to 80% of their distribution area. Medicinal plant species on the islands of Papua, Java, and Sulawesi are predicted to have the largest reduction in distribution area. In addition, two-thirds of species will lose rather than gain areas of suitable climate under the future climate scenarios. Twenty medicinal plant species are identified as potentially being the most threatened by climate change in the future and are therefore the highest priority for conservation actions within Indonesia. Using these results, we recommend areas and species suitable for long term *in situ* and ex situ conservation within Indonesia.

1. Introduction

Indonesia is a vast country with 3 out of 25 global biodiversity hotspots, including Asian and Australasian biodiversity (Myers et al., 2000). About 30–40% plant species of Asia and10% of global plant species can be found in Indonesia (Myers et al., 2000; Walujo, 2008; Ma, 2010; Ministry of National Development Planning, 2016). Of the total flora of Indonesia,10% are predicted to be medicinal plants (Eisai, 1995; Erdelen et al., 1999; Cahyaningsih et al., 2021a). The medicinal plant has immense use to Indonesian people not only for curing sickness (de Padua et al., 1999) but also as economic sources (FAO, 1995) and has potential wider use globally and in the future (Hawkins, 2008; Soejarto et al., 2012). Taking a broader view, medicinal plants are part of biodiversity and have a role as a provisioning ecosystem service (Millennium Ecosystem Assessment, 2005).

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Like other plant species, threats to medicinal plants in Indonesia may come from deforestation, specifically as result of the oil palm, logging, fibre, and mining industries (Abood et al., 2015). Threats can also come from over-exploitation in the commercial trade of medicinal plants (Hawkins, 2008), invasive species (Ma et al., 2010), climate change (Ma et al., 2010; Harish et al., 2012), seasonal forest fires, land and water pollution, and various natural disasters (Tambunan, 2008). Thus, Indonesian medicinal plants need to be conserved.

Conserving medicinal plants means conserving ecosystems and natural habitats and all other species that co-occur with them, that are suited to *in situ* conservation, as defined by the UN (1992). As targets of conservation, they can be used as flagship species and also to raise public awareness and to initiate local projects, combining economic development and protecting biodiversity (Qian et al., 2020). As such, a climate change study related to conservation planning of medicinal plants in Indonesia is important to conduct and might complete the previous study conducted by Cahyaningsih et al. (2021a).

Regarding climate change, it is well known that the earth surface in particular, has been warmer during the past thirty years (Stocker et al., 2013; Clem et al., 2020) due to climate change, whether due to natural variability or as a result of human activity (IPCC, 2007). Predicted changes in climate and impacts on living species are correlated (Foden et al., 2019), including upon medicinal plants. For medicinal plants, increasing temperature might cause stress and affect production of compounds in, for instance, St. John's Wort (*Hypericum perforatum,* cv. 'Topas') (Zobayed et al., 2005) and *Crataegus* spp. (Kirakosyan et al., 2003). Medicinal plants may also change their phenology and distribution due to climate change, such has been recorded in medicinal species in the Central Himalaya (India) (Maikhuri et al., 2018).

Studies regarding effects of climate change on medicinal plants have been conducted in Thailand (Tangjitman et al., 2015), China (Yi et al., 2016; Wei et al., 2018), Pakistan (Khanum et al., 2013) and Africa (Asase and Peterson, 2019), but not yet in Indonesia. As an archipelagic country with seven main islands/areas (Sumatra, Java, Kalimantan, Lesser Sunda Islands/LSI, Sulawesi, Maluku, and Papua) on the equator line that spans almost 1/8 of the world's circumference and with a long coastal area (BPS Statistics Indonesia, 2020), Indonesia is vulnerable to climate change. Climate change has caused rising sea levels, larger wave heights, higher ocean temperatures (Zikra et al., 2015) and increasing temperature and rainfall in some big cities (Medan, Palembang, and Semarang) (Suryadi et al., 2018). Furthermore, Sundaland, which comprises Sumatra, Java, and LSI (which is one out of thirty-six global biodiversity hotspots) (Myers et al., 2000) and where many rare plants are found (Enquist et al., 2019) is predicted to be lost by 2100 due to a rise in sea levels (Bellard et al., 2014).

Studies of the impact of climate change have been used to help identify areas suitable for *in situ* and *ex situ* conservation (Sanchez et al., 2011; Asase and Peterson, 2019; Vincent et al., 2019; Gaisberger et al., 2020). Thus, we analyse the impact of climate change on medicinal plant species distribution and vulnerability in Indonesia under two future climate scenarios, RCP 4.5 and RCP 8.5 for the years 2050 and 2080. The objectives of this study were; to estimate the richness of species under current and future scenarios for all medicinal plant species in Indonesia (Cahyaningsih et al., 2021a): to identify the environmental variables affecting the distribution of the species: to assess the potential impacts of climate change on the predicted distribution of the species under future scenarios; and to aid further prioritisation of species for conservation.

2. Materials and methods

2.1. Medicinal plants and occurrence records

The species listed as priority medicinal plants in Indonesia, a total of 139 (Cahyaningsih et al., 2021b) were used in this climate

Table 1
Environmental variables used for the analyses (generated from CAPFITOGEN 2.0 tools; Parra-Quijano et al., 2016).

Variable	Code	Description	Unit	Source
Geophysics	alt	Altitude, metres above sea level	M	A
	Aspect	Orientation (in degrees) of the land surface	°	B
	Slope	Gradient (in degrees) of the land surface	°	
	northness	Northness. 1 if it faces northwards, - 1 if it faces southwards		
	eastness	Eastness. 1 if it faces eastwards, - 1 if it faces westwards		
Bioclimatic	bio_4	Temperature seasonality (standard deviation*100)	A	
	bio_12	Annual rainfall	Mm	
	bio_13	Rainfall during the wettest month	Mm	
	bio_14	Rainfall during the driest month	Mm	
	bio_16	Rainfall during the wettest quarter (three rainiest months)	Mm	
	bio_17	Rainfall during the driest quarter (three driest months)	Mm	
	bio_18	Rainfall during the hottest quarter (three hottest months)	Mm	
	bio_19	Rainfall during the coldest quarter (three coldest months)	Mm	
Edaphic	s_oc	Content of organic carbon in subsoil	% weight	C
	s_ph_h2o	pH in subsoil in soil-water solution	-log(H+)	
	s_teb	Total exchangeable bases in subsoil	cmol/kg	
	t_oc	Organic carbon content in surface soil	% weight	
	t_ph_h2o	Surface soil pH in a soil-water solution	-log(H+)	
	t_teb	Total exchangeable bases in surface soil	cmol/kg	

Note: a= Worldclim Version 1.4; b= SRTM DEM Version 4; c= HWS Database Version 1.2

change analysis. They are native medicinal plants (some endemic) to Indonesia, have limited distributions, are harvested in a destructive manner and include species listed in international legislation (Table Appendix 1). Occurrence records, consisting of GPS coordinates and location descriptions, were gathered from GBIF (http://www.gbif.org; GBIF, 2020), BOLD database (http://www.boldsystems.org; (Ratnasingham and Hebert, 2007) and Genesys (https://www.genesys-pgr.org; Genesys, 2020) Herbarium databases from Indonesia (Herbarium Bogoriense and Bogor Botanic Gardens–Indonesian Institute of Sciences), the United Kingdom (Royal Botanic Garden, Kew, London and Royal Botanic Garden, Edinburgh) and the Netherlands (Naturalis herbarium) were also used to gather distribution data. Only those species with ten or more occurrence points were selected to ensure a more accurate analysis (Wisz et al., 2008), resulting in 4446 presence points for the 139 species. Occurrence points were checked for consistency of their coordinates at the country level using DIVA GIS 7.5.

2.2. Environmental variables for current and future analyses

A total of 19 environmental variables were used in the predictive analysis which consisted of bioclimatic, edaphic, and geophysical layers at a resolution of five arc-minutes (approximately 10×10 km^2 at the equator). They were selected with the Random Forest (RF) procedure (Cutler et al., 2007) implemented in the SelecVar tool of the CAPFITOGEN 2.0 tools (Parra-Quijano et al., 2016, www.capfitogen.net/en) (Table 1). Additionally, correlation analysis with MINITAB 19 showed there was no significant correlation between any variables within the 19 selected variables.

The current climate refers to a representation of the years 1960–1990 (Hijmans et al., 2005). Future bioclimatic variables were collected from CCAFS (www.ccafs-climate.org), which are based on the fifth IPCC report (IPCC, 2014). Edaphic and geophysical variables are assumed not to be significantly affected by climate change (Pearson and Dawson, 2003; Phillips et al., 2017). The future climatic model used was the Model for Interdisciplinary Research on Climate-Earth System Models (MIROC-ESM) (Watanabe et al., 2011) for the Representative Concentration Pathways (RCP), RCP4.5 (Thomson et al., 2011), and RCP8.5 (Riahi et al., 2011) for a mid-term future projection of 2050 and a long-term future projection of 2080. The MIROC-ESM model has been used in plant species distribution studies individually or combined with other models (Robiansyah, 2018; Shabani et al., 2020; Xu et al., 2019). RCP4.5 represents a medium-range emission scenario and RCP8.5 represents a high range emission scenario, with the latter being selected for this study as it represents a possible projection for a large population with high fossil fuel use (Moss et al., 2010; van Vuuren et al., 2011) such as Indonesia.

2.3. Species distribution modelling (SDM)

Current and future climate scenarios for the potential distribution of medicinal plants in Indonesia were generated. The maximum entropy (MaxEnt) algorithm (Phillips et al., 2006) was used to generate for each species an individual distribution model, under both current and future conditions. A cross-validated method was chosen to train and test the models (Elith et al., 2011). Equal test sensitivity and specificity was used for the threshold in MaxEnt (Liu et al., 2005; Gaisberger et al., 2020). To check whether models were accurate and stable, three criteria were applied; the Area under the ROC (Receiver Operating Characteristic) Curve of the test data (AUCTest) > 0.7; standard deviation of the AUCTest data (STAUC) $< (\pm)\ 0.15$, and the proportion of potential distribution area with a STAUC > 0.15 below 10% (ASD15 $<$ 10%) (Ramírez-Villegas et al., 2010; Castañeda-Álvarez et al., 2015; Contreras-Toledo et al., 2019). Models meeting this criteria under current and future climate conditions were displayed and analysed in DIVA-GIS 7.5 (Hijmans et al., 2001). The environmental variables that contributed most to the models under the current climatic projection were identified in order to understand variables which may affect medicinal plant species distribution the most (Tangjitman et al., 2015).

2.4. Impact of climate change

The impact of climate change on medicinal plants in Indonesia was analysed using species richness, loss and gain of species, turnover, and threat level based on the IUCN Red List (2019), with methods adopted from Thuiller et al. (2005), Ramirez-Villegas et al. (2014), and Phillips et al. (2017).

Gain and loss of species was calculated based on presence or absence of species within the grid cells (approximately 10×10 km^2) resulting from the MAXENT analysis. Gain in species richness was measured when a species was absent in the current SDM but present in the future SDM, while loss was calculated based on the species present in the current SDM but absent in the future SDM. Gain has a positive value, while loss has a negative value.

The turnover rate (T) was calculated for both RCP scenarios with the formula $T = 100 \text{ x } (L+G)/(SR+G)$, where SR was the current species richness, L was the loss of species per grid cell, and G was the gain of species per grid cell (Phillips et al., 2017; Ramirez-Villegas et al., 2014; Thuiller et al., 2005). The turnover rate always ranges from 0 to 100: that is, 0 when no species are gained or lost, and therefore species composition remains the same, and 100 when the full set of species within a grid cell has changed (Phillips et al., 2017; Ramirez-Villegas et al., 2014).

The threat level for each medicinal plants species in Indonesia under future scenarios was assessed using the IUCN Red List criterion A3(c): namely, Extinct (EX) when predicted a loss of 100%, Critically Endangered (CR) when predicted a loss of $>$ 80%, Endangered (EN) when predicted a loss of $>$ 50%, and Vulnerable (V) when predicted a loss of $>$ 30%; the time frame used for Criterion A should be 3 generations or 10 years, whichever is longer (IUCN, 2019). Due to the variable generation length of the medicinal plant species used, the time frame used for the future climate change assessment is assumed applicable for each species. The medicinal plants identified as threatened in the future scenario by the IUCN red list (*i.e.* those species assessed as V, EN, CR, or EX) were listed as species of the highest conservation priority in this study. In addition, ten species identified with the smallest projected future distribution area in each scenario were also identified as species of the highest conservation priority (Jarvis et al., 2008).

3. Results and discussion

3.1. Species richness of medicinal plants in Indonesia under current and future scenarios

The species richness of medicinal plants in Indonesia is shown in Fig. 1, where it is predicted, that under the present climate, between 1 and 21 species are found in every grid cell (approximately 10×10 km^2). The majority of areas with the richest medicinal plant diversity are found on four main islands, Java, LSI, Sumatra, and Sulawesi. Looking in detail at these four islands, the areas with highest richness on Java extend from the western to eastern part of the island; on LSI, the most species rich areas are seen on Bali, Lombok, Sumbawa, and Flores (the islands nearest to Java); on Sumatra, the most species rich areas spread from the north to the south (lower species richness); on Sulawesi, the areas in the north and south are the most species rich. On Kalimantan, there is lower species richness compared to the other islands, with species rich areas located in the northern parts of the island. The overall predicted species richness under the current climate (Fig. 1), covers a larger area than the species richness identified based on actual observational data in Cahyaningsih et al. (2021a). Fig. 1 may be a more reliable reflection of the full species distribution as the results are based upon the area predicted to be favourable to species presence. This does not rely upon collecting GPS coordinate data for each species across its entire distribution range (Bini et al., 2006; Monsarrat et al., 2019), however field surveying will be needed to confirm the predicted distribution of these species. Moreover, Sumatra, Java, Sulawesi, and LSI are mountainous areas which contain either active or inactive volcanoes (Adisoemarto, 2004; GADM, 2020), while Kalimantan is not. Due to the geology and the biological interactions within these mountainous areas and the fertile soils from volcanic ash, plants are provided with high levels of nutrients for growth and these areas tend to have more plant species diversity (Fiantis et al., 2019; Rahbek et al., 2019), therefore our results for high medicinal plant species richness on these islands are not unexpected.

Forty-three out of 139 medicinal plants had valid species distribution models under the current climatic scenario. This low number of stable predictions might be due to the limited distribution of the species studied and therefore the low number of occurrence data available (Cahyaningsih et al., 2021b). Each individual species distribution on the predicted species distribution map under the current climate (Fig. 1) was influenced by a different combination of environmental variables (Table Appendix 2). The dominant environmental variables which have influenced the model are: altitude/alt (metres above sea level), temperature seasonality ((SD*100)/bio4) and rainfall during the driest month ((mm)/bio14) (Fig. 1). Altitude as a non-climatic environmental variable had an obvious impact on species richness at a large scale within this study, even though Pearson and Dawson (2003) and Blach-Overgaard et al. (2010) in their studies found otherwise.

The average value of species richness in the future within each grid cell is lower than the predicted species richness under the current climate (Table 2), even though the area containing the highest number of species apparently increases according to the four predicted future conditions: two scenarios of RCP4.5 in 2050 and 2080 (Fig. 2), and two scenarios of RCP8.5 in 2050 and 2080 (Fig. 3). This is illustrated by the grid cells of high diversity (with darker colours in the maps) seen as increasing in both future scenarios,

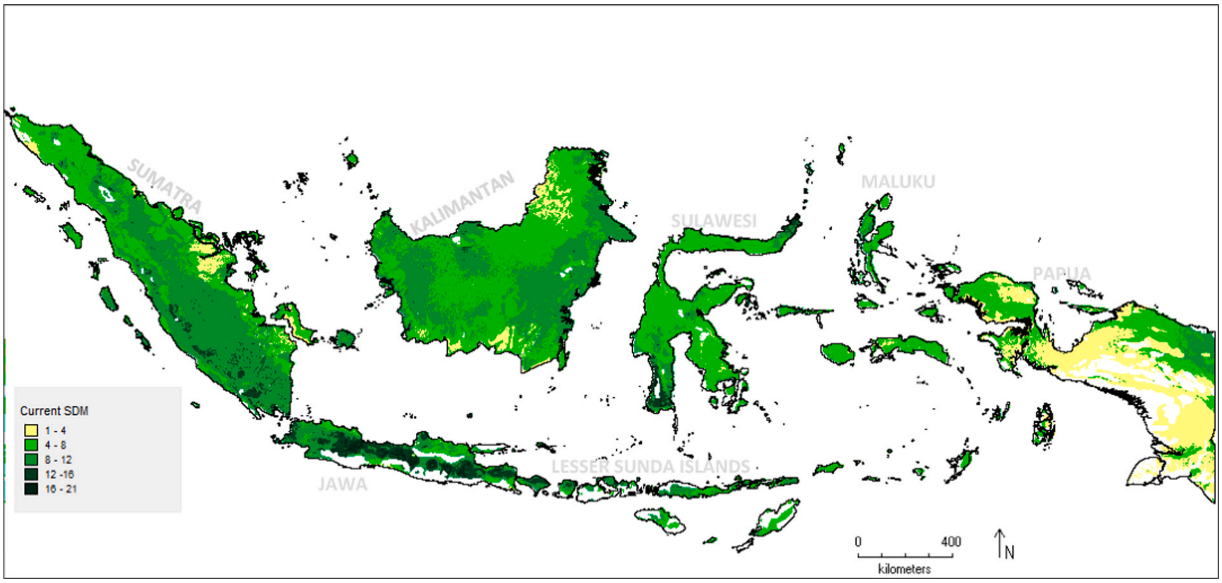

Fig. 1. The predicted species richness of 43 medicinal plants in Indonesia under the current climatic conditions with a grid cell resolution of five minutes (approximately equal to 10×10 km^2) used.

although the average value of both future species richness is lower than current (Table 2). The four islands (Sumatra, Kalimantan, Jawa, and Sulawesi) are predicted to have more area with the highest species richness, although with fewer species richness compared to the present climate. The areas with highest species richness follow the pattern of high elevation or mountainous areas in each island (around 2000 m and up above sea level). This is unsurprising as mountainous areas have higher species diversity and endemicity compared to lowland areas (Noroozi et al., 2018; Rahbek et al., 2019).

The minimum and maximum species richness value per grid cell (10×10 km^2) under future climatic conditions was projected to change. In the RCP4.5 future scenario, the richness value was within the range 1–22 (2050) and 1–20 (2080) species per grid cell (Fig. 2) while under the RCP8.5 scenario the value was 1–20 (2050 and 2080) species per grid cell (Fig. 3). It is assumed that an unlimited migration scenario is applied in the future models, and therefore, species move freely across the landscape in response to climate change. The species might have a chance to migrate to a suitable area by expanding their roots and dispersing their seed (Pitelka and Plant Migration Workshop Group, 1997), therefore extinction, due to lack of favourable areas to migrate too, might not happen (Thuiller et al., 2005; Phillips et al., 2017; Sentinella et al., 2020).

3.2. Loss and gain of distribution area

The total distribution area of medicinal plants in Indonesia are predicted to decrease by 2050 under RCP4.5 and RCP8.5 scenarios, but some species will shift their distribution into new areas (shown in overall average value; Table Appendix 2). Species are predicted to lose the largest area of distribution on Papua, Java and Sulawesi islands. One reason these species may lose distribution area on these islands might be that sea level rise is predicted to lead to major distribution loss of species (Bellard et al., 2014).

By 2080 under both scenarios species on all islands might shift to new distribution areas, for example Sumatra shows the largest gain of species in some areas (Fig. 4). In the future scenario of RCP8.5 in 2050 and 2080, the gain in species distribution is predicted to be more widespread when compared to RCP4.5, even though the overall pattern of loss and gain are similar on each island (Fig. 5). Nevertheless, the average of gain and loss of species distribution area in both years of RCP8.5 are smaller, while the loss of species distribution area is bigger than species distribution area in RCP4.5 (Table 3). Under the future scenario of RCP8.5, the loss of the distribution area of species is most extensive, this may be because this is the pessimistic climate change scenario (IPCC, 2014).

The areas which gain species in the future, compared to the current distribution, may have more suitable habitat available for the species (Sanchez et al., 2011; Robiansyah, 2018; Asase and Peterson, 2019; Vincent et al., 2019; Gaisberger et al., 2020). Here, ***in situ*** conservation with sustainable utilisation is recommended (Asase and Peterson, 2019). In particular where these areas overlap with recommended potential reserve sites for medicinal plant conservation (as shown in Cahyaningsih et al., 2021a) these areas are suitable for long term *in situ* conservation sites for Indonesian medicinal plant species as they are also areas where high diversity of medicinal plants is currently located. On the contrary, the areas showing the highest loss of species, such as those found in Papua, East Java and South Sulawesi (Fig. 4 and Fig. 5) may have unsuitable habitat for Indonesian medicinal plant species in the future. Thus, these areas are a priority for *ex situ* conservation action, where species should be collected and stored in seed banks for future sustainable use (Asase and Peterson, 2019).

3.3. Turnover

The overall average turnover rates for medicinal plant species in Indonesia was negative, meaning loss of species distribution area is expected to be higher than the gain in distribution area. The average turnover rate in the RCP4.5 2050 and RCP8.5 2050 was higher than the turnover rate under both RCP scenarios in 2080. Some species may loss distribution in one area but gain distribution in another area (Table 4), therefore shifting their distribution range. Two-thirds of medicinal plant species have negative turnover rates, under RCP4.5 and RCP8.5 scenario in both 2050 and 2080 (Table Appendix 2).

However, based on the predicted gain and loss of species richness (Figs. 4–5), there are predicted to be an increase in species richness in each grid cell (10×10 km^2 in size). The areas that experience gains are most likely a result of other species migrating into the grid cell. Plants species may shift to areas outside their usual favourable bioclimatic variables and thrive at different altitude or latitudes due to changing climatic conditions (Phillips et al., 2017; Sentinella et al., 2020; Thuiller et al., 2005).

3.4. Identifying target species for highest conservation

Some plant species are predicted to face a high level of distribution loss under future RCP4.5 and RCP8.5 scenarios (Robiansyah, 2018; Asase and Peterson, 2019) or only under RCP8.5 scenario (Gaisberger et al., 2020). On the other hand, some species might have a more extensive distribution than under RCP8.5 scenario (Li et al., 2019; Yi et al., 2016). In this study of medicinal plants in Indonesian,

Table 2
Overall descriptive value of species richness of medicinal plants in Indonesia under different scenarios.

Observation	Current	RCP4.5 2050	RCP4.5 2080	RCP8.5 2050	RCP8.5 2080
Average	17,349.44	16,084.88	15,716.74	15,979.28	14,831.67
±stdev	8154.586	8193.829	8857.813	8356.029	9090.073
Min. value	2110	1858	1629	1562	1163
Max. value	31,140	32,519	33,915	32,653	34,533

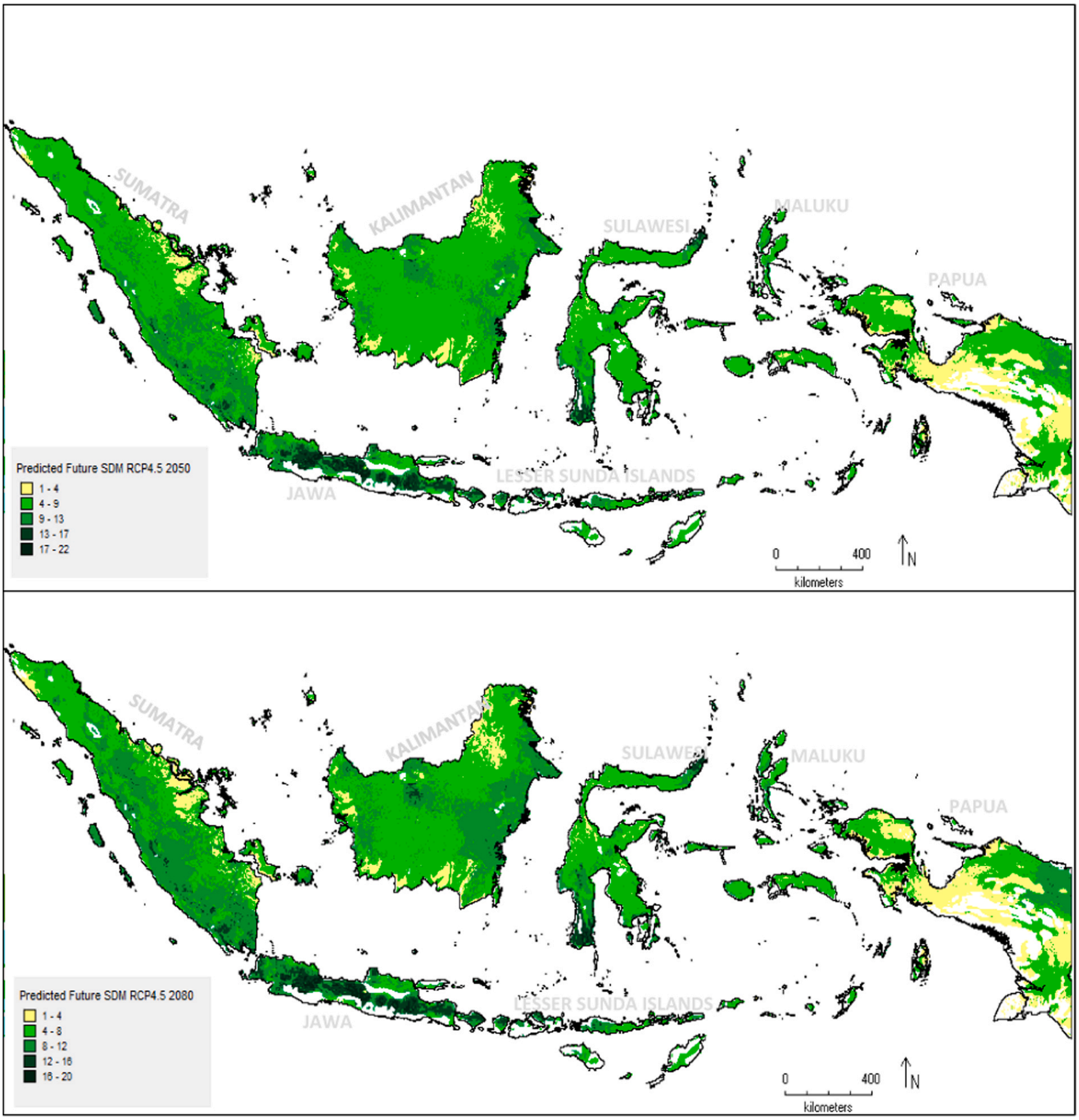

Fig. 2. The predicted future species richness of 43 medicinal plants in Indonesia under the RCP4.5 scenario year of 2050 (above) and 2080 (below) with a grid cell resolution of five minutes (approximately equal to 10×10 km^2) used.

two thirds of species are predicted to lose distribution area than gain area, across both RCP scenarios and in 2050 and in 2080, with the remaining species potentially gaining distribution area. The number of species that gain distribution area under the RCP4.5 scenario are increasing from 2050 to 2080, contrary to the species number under future RCP8.5 which are decreasing.

More than half of the studied Indonesian medicinal plant species are predicted to reduce their population size because of losing an estimated 30–80% of their distribution area (Table 5). This would result in them being assessed as Vulnerable and Endangered based on the IUCN Redlist criteria (IUCN, 2019) regardless of their generation length information (Fig. 6). The remainder of the species are predicted to suffer $<$ 30% loss distribution area or gain a new distribution area. These results are in line with studies by Tangjitman et al. (2015) suggesting that 77% of studied medicinal plants are highly threatened by climate change and need conservation. Jarvis et al. (2008) suggest that species losing distribution area of above 50% in the future should be targeted for the highest level of conservation, which is similar to the criteria for Endangered and Critically Endangered Species (IUCN, 2019).

The target species for highest conservation was defined based on the smallest distribution area in the future (Jarvis et al., 2008) and

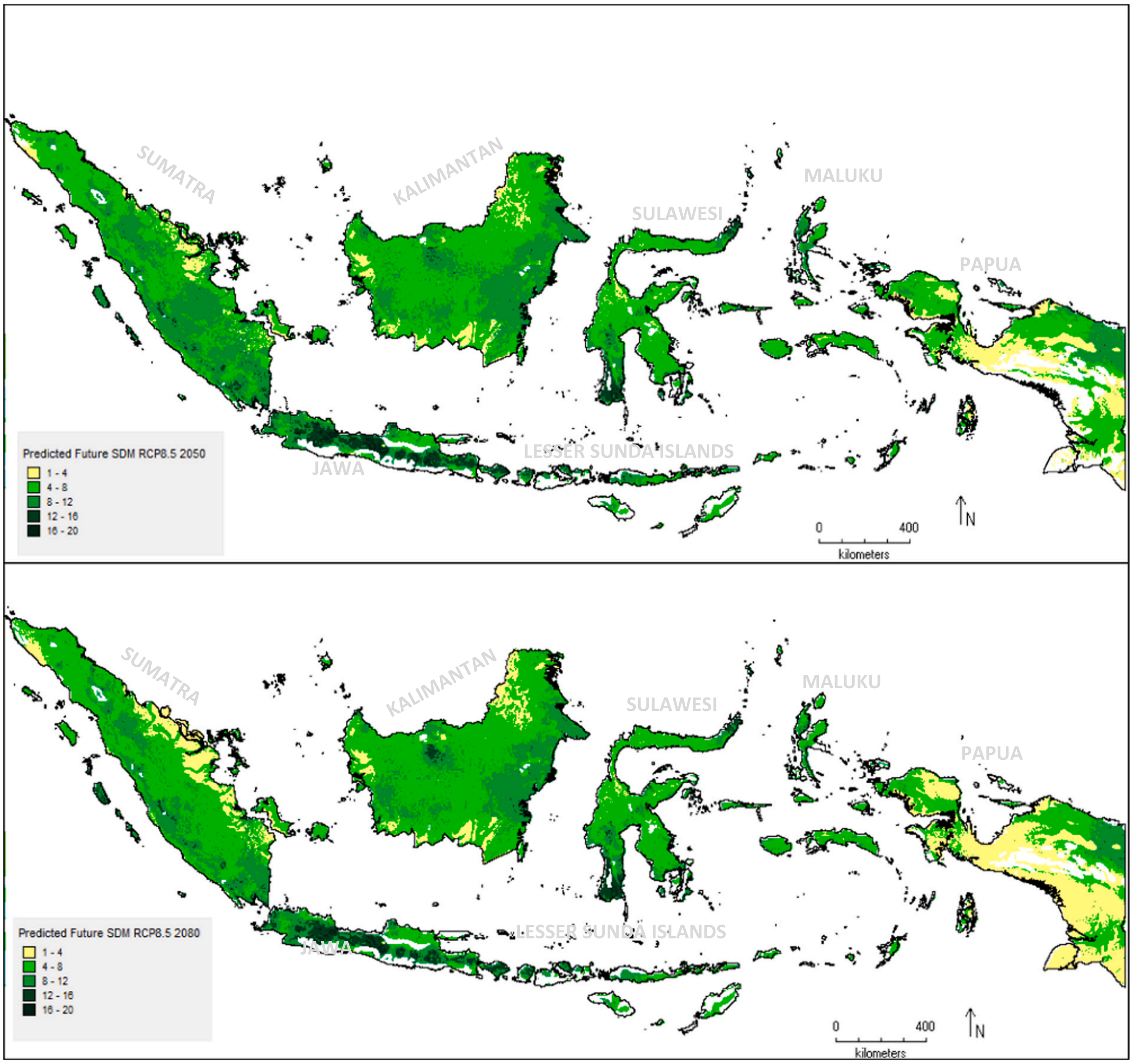

Fig. 3. The predicted future species richness of 43 medicinal plants in Indonesia under the RCP8.5 scenario year of 2050 (above) and 2080 (below) with a grid cell resolution of five minutes (approximately equal to 10 × 10 km^2) used.

IUCN red list A3 criterion (IUCN, 2019) (Table 6). Eleven Indonesian medicinal plants are predicted to have the smallest distribution area in all studied future scenarios and these species are included in a future IUCN red list A3 criterion (IUCN, 2019). The average value of the distribution area and range of their distribution area are both predicted to decrease (Table 7).

All target medicinal plant species in Table 6 are priority species that are rare or endemic (Cahyaningsih et al., 2021b) and prone to vulnerability and thus extinction due to climate change (Işik, 2011). Based on Table 6, the majority of these species are tree species (68.18%) and shrub species (18.18%), meanwhile the rest are herbs (9.09%), and climbers (4.54%) (Table Appendix 2). In spite of incomplete generation length data due to lack of monitoring, in the long term, those tree species which have longer generation lengths are more vulnerable to climate change (Chichorro et al., 2019; García-Valdés et al., 2018), as illustrated by our results.

The composition of Indonesian medicinal plant species predicted to be listed in the IUCN Redlist is predicted to change in each scenario (Table Appendixes 2, Table 5, and Table 6). Based on our study, the medicinal plant species included in Redlist categories by the IUCN currently, are expected to shift their distribution range from their current locations. Likewise, Benavides et al. (2020) found the same pattern for tropical cacti species distribution in Baja California Peninsula (Mexico), where some species might benefit from climate change and the total number of threatened species might decrease significantly.

Identifying climate change impact on plant species could be overestimated because the species or population character and its interaction with habitat were usually not considered (Thuiller et al., 2005; Fordham et al., 2012). The species may gain new distribution area, but they may be unable to move there, due to many factors, including altitude (Dobrowski and Parks, 2016; Liu et al.,

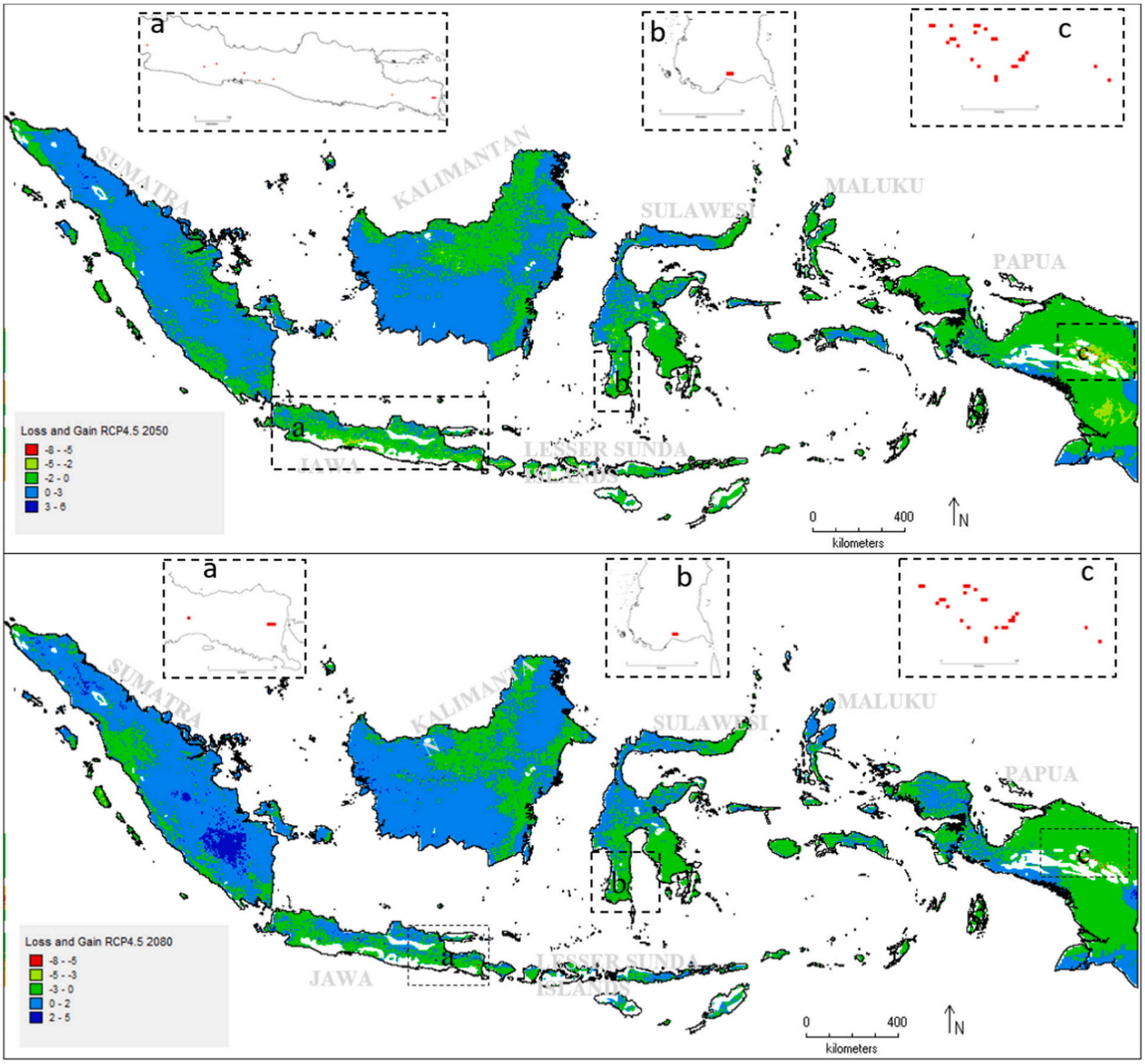

Fig. 4. The predicted loss and gain of 43 medicinal plants in Indonesia distribution under the RCP4.5 scenario year of 2050 (above) and 2080 (below) with a grid cell resolution of five minutes (approximately equal to 10 × 10 km^2) used, with insert map where highest loss predicted.

2018) and human impacts in the surrounding area (Hunter, 2007). Moreover, using the population size of plants with long generation lengths might be an inadequate predictor of population viability in the long term due to the time lag in its response to habitat degradation (Colling and Matthies, 2006). However, gain and loss patterns of the species over their distribution areas might remain (Thuiller et al., 2005). Harnik et al. (2012) states that geographic range, habitat breadth, and local abundance respectively had effects in determining extinction and that geographic range loss will lead to the extinction level increasing even though the current local population is abundant. Given the higher threat level seen by the loss of distribution area for many Indonesian medicinal plant species, the RCP8.5 scenario negatively affects species more than RCP4.5. The data shows that major medicinal plant species that grow in Indonesia might be under threat due to climate change, supporting Sentinella et al.'s (2020) study, which identified that more than 50% of tropical species have a declining germination rate caused by climate change.

4. Conclusions

This study shows that overall species richness of Indonesian medicinal plant species is predicted to be negatively affected due to future climate change, even though the impact on species distribution varies from species to species. Our results predict that the number of medicinal plant species listed in the threatened IUCN Red List categories will increase under all future scenarios. In addition, the major environmental variables that contributed to the SDM are altitude (metres above sea level), temperature seasonality

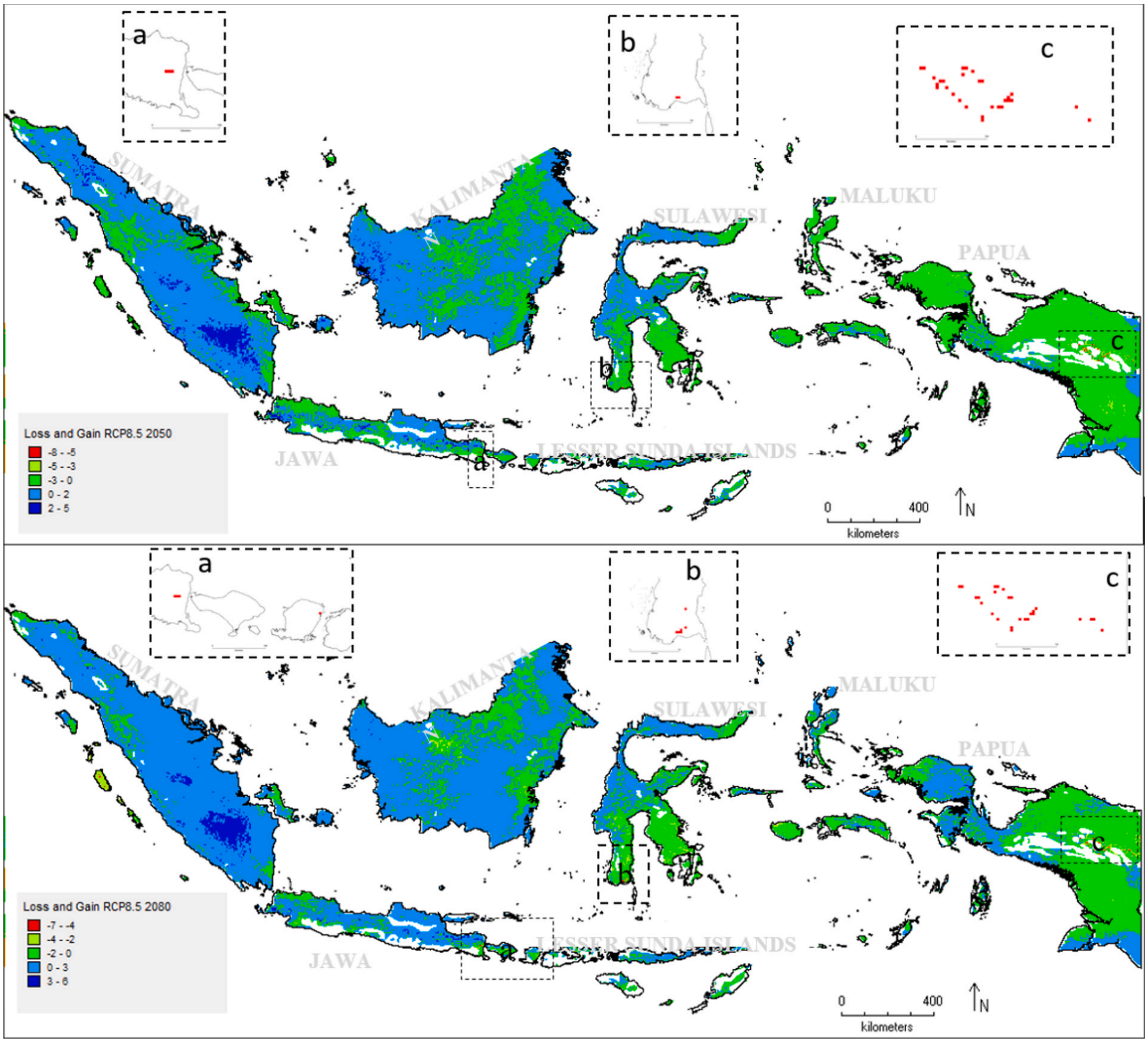

Fig. 5. The predicted loss and gain of 43 medicinal plants in Indonesia distribution under the RCP8.5 scenario year of 2050 (above) and 2080 (below) with a grid cell resolution of five minutes (approximately equal to 10 × 10 km^2) used, with insert map where highest loss predicted.

Table 3
Overall descriptive value of loss and gain of medicinal plant's distribution area in Indonesia per future scenario.

Observation	RCP4.5 2050	RCP4.5 2080	RCP8.5 2050	RCP8.5 2080
Average	- 0.30	- 4.05	- 0.40	- 4.63
±stdev	1.35	40.74	1.78	31.79
Min. value	- 4.07	- 68.27	- 5.09	- 54.38
Max. value	2.64	131.13	4.18	97.34

Table 4
Overall descriptive value of turnover rate per future scenario.

Observation	RCP4.5 2050	RCP4.5 2080	RCP8.5 2050	RCP8.5 2080
Average	- 4.63	- 0.32	- 10.03	- 0.60
±stdev	31.79	1.41	43.22	1.90
Min. value	- 54.38	- 3.90	- 71.32	- 5.33
Max. value	97.34	3.14	138.41	4.41

Table 5
Observation on all studied medicinal plant species impacted by climate changes per future scenario.

Observation	RCP4.5 2050	RCP4.5 2080	RCP8.5 2050	RCP8.5 2080
Species gaining distribution area	17	18	18	17
Species losing distribution area	26	25	25	26
IUCN Redlist	7	13	12	14
Not IUCN Redlist	19	12	13	12

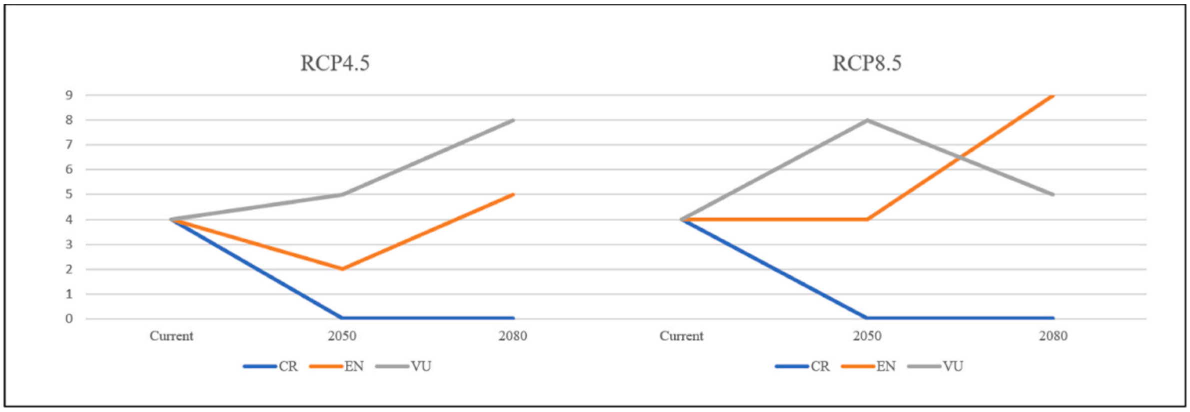

Fig. 6. The predicted number of threatened medicinal plants in Indonesia per future scenario, as determined by the IUCN category A3(c).

Table 6
List of target species for highest conservation due to predicted climate changes impact.

No.	Species	Gen. Length (year) (IUCN, 2021)	RCP4.5 2050	RCP4.5 2080	RCP8.5 2050	RCP8.5 2080
1	*Agathis borneensis*[d] (EN)	70	VU		VU	EN
2	*Alstonia iwahigensis*[abcd]	NA	EN		EN	EN
3	*Anaxagorea javanica*	NA	VU		VU.	VU.
4	*Anisoptera costata*[abcd] (EN)	100	VU		EN	EN
5	*Aquilaria malaccensis* (CR)	50–100			VU	VU
6	*Barleria prionitis*[abc]	75				
7	*Castanopsis argentea* (EN)	NA				VU
8	*Dicksonia blumei*[abcd]	100		EN		
9	*Dipterocarpus baudii* (VU)	NA			VU	EN
10	*Euchresta horsfieldii*[abcd]	NA		EN	VU	EN
11	*Eurycoma longifolia*	NA	VU		EN	EN
12	*Eusideroxylon zwageri* (VU)	NA	EN		EN	EN
13	*Gentiana quadrifaria*[abcd]	50		VU		
14	*Macaranga griffithiana* (VU)	NA				VU
15	*Nepenthes reinwardtiana*	NA	VU		VU	EN
16	*Pinus merkusii*[abcd]	NA		VU	VU	EN
17	*Rauvolfia serpentina*[abcd]	50				
18	*Santalum album*[abcd] (VU)	NA		EN		
19	*Scutellaria javanica*[abcd]	NA		EN		
20	*Shorea seminis* (CR)	NA				VU

Notes: Species in grey column are included in 10 smallest distribution area as recommended by Jarvis et al. (2008); a, b, c, and d refers to species included in 10 species with the smallest size in the future scenario of RCP4.5 2050, RCP4.5 2080, RCP8.5 2050, and RCP8.5 2080 respectively.

Table 7
Overall descriptive value of target species' distribution area for highest conservation.

Observation	Current	RCP4.5 2050	RCP4.5 2080	RCP8.5 2050	RCP8.5 2080
Average	15,693.4	10,415.65	8831.75	10,047.8	7831
±stdev	9835.55	5599.05	4724.41	5602.87	4343.80
Min. value	2110	1858	1629	1562	1163
Max. value	31,140	19,738	18,732	19,914	17,256

(SD*100), and rainfall during the driest month (mm).

The medicinal plant distribution areas in Indonesia with the biggest loss and the areas with largest gain in species are recommended for *ex situ* conservation and *in situ* conservation planning respectively. Moreover, twenty species of Indonesian medicinal plants are predicted to be listed as the most threatened in the future according to the IUCN Redlist criteria, but the generation length would need to be better understood to determine the appropriate conservation plans for these species to ensure long-term preservation and sustainable use. We recommend that conservation planning starts with species that are predicted to become critically endangered in the future and within those areas with the highest loss of species, which are found on East Java, South Sulawesi and Papua. This will guarantee their existence for utility and other research, such as ethnobotany, identification of medicinal plant compounds and clinical experiments with medicinal plants in Indonesia, and at regional and global levels.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gecco.2021.e01752.

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