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Potential of agrivoltaics in ASEAN considering a scenario where agroforestry expansion is also pursued

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ABSTRACT

Integration of solar photovoltaics on croplands ("agrivoltaics") has been promoted as an environmentally-friendly approach for solar energy deployment. Past studies, however, have not considered that these croplands could alternatively be used as sites for expanding agroforestry, a practice which provides important ecosystem services to the neighbouring environment. We assessed the potential of agrivoltaics on herbaceous croplands in ASEAN, considering potential trade-offs with agroforestry. We assumed that croplands located in environmentally sensitive areas (ESAs) – including protected areas, key biodiversity areas, forests, wetlands/inland water bodies, their buffer zones, and areas with steep slopes – were better suited for agroforestry than agrivoltaics. We found that even if agrivoltaics are prohibited on all croplands located in ESAs, using just 10 % of the remaining land for agrivoltaics can still allow it to provide most of ASEAN's electricity generation needs. Thus, large-scale expansion of agrivoltaics need not conflict with regional efforts to enhance biodiversity/ecosystem services through agroforestry.

1. Introduction

Solar photovoltaics (PV) has become one of the most promising renewable energy technologies due to its increasing economic attractiveness, and recent projections show that it may generate more than half of the world's electricity by 2050 (Nijsse et al., 2023). Deploying solar PV at such a scale would require a large amount of land, however, causing concerns that solar PV expansion might result in significant loss of natural/semi-natural ecosystems if unabated land-use conversion occurs (Hernandez et al., 2015; Zhang et al., 2023). As an alternative to converting land from other uses to build monofunctional solar power plants, another option is to integrate solar PV into the existing land uses. In particular, integrating solar PV panels in agricultural areas (i.e., "agrivoltaics" (Dupraz et al., 2011)) can potentially provide a large share of global energy demand due to the massive extent of croplands globally and their typically high solar irradiation (Adeh et al., 2019). Agrivoltaics typically involves mounting solar panels above or between rows of crops or pasture (Fig. 1), and recent estimates indicate that converting less than 1 % of croplands worldwide to agrivoltaics could theoretically offset the entire global energy demand (Adeh et al., 2019).

1.1. Overview of benefits and trade-offs of agrivoltaics

Previous studies have identified many potential benefits of agrivoltaics, with an obvious one being the ability to increase land use efficiency by allowing for crop cultivation and electricity generation within the same land area (Dupraz et al., 2011). Agrivoltaics can also help to diversify and increase farmers' incomes (Chae et al., 2022; Wagner et al., 2024) and reduce water consumption (Widmer et al., 2024). Because shading beneath solar panels can affect crop growth, however, much research has focused on analysing the relationships between crop yields and agrivoltaics design to optimize the selection of crops and the layout of solar panels (e.g., their height, ground cover ratio, and solar tracking capabilities) (Ali Khan Niazi and Victoria, 2023; Toledo and Scognamiglio, 2021; Yeligeti et al., 2023). These past studies found that shade-loving crops (e.g., berries and lettuces) may have even higher yields when partially shaded by solar panels, as compared to open field conditions (Laub et al., 2022; Marrou et al., 2013; Yeligeti

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et al., 2023). Many shade-tolerant crops have also been found to be promising for agrivoltaics, experiencing only minor reductions in yield when under moderate shading from solar panels (Laub et al., 2022; Widmer et al., 2024).

Not all types of crops or agricultural areas, however, are well-suited for agrivoltaics. For example, shade-intolerant crops like maize are typically unsuitable because they require abundant sunlight (Laub et al., 2022). Agricultural lands located far from electricity transmission infrastructure or areas of high electricity demand (e.g., urban areas or other large settlements) are also often unprofitable for large-scale agrivoltaics due to high costs of connecting to the grid and transmitting the generated electricity long distances, respectively (Silva Herran and Ashina, 2023). That said, smaller-scale (e.g., off-grid or micro-grid) deployment of agrivoltaics in these areas have the potential to increase rural electrification rates, which remain low in some developing countries (Gonocruz et al., 2023). Non-economic barriers also exist, including community concerns that agrivoltaics disrupt the local landscape aesthetics (Maity et al., 2023), and farmers' concerns over the (sometimes complex) regulatory processes required to add solar panels to their croplands (Wagner et al., 2024).

1.2. Agroforestry and its potential competition with agrivoltaics

Analyses of the benefits and trade-offs of agrivoltaics have typically been based on comparisons between agrivoltaic systems and open cropping systems (in which there is no shading of crops). Often, however, areas suitable for agrivoltaics may also be suitable for other multifunctional agriculture practices. Multifunctional agriculture activities are defined as those which serve additional purposes beyond food and fibre provisioning, by, e.g., contributing to biodiversity conservation, natural resource management, and/or the socioeconomic prosperity of rural areas (Renting et al., 2009). Agroforestry is a common type of multifunctional agriculture, typically characterized by the integration of trees (and other woody permanent or perennial plants) in croplands. Importantly, because solar panels and trees (or other overstory woody vegetation) on cropland both cause shading of the vegetation below, agrivoltaics and agroforestry may compete with one another for suitable croplands, i.e., those where shade-loving/shade-tolerant crops grow well. Considering this, it is important that studies on agrivoltaics consider their benefits and trade-offs relative to agroforestry, rather than open cropping systems alone.

Agroforestry systems can be designed in various ways depending on the local context. For example, hedgerow agroforestry systems involve planting trees/shrubs along contours in sloping terrain (with crops grown between the hedgerows) to minimize soil erosion (Fig. A1(a)). Parkland agroforestry systems involve a more regular intermixing of trees/shrubs and crops, and can help maintain soil quality and favourable microclimate conditions throughout a farm (Fahmi et al., 2018) (Fig. A1(b)). Windbreak agroforestry systems involve planting trees/shrubs in rows alongside crops to reduce wind damage, while riparian buffer agroforestry systems involve planting trees/shrubs intermixed with crops along water bodies to, e.g., reduce bank erosion (Fig. A1(c)) (Nerlich et al., 2013; Prastiyo et al., 2020). Various other types of agroforestry systems exist, and have been highlighted in different reviews (Kuyah et al., 2019; Nerlich et al., 2013; Rodenburg et al., 2022).

Environmentally-friendly agroforestry practices like planting native trees/shrubs on croplands can provide numerous benefits to the local environment. Similarly to agrivoltaics, environmentally-friendly agroforestry (hereafter simply "agroforestry") can contribute to climate change mitigation, as the planted trees/shrubs can capture and store atmospheric CO_2 (Getnet et al., 2023; Terasaki Hart et al., 2023). Another important benefit of agroforestry is its ability to reduce soil erosion on farmlands with sloping terrain; Growing trees/shrubs along contours can lead to the natural formation of terraces over time (Do et al., 2023; Hoang et al., 2017; Pattanayak and Evan Mercer, 1998; Pellek, 1992). Agroforestry can also contribute to local biodiversity conservation by, e.g., providing an alternative wood supply that reduces harvesting from nearby forests (Tsegaye, 2023), and providing cover for wildlife to safely move between habitats (Smith et al., 2013). When practiced nearby inland water bodies, agroforestry can help protect the water bodies and their shoreline areas by, e.g., reducing bank erosion, surface runoff, and water pollution (by trapping sediments and pollutants), and providing shade to help regulate water temperatures (Graziano et al., 2022; Smith et al., 2013). Not all agroforestry practices are environmentally friendly, e.g., those that involve planting invasive alien species or clear-cutting existing forests (Ollinaho and Kröger, 2021). Environmentally-harmful agroforestry practices, however, are not the focus of our study, and we do not advocate them as a desirable alternative to agrivoltaics.

Notably, agroforestry will need to be expanded to help meet new global goals related to enhancing biodiversity and ecosystem services, especially in areas which lack natural forests (Mulyoutami et al., 2023). For example, in 2022, the parties to the Convention on Biological Diversity (CBD) agreed upon the "Kunming-Montreal Global Biodiversity Framework", which includes a series of goals for the 2030–2050 period. Because of its ability to provide ecosystem services, agroforestry is relevant for several of the Framework's goals, e.g., Goal B: "*Biodiversity is sustainably used and managed and nature's contributions to people, including ecosystem functions and services, are valued, maintained and enhanced, with those currently in decline being restored… by 2050*" (CBD, 2022). Efforts to enhance ecosystem services can be particularly effective when implemented in environmentally sensitive areas (ESAs), i.e., areas important for the long-term maintenance of biodiversity, soil,

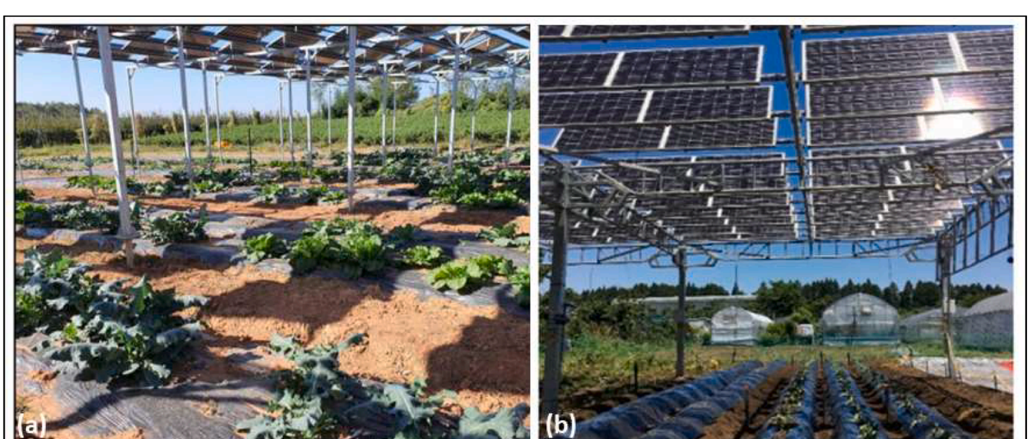

Fig. 1. Tilted solar panels installed on platforms above crops. Photos from Chae et al. (2022) (a) and Yajima et al. (2023) (b).

water, and other natural resources at the site and regional level (Jennings and Reganold, 1991). Thus, it may be sensible to promote the future expansion of agroforestry in ESAs. Examples of ESAs include forests, wetlands, water bodies, other wildlife habitats, and the buffer zones surrounding these areas (which may contain croplands) (Ndubisi et al., 1995).

1.3. Objective and related research

Our objective in this study was to analyse the potential of agrivoltaics, while also considering the simultaneous goal of expanding agroforestry in ESAs. As the study area, we selected the 10 member countries of the Association of Southeast Asian Nations (ASEAN): Brunei Darussalam, Cambodia, Indonesia, Laos, Malaysia, Myanmar, the Philippines, Singapore, Thailand, and Vietnam. ASEAN has a high energy demand, a high potential for solar PV (Siala and Stich, 2016), and a large extent of natural ecosystems and croplands, so there is a need for research to support the environmentally-friendly deployment of agrivoltaics in the region.

A few prior studies have analysed the potential of solar PV in general, or of agrivoltaics in particular, in ASEAN countries. Siala and Stitch (2016) estimated the total amount of land available for solar PV in ASEAN considering all types of land use/land cover. Their study, however, only considered protected areas and wetlands as constraints related to ESAs, and did not consider the need for buffer zones around these ESAs to help protect them. Vidinopoulos et al., (2020) estimated the potential of agrivoltaics in ASEAN, assuming all agricultural land was potentially available for agrivoltaics (i.e., without excluding land located in ESAs). Gonocruz et al., (2022) conducted a more focused study on the potential of agrivoltaics on rice farms in the Philippines, and also assumed that all rice fields were potentially available for agrivoltaics. These past studies are valuable in that they show the maximum potential of agrivoltaics in ASEAN countries. Our study, on the other hand, intends to provide a more conservative estimate of the potential of agrivoltaics, considering the simultaneous need for enhancing biodiversity/ecosystem services through agroforestry expansion.

This research can be considered as a policy-screening scenario analysis (IPBES, 2016) that considers two policy scenarios: One in which any existing herbaceous cropland can potentially be used for agrivoltaics, and another in which croplands in ESAs are prohibited from being used for agrivoltaics. In the 2nd scenario, we assume that croplands in ESAs could instead be set aside as potential sites for agroforestry. The following types of ESAs were considered for this analysis:

i. Internationally recognized sites of high importance for biodiversity conservation, including protected areas (UNEP-WCMC and IUCN, 2023), key biodiversity areas (BirdLife International, 2023; IUCN, 2016), and Ramsar wetland sites;
ii. Wetlands and permanent water bodies of 1 ha or larger in area;
iii. Forests, defined as defined by FAO (FAO, 2010);
iv. Areas with slopes of greater than 15°, i.e., “steep” or “very steep” slopes (FAO, 2006)
v. Buffer zones surrounding areas (i-iii).

The rationale for this analysis is that agrivoltaics, once installed, may be cost-prohibitive to remove during the operational lifetime of the solar panels (~25 years). This “lock-in” period of agrivoltaics should be considered in the renewable energy planning phase, to avoid deploying agrivoltaics on land that may soon be needed for other purposes like expanding agroforestry.

2. Methods and materials

2.1. Study area

The 10 ASEAN member countries cover most of Southeast Asia, a region known as a biodiversity hotspot as well as a hotspot for biodiversity *loss* (due to its high rate of deforestation and forest degradation) (Morand et al., 2017). It is also a region with rapidly increasing energy demand. For example, ASEAN’s electricity consumption is expected to triple from 2020 to 2050 under a baseline scenario, to 3388 TWh/year (ASEAN Centre for Energy, 2022). Thus, there is a high demand for expanding renewable energy supplies, including solar PV.

Southeast Asia is also the worlds’ primary home of agroforests, containing 29 % of all global agricultural land with tree cover of at least 30 % (Van Noordwijk et al., 2020). One reason for this is that the region’s soil and climate are highly conducive to growing trees. As shown in the “tree carrying capacity” map in Fig. A2, nearly all of the land in ASEAN is suitable for tree cover of at least 10 %, and most is suitable for tree cover of at least 30 % (Bastin et al., 2019). Thus, for the purpose of this study we assumed that agroforestry can potentially be implemented on any herbaceous cropland (areas with extremely steep slopes or poor soil may be unsuitable for agrivoltaics, but they are also unsuitable for growing crops).

2.2. Datasets used

We utilized several freely-available geospatial datasets with global coverage for this research (Table A1), with the aim of developing a methodology that would be feasible and inexpensive to apply in other countries/regions. Two main types of data were used: (1) a high-resolution map of herbaceous croplands, and (2) high-resolution maps of different types of ESAs.

For the cropland extent map, we used the 30 m resolution global map produced by Potapov et al., (2021) for the year 2019. Cropland in this dataset includes land used for growing annual/perennial herbaceous crops for human consumption, forage (including hay), and biofuel. On the other hand, land used for perennial woody crops, permanent pastures, and shifting cultivation are excluded from this dataset (Potapov et al., 2021). Accordingly, we used this dataset to extract all areas containing herbaceous cropland in ASEAN. Although other global maps of agricultural areas exist, this particular dataset was selected for its high spatial resolution, high thematic accuracy (~85 % user’s and producer’s accuracies in Southeast Asia (Potapov et al., 2021)), and because it excludes areas containing perennial woody crops (where agroforestry may already be practiced). Permanent pastures are also potentially suitable for agrivoltaics/agroforestry, but they are not considered in this study because high-resolution and up-to-date maps of permanent pastures do not yet exist at the global (or ASEAN) scale. The remaining datasets, all described in Table A1, were used to identify ESAs in ASEAN countries, and had similarly high spatial resolutions (~30 m or finer) to the global cropland map.

2.3. Methods

2.3.1. Data preprocessing

First, all datasets in Table A1 were downloaded and projected to the “Asia South Albers Equal Area Conic” coordinate system to permit accurate area calculations. Further pre-processing was performed for several of the datasets. We extracted all wetlands of at least 1 ha in size from the global wetland map (smaller areas were excluded because they were typically not natural wetlands/water bodies). We generated a slope map from the ALOS World 3D digital elevation model (Takaku et al., 2020), and extracted all pixels having a slope of >15° From the OpenStreetMap "waterways" dataset, we extracted all rivers and streams. The global wetlands map also contained rivers and streams (mapped as "permanent water" (N. X. Zhang et al., 2023)), but we supplemented it with the OpenStreetMap data because many narrow rivers/streams (e.g., those with widths of less than ~30 m) were found to be missing. From the PALSAR-2 Forest/Non-Forest map, we merged the two "forest" classes (one with 10–90 % crown cover, and one with >90 % crown cover (JAXA, 2022)) into one because the result matches the FAO's definition of "forest" (≥10 % crown cover) (FAO, 2010). Several other global forest maps exist, but we used the PALSAR-2 map because it is the most consistent with FAO's definition of "forest" (Johnson et al., 2023). Finally, from all of the global datasets, we extracted the data for each ASEAN country using the national boundaries from the global administrative areas dataset.

2.3.2. Calculating the geographic potential of agrivoltaics

Next, we calculated the *geographical potential* of agrivoltaics, i.e., the total amount of herbaceous cropland available after accounting for geographic constraints (McKenna et al., 2022). The geographic constraints considered were the ESAs identified in Section 2.3.1. and their buffer zones. The workflow for calculating the geographic potential is shown in Fig. 2.

Buffer zones surrounding each ESA were generated using QGIS software, version 3.28.2. Areas considered to be internationally-recognized sites of importance for biodiversity conservation, including protected areas, key biodiversity areas, and Ramsar wetland sites (Table A1), were assigned a buffer zone of 1 km, assuming that croplands within these buffer zones could alternatively be used for agroforestry to allow for enhanced the biodiversity and ecosystem services of these sites. Keeping a large buffer around these important sites is also helpful to allow for the potential expansion of the biodiversity sites in the future (Sweeney and Newbold, 2014). This is an important consideration given that one of the Kunming-Montreal Global Biodiversity Framework's goals is to expand the extent of protected areas (and other effective area-based conservation measures (OECMs)) to at least 30 % of all terrestrial, inland water, coastal and marine areas by 2030 (CBD, 2022). In comparison, the current global extent of protected areas and OECMs is only 17.22 % (https://www.protectedplanet.net/en, last accessed December 15, 2023), with croplands occupying approximately 6 % of protected areas (Vijay and Armsworth, 2021).

All other ESAs in Table A1, including wetlands, rivers/streams, and forests, were assigned a smaller buffer zone of 100 m. This buffer distance was selected considering that, for wetlands/rivers/streams, buffer zones of 100 m or smaller can effectively remove many pollutants in surface runoff as well as provide organic materials from trees to these areas and regulate water temperatures (Graziano et al., 2022; Sweeney and Newbold, 2014). After generating the maps of the ESAs, including their respective buffer zones, we overlaid them on the 30 m resolution cropland map. All overlapping cropland areas were identified, allowing us to calculate the how much cropland was potentially available for agrivoltaics after excluding the ESAs.

2.3.3. Calculating the technical potential of agrivoltaics

Next, we calculated *technical potential* of agrivoltaics, defined as the amount of power that can be generated considering a particular type of agrivoltaic technology (e.g., the solar panel specifications and solar tracking capabilities) and layout (e.g., panel spacing) within the geographical potential (McKenna et al., 2022). The technical potential of agrivoltaics by country, in TWh/year, was calculated by:

$$\text{Technical potential} = \text{geographic potential x electricity yield per ha} \quad (1)$$

$$\text{Electricity yield per ha} = \text{installed capacity per ha x capacity factor x 8760} \quad (2)$$

Where 8760 is the number of hours in a year. For estimating the installed capacity, we assumed the same agrivoltaics system and layout as Schindele et al., (2020), i.e., SolarWorld SW270 duo bifacial PV modules aligned in rows, with the module row spacing being 27 % greater than that of a conventional solar PV power plant (to allow for sufficient photosynthetically active radiation for crops below the solar panels), and no solar tracking capability. Based on these specifications, the installed capacity is 519.18 kWp/ha (Schindele et al., 2020). For the capacity factor, i.e., the actual power output compared with the maximum theoretical output of 8760 h of full sunshine/year, we used the average values for "cropland/natural vegetation" areas calculated by Siala and Stich (2016) (Table 1). Eq. (1) gives the total annual electricity generation for each country, assuming all croplands within the geographic potential are used for agrivoltaics. As already mentioned, however, agrivoltaics is only profitable for some croplands. Thus, as was done in other previous studies (Adeh et al., 2019; Jamil et al., 2023; Yeligeti et al., 2023), we calculated the technical potential assuming only a small percentage (1–10 %) of the geographic potential will actually be used for agrivoltaics.

3. Results and discussion

3.1. Geographic potential of agrivoltaics on herbaceous croplands

After excluding ESAs, the geographic potential of agrivoltaics on herbaceous croplands in ASEAN was 369,841 km^2, which represents 68 % of the initial cropland extent (541,998 km^2). The remaining 32 % (172,157 km^2) of herbaceous croplands, on the other hand, were deemed as potential sites for agroforestry expansion due to their location within ESAs. There was significant variation in the degree to which excluding ESAs reduced the geographic potential of agrivoltaics in each country (Table 1). For example, the geographic potential in Malaysia, Indonesia, and Vietnam was reduced by only 20–30 %, while at the other extreme, in Brunei and Singapore it was reduced by 89 % and 63 %, respectively. This was due to variations in the extent of ESAs, as well as their spatial configuration relative to croplands, in each country.

In terms of the total amount of land available for agrivoltaics,

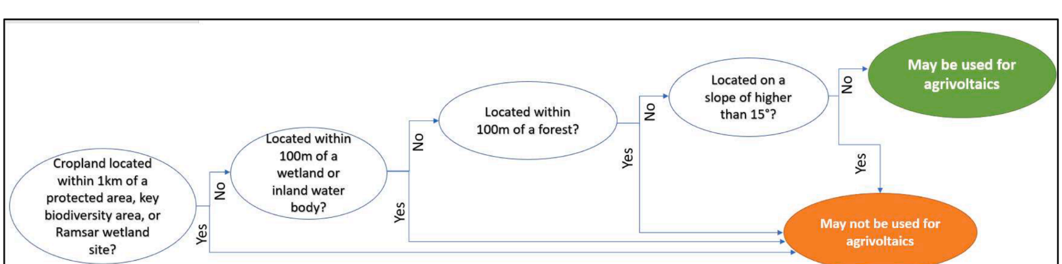

Fig. 2. Workflow for calculating geographic potential of agrivoltaics under a scenario where they are prohibited in environmentally sensitive areas.

Table 1
Average capacity factor of "cropland/natural vegetation" land in each ASEAN country, from Siala and Stich (2016), and geographic potential of agrivoltaics in each country after sequentially excluding each type of environmentally sensitive area.

Country	Average capacity factor (%)	Initial extent of herbacious cropland (km^2)	Cropland farther than 1 km from internationally-recognised biodiversity sites (km^2)	…And, farther than 100 m from wetlands, rivers, or streams (km^2)	…And, farther than 100 m from forests (km^2)	…And 15° or lower slope
Brunei	14.6	3	1	1	1	0.36
Cambodia	14.5	59,699	47,568	43,121	38,157	38,157
Indonesia	14.9	87,674	82,459	76,295	71,929	69,326
Laos	14.6	13,602	11,229	10,598	7582	7582
Malaysia	14.3	3075	2958	2772	2253	2253
Myanmar	14.3	117,392	106,986	100,264	88,314	88,101
Philippines	14.3	36,679	32,016	27,941	18,031	17,879
Singapore	13.8	5	4	3	2	2
Thailand	14.5	173,777	158,224	153,142	111,151	111,077
Vietnam	14.1	50,093	44,605	42,054	35,748	35,463
Total		**541,998**	**486,049**	**456,190**	**373,163**	**369,841**

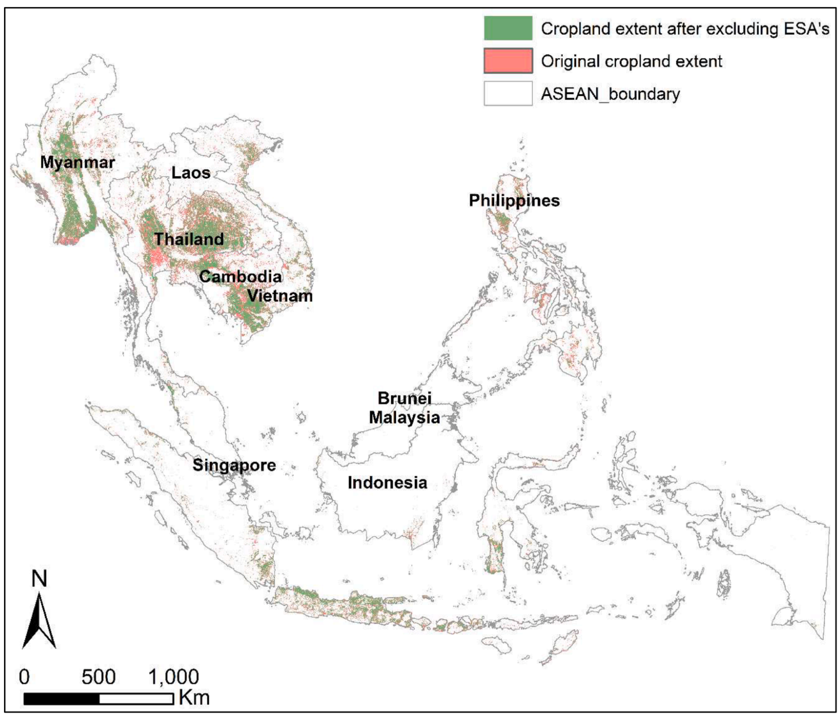

Fig. 3. Map of herbaceous croplands in ASEAN after excluding those located in environmentally sensitive areas (ESAs). This represents the geographic potential of agrivoltaics in ASEAN. The initial cropland extent is shown for comparison (extracted from Potapov et al. (2021)).

Thailand (111,077 km^2), Myanmar (88,101 km^2), and Indonesia (69,326 km^2) had the most, together accounting for 73 % of the entire geographic potential of ASEAN. In contrast, Brunei and Singapore had very little land available for agrivoltaics (0.36 km^2 and 2 km^2, respectively), due to both the relatively large extent of ESAs and small initial cropland extent in these countries. The final map of the geographic potential of agrivoltaics in ASEAN countries is shown in Fig. 3, and the data is available for download in shapefile (.shp) format at https://www.iges.or.jp/en/pub/maps-agrivoltaics/en.

Interestingly, as each additional type of ESA was added as a new constraint, the change in the amount of available land for agrivoltaics became smaller. For example, the final ESA included as a geographic constraint in our study, areas with slopes >15°, had little-to-no impact on the amount of land available for agrivoltaics in Cambodia/Laos/Malaysia/Myanmar/Vietnam, despite the fact that many croplands in these countries were located in areas having slopes >15° This was because many croplands were located within multiple overlapping ESAs, e.g., within the buffer zone of a forest area and on land with a slope of >15° These results suggest that, because many different types of ESAs overlap, including even more types of ESAs as constraints for agrivoltaics may have a relatively limited impact on the estimated geographic potential. Considering these results, it may also be desirable to prioritize agroforestry in areas where multiple ESAs overlap (to maximise the benefits agroforestry provides to these important environments), and this could be an interesting topic for future agroforestry studies.

Land-use change is prevalent in many ASEAN countries, especially urban expansion (Johnson et al., 2021; Potapov et al., 2022), and these changes could affect the geographic potential of agrivoltaics in different ways. For example, expansion of protected areas, forests, and/or wetlands in the future would lead to a further increase in the extent of ESAs in ASEAN, which would reduce the amount of cropland available for agrivoltaics (assuming our methodology is followed). Conversion of croplands to built-up/urban or other land uses would also reduce the land available for agrivoltaics. On the other hand, loss of forest areas or wetlands could potentially lead to an increase in the amount of available cropland for agrivoltaics by, e.g., reducing the extent of ESAs and/or increasing the total cropland extent (if forest areas or wetlands are

Table 2
Technical potential of agrivoltaics on herbaceous croplands in each ASEAN country, after sequentially excluding each type of environmentally sensitive area. This estimate assumes 1 % [or 10 %] of the geographic potential of cropland (See Table 1) will actually be utilised for agrivoltaics.

Country	Annual electricity generation using 1 % [or 10 %] of initial extent of herbacious cropland (TWh)	Limited to cropland farther than 1 km from "designated" biodiversity sites (TWh)	…And farther than 100 m from wetlands, rivers, and streams (TWh)	…And farther than 100 m from forests (TWh)	…And 15° or lower slope (TWh)
Brunei	0.00 [0.00]	0.00 [0.00]	0.00 [0.00]	0.00 [0.00]	0.00 [0.00]
Cambodia	39.37 [393.70]	31.37 [313.69]	28.44 [284.37]	25.16 [251.63]	25.16 [251.63]
Indonesia	59.41 [594.13]	55.88 [558.79]	51.70 [517.02]	48.74 [487.43]	46.98 [469.79]
Laos	9.03 [90.32]	7.46 [74.56]	7.04 [70.37]	5.03 [50.35]	5.03 [50.35]
Malaysia	2.00 [20.00]	1.92 [19.24]	1.80 [18.03]	1.47 [14.66]	1.47 [14.66]
Myanmar	76.35 [763.48]	69.58 [695.80]	65.21 [652.08]	57.44 [574.36]	57.30 [572.98]
Philippines	23.85 [238.55]	20.82 [208.22]	18.17 [181.72]	11.73 [117.27]	11.63 [116.28]
Singapore	0.00 [0.03]	0.00 [0.02]	0.00 [0.02]	0.00 [0.01]	0.00 [0.01]
Thailand	114.60 [1145.9]	104.34 [1043.43]	100.99 [1009.91]	73.30 [733.00]	73.25 [732.51]
Vietnam	32.12 [321.23]	28.60 [286.04]	26.97 [269.68]	22.92 [229.24]	22.74 [227.42]
Total	**356.74 [3567.44]**	**319.98 [3199.80]**	**300.32 [3003.20]**	**245.79 [2457.94]**	**243.56 [2435.62]**

converted to croplands). Future research may focus on how projected land-use/land-cover changes could affect the geographic potential of agrivoltaics.

3.2. Technical potential of agrivoltaics on herbaceous croplands

Based on an assumption that 1–10 % of the geographic potential is actually used for agrivoltaics, the technical potential of agrivoltaics on herbaceous croplands in ASEAN is estimated to be 243.56–2435.62 TWh/year (Table 2). In comparison, official projections of ASEAN's electricity generation for the year 2050, as described in ASEAN Centre for Energy (2022), range from 2108 to 3388 TWh/year. The "ASEAN Plan of Action for Energy Cooperation (APAEC) Regional Targets Scenario", which projects 2108 TWh/year electricity generation in 2050, is the most stringent scenario that has been officially announced by ASEAN, and assumes that various regional policies will be put in place to enhance energy efficiency. Our results indicate that agrivoltaics can theoretically supply 12–116 % of the total electricity generated under this scenario (Table 3). This, of course, assumes an ideal situation where countries' power grids are fully interconnected, and power can be stored and flexibly used when it is needed.

Table 3
Comparison of electricity generation potential of agrivoltaics with projections of electricity consumption under the APAEC target scenario (ASEAN Centre for Energy, 2022). The ASEAN centre for energy kindly provided us with projections for each country, as only regional-level projections were listed in their original report (ASEAN Centre for Energy, 2022).

Country	2020 (TWh)	2050, Baseline scenario (TWh)	2050, APAEC Regional Targets Scenario (APS) (TWh)	Agrivoltaics potential relative to APAEC Regional Target Scenario, if 1 % [or 10 %] of the geographic potential is used
Brunei	4.73	7.78	8.99	0 % [0 %]
Cambodia	11.09	30.95	17.34	145 % [1451 %]
Indonesia	275.58	960.79	642.27	7 % [73 %]
Laos	7.78	44.95	48.21	10 % [104 %]
Malaysia	152.13	485.97	220.88	1 % [7 %]
Myanmar	20.29	42.04	32.91	174 % [1741 %]
Philippines	83.24	359.46	231.65	5 % [50 %]
Singapore	50.78	90.31	67.76	0 % [0 %]
Thailand	187.26	461.44	355.11	21 % [206 %]
Vietnam	218.02	904.27	483.16	5 % [47 %]
Total	1010.91	3388.00	2108.00	12 % [116 %]

Cambodia and Myanmar can theoretically achieve all of their electricity generation needs (also based on the APAEC Regional Targets Scenario) if less than 1 % of its geographic potential is used for agrivoltaics, while Lao PDR and Thailand can also be self-sufficient if less than 10 % of their geographic potential is used (and Vietnam can satisfy 99 % of its projected electricity generation). Notably, Cambodia, Myanmar, and Thailand can all generate more than 10 times their projected electricity generation if 10 % of their geographic potential is used, indicating that they could also potentially serve as energy exporters to help neighbouring countries like Brunei, Singapore, and Malaysia meet their demand. Along these lines, cross-border transmission systems and energy trading schemes are being developed/enhanced through the ASEAN Power Grid (Aris and Jørgensen, 2020; International Renewable Energy Agency and ASEAN Centre for Energy, 2022).

Due to the variable nature of solar PV power, ASEAN countries also utilize power generated from other renewable sources like wind and hydropower, and several projections of ASEAN's future renewable energy mix exist. For further context, we also compare our results with different projections of ASEAN's total solar PV power generation in 2050. Table 4 shows the 2050 renewable energy share and solar PV power generation estimated under 11 different scenarios developed by the ASEAN Centre for Energy, the International Renewable Energy Agency, and Handayani et al. (2022). According to these scenarios, ASEAN's 2050 projected solar PV power generation varies widely, from less than 130 TWh/year to nearly 3000 TWh/year. Our estimates indicate that using 10 % of the geographic

Table 4
Different projections of solar PV power generation in 2050, compared with the technical potential of agrivoltaics estimated in this study.

Source	Scenario	Total power generation in 2050 (TWh)	Renewables share in 2050 (%)	Solar PV power generation in 2050 (TWh)	Agrivoltaics potential[b]/total solar PV power generation (%)
ASEAN Centre for Energy (2022)	Baseline	3388	35.0	131.6	1868.7 %
	ASEAN member states national targets	2566	49.3	129.9	1893.2 %
	APAEC regional targets	2108	63.2	159.3	1543.8 %
	Least-cost optimisation	2114	57.6	NA	NA
IRENA and ACE (2022)	Planned energy	3797	77.0	1374.8[c]	178.9 %
	Transforming energy	4697	86.0	2121.7[c]	115.9 %
	1.5-S RE90[a]	5128	88.0	2585.3[c]	95.1 %
	1.5-S RE100[a]	5128	99.0	2945.8[c]	83.5 %
Handayani et al. (2022)	Reference	3715	38.0	185.8	1323.6 %
	Renewable energy	3715	50.0	442.1	556.3 %
	Net zero emissions	3715	93.0	2266.2	108.5 %

[a] 1.5 °C scenarios aiming to reach net-zero emissions globally by 2050, one with 90 % renewable power generation (1.5-S RE90) and one with 100 % renewable power generation (1.5-S RE100) (International Renewable Energy Agency and ASEAN Centre for Energy, 2022).
[b] Assuming 10 % of the geographic potential is used for agrivoltaics.
[c] Calculated based on the installed capacity of solar PV, assuming an average capacity factor of 14 %.

potential of agrivoltaics on herbaceous croplands can theoretically allow for ASEAN to meet/exceed the projected solar PV power generation in all but two scenarios, “1.5-S RE90” and “1.5S RE100” (Handayani et al., 2022), which assume 90 % and 100 % renewable energy generation, respectively. This gives further evidence that the technical potential for agrivoltaics on herbaceous croplands is large, and importantly, that it does not to conflict with the goal of conserving/enhancing biodiversity and ecosystem services in the region. Future research could consider if/how ASEAN can meet even these most ambitious scenarios by supplementing agrivoltaics with other solar PV technologies that can also be integrated with the existing land uses, e.g., rooftop solar or floating solar PV (Almeida et al., 2022; Yeligeti et al., 2023). For this to be realized, however, batteries and other means of storing the generated solar power would also need to be significantly scaled up.

3.3. Sources of uncertainty

The main sources of uncertainty in our study relate to errors in the geospatial datasets used to estimate the geographic potential of agrivoltaics, and uncertainties in the agrivoltaics technologies used. An accuracy assessment of the herbaceous croplands map used in this study indicated that it had an overall accuracy of 96.6 % for the “South-east Asia” region, and underestimated the actual extent of herbaceous cropland by 3.6 % (Potapov et al., 2021). If we assume a similar accuracy for only the croplands located outside of ESAs, our estimates of the geographic and technical potential of agrivoltaics may also be slightly underestimated. The maps of wetlands and forest areas we used to identify ESAs have reported overall accuracies of 86.4 % (Zhang et al., 2023) and 90.4 % (JAXA, 2022), respectively, while the elevation data used to identify areas with steep slopes had a root mean square error of 3.27 m in height (Takaku et al., 2020). The remaining maps used to identify ESAs were generated by manually digitising polygons, so their accuracy should be quite high (although quantitative accuracy assessment results are unavailable). Because the final map of ESAs in this study was a union of these individual maps, however, not all errors were propagated to our final estimates of the geographic/technical potential of agrivoltaics. Errors in the individual maps could be eliminated in areas where multiple maps of ESAs were overlapping, as long as one of the maps was classified accurately, and as discussed in Section 3.1., there was a high degree of overlap among the different maps of ESAs. Finally, the capacity factor values we used to calculate electricity yield per ha were average values for each country (Siala and Stich, 2016), so they may be somewhat over- or underestimated at the subnational level, depending on the local meteorological conditions. If other researchers intend to use our final map or herbaceous croplands outside ESAs to calculate the technical potential of agrivoltaics at the subnational level, it is recommended to use finer resolution meteorological data to calculate the appropriate capacity factor(s).

Relatively large uncertainty exists with regards to the agrivoltaics technologies that will be used by ASEAN countries in the future. Solar PV conversion efficiency is constantly increasing, so the efficiency assumed for our estimates of the technical potential of agrivoltaics (which are based on the current technology) are likely much lower than what will be achievable in the near future. Our analysis also assumed fixed PV panels, while the use of panels with solar tracking systems may lead to higher energy generation (although they have higher costs as well) (Ali Khan Niazi and Victoria, 2023). In addition, our assumptions regarding the spacing of solar PV panels in agrivoltaics systems are based on current technologies that cause shading of the understory crops, while (semi-) transparent PV panels are in development that could allow for denser installation of PV panels on croplands as well as the use of agrivoltaics in areas with less shade-tolerant crops (although the additional costs may be an issue for this as well) (Stallknecht et al., 2023). On the other hand, because our estimates of the installed capacity (kWp/ha) of agrivoltaics are based only on the specifications and spacing of the solar panels on the agricultural lands (Schindele et al., 2020), a final source of uncertainty is the amount of additional land that would be required for other components of agrivoltaics systems, e.g., inverters, energy storage systems, and/or monitoring systems (Maity et al., 2023).

4. Conclusions

Agrivoltaics has the potential to meet a significant share of ASEAN’s projected electricity generation needs, even if its deployment is prohibited on croplands located in ESAs. Utilizing just 10 % of the geographic potential of agrivoltaics would allow it to theoretically fulfill ASEAN’s projected solar PV generation needs under all but the most ambitious renewable energy scenarios (i.e., 1.5-S RE90 and 1.5-S RE100 in Table 4). Notably, the future expansion of agrivoltaics, even at such a large scale, does not need to conflict with the simultaneous goal of enhancing biodiversity and ecosystems services through expanding agroforestry. Some ASEAN countries can generate more power with agrivoltaics than they need, while others can generate very little, so further enhancement of transmission infrastructure like the ASEAN Power Grid would be essential to ensure that the power generated from agrivoltaics can reach where it is needed. Our map of herbaceous croplands located outside ESAs (https://www.iges.or.jp/en/pub/maps-agrivoltaics/en) can help with the identification of potential sites for agrivoltaics, but local environmental impact assessments and community consultations would still be important to ensure that negative environmental and social impacts are minimized. Finally, our study demonstrates that it can be useful to analyse the benefits/trade-offs of agrivoltaics as compared with multifunctional agricultural systems like agroforestry, rather than just open croplands.

CRediT authorship contribution statement

Brian A. Johnson: Validation, Visualization, Writing – original draft, Investigation, Methodology, Data curation, Formal analysis, Conceptualization. **Yosuke Arino:** Writing – review & editing, Writing – original draft, Resources, Project administration, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Damasa B. Magcale-Macandog:** Writing – review & editing, Visualization, Resources, Formal analysis, Data curation. **Xianbing Liu:** Writing – original draft, Visualization, Validation, Formal analysis, Data curation, Conceptualization. **Makino Yamanoshita:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization.

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.

Data availability

Data will be made available on request.

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Appendices

Fig. A1. Examples of hedgerow agroforestry (photo by authors) (a), parkland agroforestry (photo by authors) (b), and riparian agroforestry (photo from Prastiyo et al. (2020)) (c).

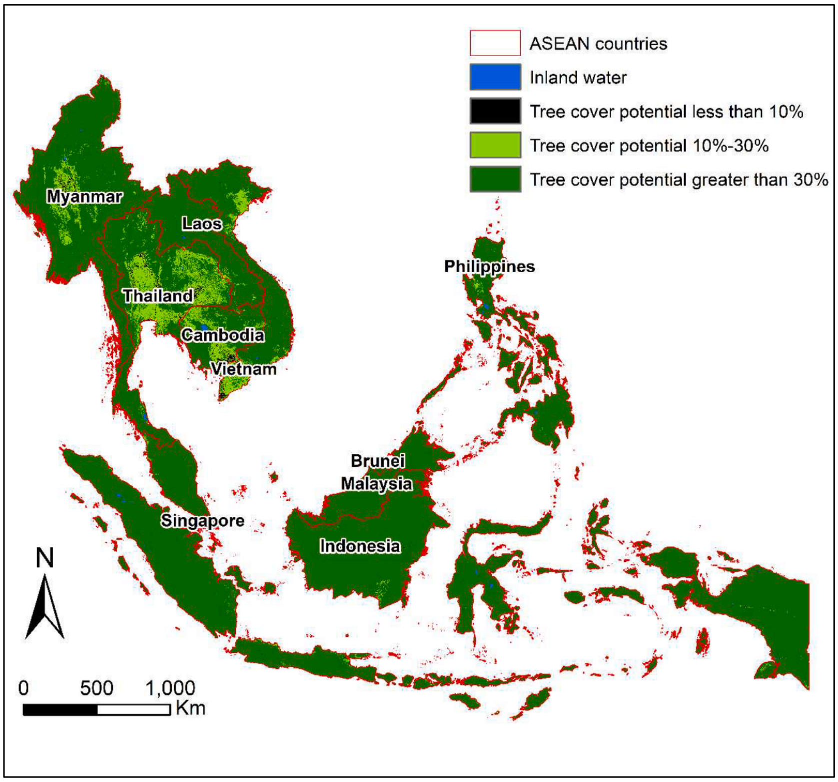

Fig. A2. Map showing the amount of tree cover that could potentially exist with minimal human intervention, created by the authors using the "earth's tree carrying capacity" map (Bastin et al., 2019).

Table A1
Datasets used in this study.

Dataset	Description	Usage in this study	Time period	Spatial resolution (for remote sensing-derived maps)	Link to dataset
1. University of Maryland 30 m global cropland map (Potapov et al., 2021)	Map of land used for annual and perennial herbaceous crops.	Extracting herbaceous croplands	2019	30m	https://glad.umd.edu/dataset/croplands (last accessed November 13, 2023)
2. World database on protected areas (UNEP-WCMC and IUCN, 2023)	Areas where special measures need to be taken to conserve biological diversity (Secretariat of the Convention on Biological Diversity, 1992, p. 8)	Identifying ESAs: protected areas and their 1 km buffer zone	Until April 2023	n/a (manually digitised polygons)	http://protectedplanet.net/ (last accessed April 13, 2023)
3. Key biodiversity areas (BirdLife International, 2023)	Sites of importance for the global persistence of biodiversity (IUCN, 2016)	Identifying ESAs: key biodiversity areas and their 1 km buffer zone	Until April 2023	n/a (manually digitised polygons)	https://www.keybiodiversityareas.org/kba-data/request (last accessed April 13, 2023)
4. Ramsar wetland sites	Wetland site of international importance	Identifying ESAs: Ramsar wetland sites and their 1 km buffer zone	Until September 2023	n/a (manually digitised polygons)	https://rsis.ramsar.org/ (last accessed September 19, 2023)
5. Global 30 m wetland map with fine classification system (X. N. Zhang et al., 2023)	Map of other wetlands, including: permanent water bodies, swamps, marshes, flooded flats, saline wetlands, mangroves, salt marshes, and tidal flats.	Identifying ESAs: wetlands of at least 1 ha in size, and their 100 m buffer zone	2020	30m	https://zenodo.org/records/7340516 (last accessed November 10, 2023)
6. OpenStreetMap "rivers" and "streams"	Rivers and streams extracted from OpenStreetMap	Identifying ESAs: rivers/streams and their 100 m buffer zone	Until May 2023	n/a (manually digitized polygons)	https://download.geofabrik.de/asia.html (last accessed May 09, 2023)
7. PALSAR-2 Forest/non-forest map, Version 2 (JAXA, 2022)	"Land spanning more than 0.5 ha with trees higher than 5 m and a canopy cover of more than 10 percent, or trees able to reach these thresholds in situ. It does not include land that is predominantly under agricultural or urban land use" (FAO, 2010)	Identifying ESAs: forests and their 100 m buffer zone	2020	25m	https://developers.google.com/earth-engine/datasets/catalog/JAXA_ALOS_PALSAR_YEARLY_FNF4.html (last accessed September 26, 2023)
8. ALOS World 3D – 30 m (AW3D30), Version 3.2 (Takaku et al., 2020)	Digital elevation model.	Identifying ESAs: areas with a slope of more than 15°	2011	30m	https://developers.google.com/earth-engine/datasets/catalog/JAXA_ALOS_AW3D30_V3_2 (last accessed February 06, 2024)

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