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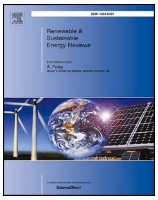

The spatial socio-technical potential of agrivoltaics in Germany

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ABSTRACT

Germany's goal of transitioning to renewable energy by 2045 presents a challenge of increased land-use competition. Agrivoltaics is a promising solution to this dilemma and benefits resilient food production and farmers' income. This study, for the first time, assesses the spatial land-use potential of agrivoltaics in Germany with a socio-technical Geographic Information System based on land use restrictions and suitability criteria. The study investigates small-scale agrivoltaics over suitable crops to enable farmers to benefit from the technology by their integration into high-value agricultural activities. The results show that agrivoltaics over permanent, moderate shade-tolerant and full shade-tolerant crops can achieve 88 % of Germany's PV energy target by 2030. About half of the 0.74 % of the German territory used for these crops has good soil quality, with a Soil Quality Rating over 60. From the small-sized permanent crop area (<2.5 ha) around 11 % is well suited due to favourable solar irradiation, orientation and slope. Most of this potential (79 %) is concentrated in the southern regions of Germany. The results indicate that agrivoltaics over permanent, moderate shade-tolerant and full shade-tolerant crops can contribute to resilient food production in small-scale farm businesses and to the political goal to increase land-based solar energy production. More financial support and further research are needed to identify the obstacles, and better understand stakeholders' perspectives on agrivoltaics and its integration into the landscape.

GM-PV Ground-Mounted Photovoltaics
PV Photovoltaics
SQR Soil Quality Rating

1. Introduction to agrivoltaics

The German government aims to achieve climate neutrality and an equitable transition to a decarbonised electricity system by 2045 [1]. Photovoltaics plays a crucial role in the transformation of the energy system due to its modularity, decreasing costs, increasing efficiency and lifetime, and the possibility of installing it on buildings and fields at different scales. Due to the competition for agricultural land – a valuable and limited natural resource in Germany – photovoltaics on roofs and integrated into buildings are favoured over ground-mounted photovoltaics (GM-PV) [2]. However, a small percentage of arable land is needed for solar energy production to reach Germany's energy transition target [3]. GM-PV can positively impact ecosystems and biodiversity [4], but concerns exist that GM-PV will trigger land use competition, increase land prices and leases, accelerate the loss of land for food production, and transform the landscape. These concerns need to be taken seriously. Otherwise, there is a risk of public resistance to using solar technology on agricultural land. This is shown by what happened in Denmark and the Netherlands. In these countries, large-scale GM-PV installations have become more controversial in recent years because of their size and impact on agriculture, wildlife, landscape, and tourism [5–7].

As public acceptance declines, suitable sites for GM-PV on degraded land become scarcer, and environmental concerns grow, the focus has shifted to more sustainable and integrated solutions for on-farm solar energy production. Agrivoltaics addresses these issues by allowing food and solar energy to be produced on the same site, and is supported by the German government [8,9]. Developed in 1981, dual land-use with agrivoltaics has remained a niche technology within the solar sector for a long time, but it has recently become more attractive [10,11]. Starting from 5 MW in 2012, around 2800 MW of agrivoltaics on 8500 ha exist globally, mainly in China, Japan, South Korea and Europe [12]. There are different definitions and designs of agrivoltaics systems, which can be vertical or horizontal with heights of 2.1 m, with fixed or with (single/dual axis) tracking modules to follow the sun's rays, and adapted to the specific site conditions, such as land use (grassland, arable land, permanent crops), crop characteristics and farm operations [8,13–15]. Vertical agrivoltaics is mainly used for forage production on grassland and landscape management, with examples in Germany and Ireland, but has also been investigated for potatoes and oats in Sweden [8,16]. Installations in Germany and Austria range from 2 MWp to over 17 MWp

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List of abbreviations

EEG	German Renewable Energy Sources Act
GIS	Geographic Information System

[17]. High-elevated horizontal agrivoltaics correlate with higher-growing crops, such as fruit trees, and offer benefits in protecting crops from sunburn, hail, wind and rain, as well as reducing evapotranspiration by 14–19 % and irrigation water use by 20 % [15,18,19]. Several examples of agrivoltaics on special crops, such as in vineyards in France, redcurrants and raspberries in the Netherlands, and fruit trees in Belgium and Germany [20,21]. Agrivoltaics modifies light conditions so that crops with a certain shade tolerance, such as berries and leafy vegetables, are better suited than others. Crop breeding and agrivoltaics design need to be optimised simultaneously to bridge the food-energy-water nexus [22]. There is no one-size-fits-all solution for agrivoltaics. Rather, the optimum holistic approach must be found based on the site conditions and the farmer's needs and expectations. Germany currently has around 16 MWp of installed agrivoltaics capacity, but the country's Renewable Energy Sources Act (EEG) and Power Purchase Agreements (PPAs) are expected to increase capacity up to 1 GW by 2025 [23]. This is equivalent to less than one part in a thousand of the PV capacity currently installed. Most of these are small-scale installations as part of research and development projects. They are designed according to regional crops and field sizes. While there are a few larger projects in the east of Germany, most of the systems in the south of Germany are in small field structures on special crops [8].

Agrivoltaics can increase the efficiency and resilience of food production, particularly under climate change conditions [24]. The technology can diversify farmers' income, create jobs, and benefit regional economies [25,26]. In areas where GM-PV is perceived to be threatening agricultural practice, agrivoltaics can increase local support for solar energy projects. Agrivoltaics does not influence direct payments to farmers under the European Common Agricultural Policy (CAP), which means that 85 % of the payments are granted if no more than 15 % of the agricultural area is lost for the installation of the system [9]. Given the economic imbalance between profits from electricity and agricultural production, previously grown crops can, however, be neglected or switched to, for example, ornamental plants and spices, which contribute less to the food supply, which is referred to as pseudo-agriculture, or even abandoned [25,27]. To prevent pseudo-agricultural practices under agrivoltaics that would lead to a loss of technology acceptance, the agricultural yield under agrivoltaics should be at least 66 % of the reference yield according to Germany's standard DIN SPEC 91434 [28]. In Japan, the regulations are much stricter: 80 % of the agricultural production must be achieved compared to the level before the agrivoltaics installation [29]. Initially, the annual harvest and crop type had to be reported. Between 2018 and 2021, the Japanese reporting requirements have been relaxed to a renewal assessment every ten years. Since 2021, yield maintenance in Japan is not necessary when utilising abandoned farmland for agrivoltaics [29]. Besides Germany, 14 EU Member States have included solar PV in their CAP strategic plans, including Austria, France, Ireland, Italy, the Netherlands and Spain, but only the Germany promotes elevated agrivoltaics [14]. The Netherlands specifically define the need for PV modules not to interfere with agricultural activities and set criteria for the distribution of PV modules by area. In France, agricultural land must be maintained for its intended use and agrivoltaics must not have a significant impact on agricultural services, must not prevent agricultural production as the main activity and must be reversible [30].

In Japan, over 120 crops have been grown under agrivoltaics, including paddy rice [25,31]. The results indicate that pseudo-agriculture exists and that the initially grown crops were changed to shade-tolerant vegetables, mushrooms, fruit trees, ornamental plants, and pastures [25]. As each crop has different growth characteristics, vegetation periods, and responses to shading, the effects of agrivoltaics on yield and crop quality can vary widely in both time and space [32,33]. There is no crop-specific optimum percentage of panel coverage that does not significantly reduce crop yield and quality in the long term, and the limited number of research studies and the inconsistencies observed, make it difficult to draw comprehensive conclusions for different crops, regions, climatic conditions, and farming practices [32]. However, it can be concluded that some crops are better suited to agrivoltaics because they are shade-tolerant or need shelter against weather extremes and solar irradiation. This is particularly true for permanent crops such as orchards, vineyards, hops and berries, where agrivoltaics can replace hail and shade nets and plastic covers [8,34]. Agrivoltaics can also create cooler microclimates under the PV panels, reducing evaporation and improving the panel lifetime and performance as a 1 °C increase in temperature can decrease panel efficiency by 0.6 % when temperatures exceed 25 °C [19,35,36]. Another study found that agrivoltaics lowered the temperature level by 1–1.5 °C, thereby increasing energy generation [37]. A significant value of 3 % increase in power generation was found for active and passive cooling approaches in agrivoltaics [38].

The main crops, i.e. wheat, show lower yields below agrivoltaics [39–41]. This was less observed in systems with orchards and vineyards and shade-tolerant fruits like blueberries, red berries and raspberries, and vegetables such as cauliflower, cabbage, beets, potatoes, radishes, tomatoes, peppers, carrots, and leafy greens, i.e. spinach and lettuce [42–44]. Given climate change, agrivoltaics can reduce inter-annual yield fluctuation by buffering the adverse effects of both frost and high temperatures on crops and lowering water consumption. These advantages have been recognised in the Netherlands, where most agrivoltaics are used for fruit production, i.e. fruit trees and berries [7,42]. Depending on system design, climate, and weather conditions, agrivoltaics can increase fruit and vegetable yields. For example, blueberry yield at high radiation intensities can benefit from up to 50 % shade [18]. Besides, vegetation below agrivoltaics benefits forage and nesting sites for pollinating insects, which are essential for fruit production [45]. In dry regions with high solar irradiation, such as under Mediterranean climate conditions, yields were increased by agrivoltaics shading and the microclimate improved, e.g. by decreasing evatransporation [46–48]. Moderate shade-tolerant crops are, e.g., legumes, carrots, and onions. They accept shading, defined as a reduction in irradiance of 15–40 %, but when shading exceeds 50 %, they cannot reach their maximum photosynthetic rates [13,24,32,49]. Full shade-tolerant crops include potatoes, forage and herbaceous crops, and leafy vegetables such as cabbage, lettuce, parsley, and spinach [32,50,51]. Lettuce is particularly suitable, with a shade tolerance of 30 % [43]. Potato yield may also decrease under shading conditions, e.g., in southern Germany, by 18 % in a wet year, while it increases by 11 % in a dry year [52].

The economic viability of agrivoltaics in Germany depends on political decisions and governmental support, in particular through the German Renewable Energy Sources Act (EEG) [53], as agrivoltaics is between 30 % and 50 % more expensive than GM-PV due to higher construction and installation costs. The costs for agrivoltaics range from 700 to 800 €/kWp for vertical and 850 to 1220 €/kWp for high-elevated systems, compared to 560 €/kWp for GM-PV, and maintenance costs are higher due to agricultural land use, e.g. for cleaning [54]. The levelized cost of energy (LCOE) for agrivoltaics is in the range of 8.3–9.5 ct/kWh, which is higher than for GM-PV [14,55]. Despite high investment costs, agrivoltaics can be financially advantageous under certain conditions and for certain crops. This can result in reasonable payback periods and a land equivalent ratio (LER) greater than one [56]. As agrivoltaics is a dual land use system, it has positive impacts on crop protection in extreme weather conditions, land and water efficiency, avoided land use change, soil protection and health, biodiversity, local economies and rural development [14,23,30,57]. Agrivoltaics panel configurations, such as height, spacing, tilt and choice of panel technology, affects agricultural and energy production. Optimising the design and economics of agrivoltaics for dual land use remains a challenge, as the impact of shading on crops can be a critical factor in determining the likelihood of success, as evidenced by yield reductions of 3 %-62 % for more than 80 % of crops tested [58]. Site-specific agrivoltaics design is also essential to meet sustainable development goals and ensure profitable operation [22,59,60]. There is potential for economically viable small-scale agrivoltaics in rural areas, which can reduce the socio-economic and environmental costs of land conversion for energy production [57,61]. Best practices for agrivoltaics [14] must be followed, for example, the need to clean PV models, as dirt and dust from agricultural activities can reduce PV performance by up to 40 % in the summer months, with a possible average daily loss of 0.35 % due to soiling [62]. As agrivoltaics is not fenced like GM-PV to allow unrestricted agricultural operations in the fields, farmers, farm workers and livestock can be at risk in the vicinity of the PV panels. Agrivoltaics operators must therefore follow strict safety requirements to avoid fire and electric shock, and must be proactive in raising awareness and communicating risks due to possible negative effects on human health and public acceptance [8,14,28]. Local acceptance of agrivoltaics is crucial for successful implementation and expansion. Acceptance may decline if the installations are located in recreational areas and are perceived as a technical transformation of the rural landscape [2,63]. In Germany, public acceptance of agrivoltaics within 5 km of residential areas is around 60 %, which is better than for biogas or wind power [64]. This is due to its unique dual land use character, the relatively small size of installations, and the innovation and research nature. Public concerns may arise if the scale of agrivoltaics increases, as with GM-PV, with sizes of 10 ha and more to be economically viable [3].

Given the higher costs and yield losses and the risk of declining acceptance in the event of irresponsible and unfair implementation of agrivoltaics subsidised by state funds and regulations, it is necessary to support policymakers with scientifically sound recommendations for action so that agrivoltaics can achieve the greatest possible benefits for farmers, energy companies and energy cooperatives, local communities, nature conservation and the general public. In this sense, the study aims to support decision-making by developing a methodology to address the key criteria for successful future land use by agrivoltaics in Germany and to enable the transparent and responsible identification and visualisation of areas well suited for agrivoltaics. This study is the first to assess the potential of agrivoltaics to promote resilience in food production and small-scale agriculture using a socio-technical Geographic Information System (GIS) model. The study aims to show how much land in Germany meets these requirements, how it is distributed across the country and how it contributes to the policy goal of increasing land-based solar energy production. By doing this, the study supports science-based decision-making for a socially acceptable transformation of Germany's energy system at different scales.

2. Methods and data

The methodology for assessing the agrivoltaics potential in Germany includes a GIS model that integrates socio-technical restrictions and suitability aspects. Fig. 1 shows that, first, aspects restricting land use by agrivoltaics were selected. These relate to preserving biodiversity, drinking water reservoirs, floodplain functions and the characteristics of the landscape. Restricted areas are biodiversity protection areas under the Federal Nature Conservation Act, including nature reserves, national parks, biosphere reserves, landscape protection areas, nature parks, natural monuments, legally protected biotopes and Natura 2000 areas, water protection areas under water protection regulations, and legally regulated flood plains to maintain natural floodplain functions and the significant landscapes.

At present, agrivoltaics has a high level of acceptance among stakeholders and citizens. To maintain acceptance, distance to settlements to avoid annoying and visually disturbing agrivoltaics in the neighbourhood is crucial. In the GIS model, a 200-m buffer zone around residential and commercial areas was defined as an area restricted for agrivoltaics. Fig. 1 shows that in the socio-technical GIS approach, restrictions and suitability aspects were defined and translated into criteria applied in the GIS model. The constrained areas were excluded by integrating the restriction and preference parts of the GIS model.

In the GIS model, the accurate crop distribution map provided by Blickensdörfer et al. [65] was used as a database to illustrate spatial crop distribution and assess land suitability by crop type. Suitable cropland for agrivoltaics was defined as low-risk areas for pseudo-agrivoltaics so that food production will not be neglected to maximise the economically more attractive solar energy production. Permanent crops, i.e. orchards, vineyards, and hops, comply best with this criterion as they are maintained for around 20 years. Synergetic effects can be captured from the protective function of agrivoltaics against weather extremes and the less disruptive impact on the landscape as they are mainly covered with hail nets [2,8]. Agrivoltaics over permanent crops have favourable economic characteristics, i.e. lower investment costs and higher crop benefits [54], and can be integrated as added-value technology and improve the sustainability and resilience of agricultural businesses. The on-site electricity supply can be used, e.g. for irrigation purposes and, in the future, to drive electrically powered autonomous cultivation equipment, which is crucial for meeting the challenges of fruit and wine cultivation in Germany [66]. Moderate and full shade-tolerant crops can also prevent pseudo-agriculture and profit from agrivoltiacs as they can benefit from shading in the context of climate change and show only a small yield reduction. In the GIS model, the accurate crop distribution map provided by Blickensdörfer et al. (2022) [65] was used as a database to illustrate spatial crop distribution and assess land suitability by crop

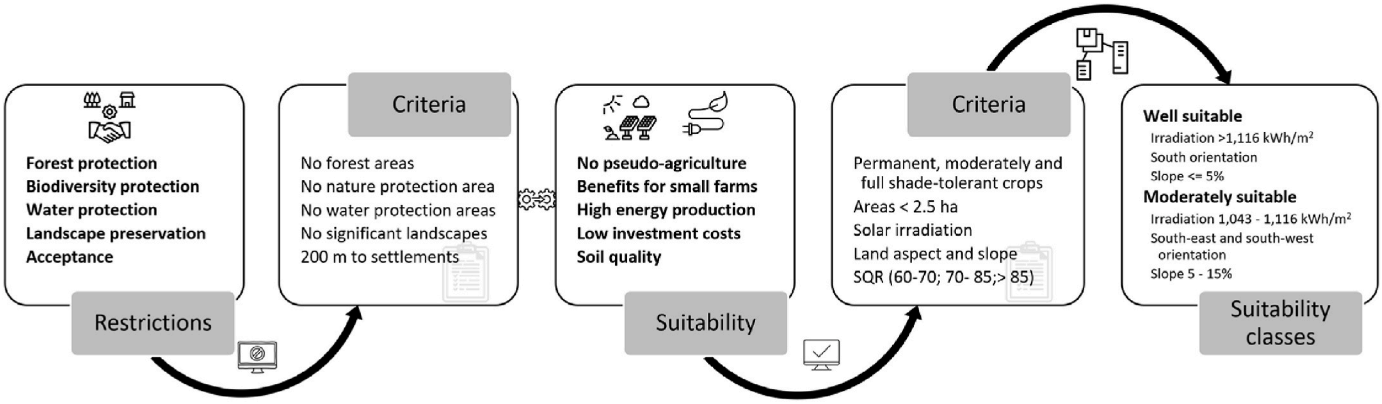

Fig. 1. The socio-technical approach for assessing the spatial agrivoltaics potential in Germany.

type.

The socio-technical GIS approach includes, in addition to land use and crop type, soil quality as a selection criterion for agrivoltaics, as in Germany agrivoltaics is seen as a technology to combat soil loss and degradation caused by agricultural practices, which is inextricably linked to agricultural practices and resilient and sustainable food production [8,14]. This is because competition for land use is most pronounced on high-quality soils, and direct and indirect changes in land use are difficult to stop. The greatest benefits of agrivoltaics can be achieved if they are placed on the best soils, where the competition for land use is high. With this in mind, soil quality was used as a criterion to assess the agrivoltaics potential and the Soil Quality Rating (SQR) map developed by the Leibniz-Centre for Agricultural Landscape Research and modified by the Federal Institute for Geosciences and Natural Resources [67] was used to characterise the quality of soils. The SQR determines the yield potential of a specific area relative to the most productive area, with a value of 100 for arable land. Soil characteristics, geological origin and condition, and climate and terrain influence the values. The soil quality classes applied in this study were defined as follows: extremely low (SQR <35), very low (SQR 35 to <50), low (SQR 50–60), medium (SQR 60–70), high (SQR 70–85), and very high (SQR >85). This study considered arable land with SQR >60 suitable for agrivoltaics. Soil quality does not play a role in agrivoltaics when soilless production is used, i.e. when the soil is covered with plastic and used to grow potted plants, as it is done in Malaysia and Japan [68].

The socio-technical preference for small-scale agrivoltaics was reflected in the GIS model by differentiating between areas smaller and larger than 2.5 ha. This aligns with the German building law, which allows simplified approval procedures for agrivoltaic systems smaller than 2.5 ha [69]. Techno-economic aspects of agrivoltaics were characterized by solar irradiation, land orientation, and slope. These criteria were applied to differentiate the agrivoltaics potential between well-suitable areas (solar irradiation >1116 kWh/m^2 per year, south orientation, and a slope $\leq$ 5 %) and moderately suitable areas (solar irradiation between 1043 and 1116 kWh/m^2 per year, south-east and south-west orientation, and a slope from 5 to 15 %). The criteria were ranked and assigned equal weight. A weight overlay analysis was conducted, multiplying the results by an unconstrained permanent GIS map.

3. Results

The study results show that 17 % of the permanent crops, 36 % of the moderate shade-tolerant crops, and around 36 % of the full shade-tolerant crops are suitable for agrivoltaics. Table 2 shows that the total agrivoltaics potential on this cropland is around 265,000 ha, corresponding to 1.6 % of Germany's agricultural and 0.74 % of Germany's total area. This area is over 20 times larger than the existing GM-PV area. Around 300,000 ha of agricultural land is required to achieve Germany's target of 215 GWp of solar energy by 2030, assuming a 50 % share of land-based PV and a specific area demand of 2.8 ha/MWp for agrivoltaics. Permanent, moderate and full shade-tolerant crops together can cover 88 % of this demand, and permanent crops around 20 %. Compared to the 32,000 ha of GM-PV in Germany, of which 30 % is on arable land, agrivoltaics over permanent crops would increase land-based PV by almost six times. The area size distribution across the different crop categories in Table 1 shows that one-third (34.2 %) of the areas are smaller than 2.5 ha. For permanent cropland, the proportion of small areas is significantly larger at 55.4 % and significantly smaller for full shade-tolerant cropland at 24.5 %.

Table 1
Germany's agrivoltaics potential on permanent, moderate and full shade-tolerate crops.

Crop types	Size of agrivoltaics		Total area (ha)	Share of Germany's area (%)
	<= 2.5 ha	>2.5 ha		
Permanent crops	33,056	26,638	59,695	0.16
Moderate shade-tolerant crops	34,206	76,111	110,317	0.31
Full shade-tolerant crops	23,160	71,317	94,477	0.26
Total	90,422	174,066	264,489	0.74

Table 2
Germany's agrivoltaics potential on arable land with high soil quality.

Soil Quality Rating (SQR)	Size of agrivoltaics		Total area (ha)	Share of Germany's area (%)
	<= 2.5 ha	>2.5 ha		
60-70	114,778	863,239	978,016	2.7
70-85	92,119	648,609	740,728	2.1
>=85	16,811	518,509	535,320	1.5
Total	223,707	2,030,357	2,254,064	6.3

Table 2 provides an overview of the agrivoltaics potential on arable land with good, very good, and the best soil quality. The results indicate that around 2.25 million ha, corresponding to 6.3 % of the total German area, have good soil quality with SQR >60. The share of the best soils (SQR >85) is 24 %, and the share of the good soils (SQR 60 to 85) is 76 %. This means that the share of best soils is twice as high as the land used to cultivate permanent, moderate, and full shade-tolerate crops and 9.5 times as high as the land used to cultivate permanent crops only. When looking at the area sizes, the picture is reversed. Most of the arable land with good soil quality is above 2.5 ha in size; only 11 % of the area is less than 2.5 ha. Of the best soils (SQR >85), 3.1 % belong to small areas (<2.5 ha). For the soil class SQR 60 to 85, the share is 12 %. This means that, statistically, the area of small permanent cropland (<2.5 ha) is twice that of the area of small areas with the best soils (SQR >85).

The spatial analysis based on the classification of crops (left) and soil qualities (right) displayed in Fig. 2 shows that the spatial distribution between the cultivation of permanent, moderate, and full shade-tolerant crops and the distribution of soil qualities varies across Germany. The soils with the highest quality (SQR $\geq$ 85) are found in northern Germany, e.g. in the Hildesheimer and Magdeburger Börde, in middle-east Germany, e.g. the Thuringian Basin and the Leipzig Lowland Bay and southern Lower Saxony, as well as in southern Germany, e.g. Lower Franconia, Lower Bavaria, Middle Franconia and the neighbouring Upper Palatinate. The superior soil quality is also prevalent in the western region of North Rhine-Westphalia, as illustrated in Fig. 2 on the right. Segments of the white areas shown in Fig. 2 (right) correspond to arable land, shown in Fig. 2 (left) indicating a lack of SQR information. This reflects the insufficient accuracy of the SQR map, which is a limitation of the study, as presented in the discussion section.

The spatial analysis of soil quality and the cultivation of permanent, moderate, and full shade-tolerant crops shows variations in the distribution of these crops across soil quality classes. Table 3 shows that 43.7 % of permanent crops are on soils with SQR 60 to 70, 44.6 % on soils with SQR 70 to 85, and 11.7 % on soils with SQR $\geq$ 85. The distribution of moderate shade-tolerant crops across soil quality classes is fairly even, with 34 %, 36 %, and 30 %, respectively. In contrast, full shade-tolerant crops are grown more on soils with SQR 60 to 70 and 70 to 85 and less on soils with SQR $\geq$ 85, with a distribution over the soil classes of 43 %, 37 %, and 20 %, respectively. These results show that agrivoltaics on permanent, moderate, and full shade-tolerate crops can protect the best soils for food production only to a limited extent because soils with less quality are also suitable for cultivating them. Permanent crops, in particular, are not cultivated on the best soils but rather on good soils.

Since most permanent crops are located in southern Germany, particularly in the states of Rhineland-Palatinate, Baden-Württemberg, and Bavaria, with an average specific solar energy yield of 1.175 kWh/kWp (ranging between 1.100 and 1.250 kWh/kWp) [69], these areas are considered well suited for agrivoltaics as shown in Fig. 3.

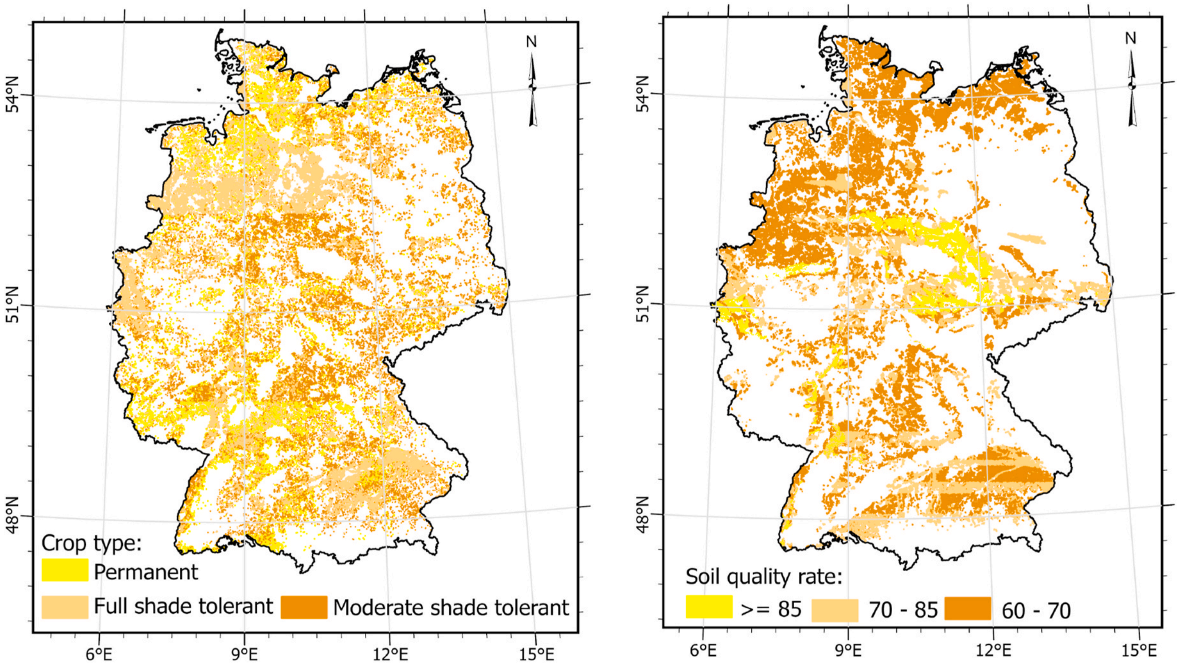

Fig. 2. Germany's spatial agrivoltaics potential on permanent, moderate and full shade-tolerate cropland (left) and soil qualities (right).

Table 3
Germany's agrivoltaics potential on permanent, moderate, and full shade-tolerant crops in relation to soil quality classes (SQR).

Crop types	SQR	Size of agrivoltaics		Total area (ha)
		<= 2.5 ha	>2.5 ha	
Permanent crops	60-70	1,816	4,410	6,227
	70-85	2,176	4,171	6,347
	>=85	658	1,010	1,668
	No data	-	-	45,453
Moderate shade-tolerant crops	60-70	13,645	7,605	21,250
	70-85	13,528	8,625	22,153
	>=85	15,147	3,532	18,680
	No data	-	-	48,234
Full shade-tolerant crops	60-70	18,215	6,287	24,501
	70-85	14,380	6,496	20,876
	>=85	8,928	2,039	10,966
	No data	-	-	38,133

The majority (81 %) of the 59,695 ha of permanent crop area is suitable for agrivoltaics, as shown in Table 4. Only 19 % is unsuitable, mainly due to orientation and slope. However, the distribution of well suitable areas is limited, with 11.2 % belonging to this category.

The results in Table 4 show that areas of less than 2.5 ha account for 79.7 % and 69.6 % of the well suitable and moderately suitable areas, respectively. If only well suitable areas were used, agrivoltiacs would double the PV area on agricultural land covered with GM-PV. As shown in Table 5, most of the permanent crops suitable for agrivoltaics (79 %) are located in southern Germany, mainly in the federal states of Rhineland-Palatinate, Baden-Württemberg, and Bavaria, the federal states most affected by climate change and weather extremes and where permanent crops are an essential part of regional value chains and agritourism. This result reflects that landownership was repeatedly divided in southern Germany due to inheritance regulations, resulting in many small farms with small fields. Compared to the national average size of a farm of 63.2 ha, the farm sizes in Rhineland-Palatinate, Baden-Württemberg, and Bavaria are 43.6 ha, 36 ha, and 36.7 ha and significantly smaller [70]. Small farms can survive on the market in these federal states by growing permanent or special crops such as moderately and full-shade tolerant crops. Using the well and moderately suitable permanent crop area would increase agricultural land coverage with PV panels 3.5 times compared to today's GM-PV area. It would benefit mainly small farms in southern Germany, as shown in Fig. 3, where the proportion of land owned by farmers is likely to be higher as they, on

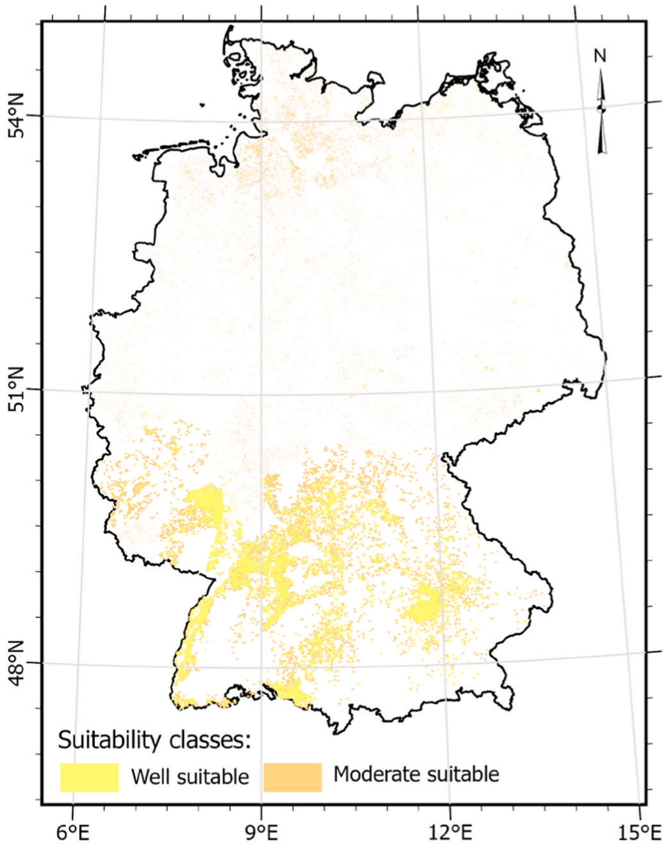

Fig. 3. Permanent crop areas well and moderately suitable for agrivoltaics in Germany.

Table 4
Suitable agrivoltaics potential over permanent crops in Germany.

Suitability Classes	Size of agrivoltaics		Total area (ha)
	<= 2.5 ha	>2.5 ha	
Well suitable area	5,310	1,353	6,663
Moderately suitable area	29,152	12,737	41,888
Total suitable area	34,462	14,089	48,551
Non-suitable area	9,639	1,504	11,143
Total area permanent crops	44,101	15,594	59,695

Table 5
Suitable agrivoltaics potential over permanent crops in southern Germany.

Federal States	Area (ha)	Share of total suitable permanent crops (%)
Baden-Württemberg	12,094	25
Bavaria	7,544	16
Rhineland-Palatinate	18,659	38
Total	38,297	79

average, comprise 6.1 ha of arable land per farm [71]. Besides, they likely will invest in agrivoltaics due to the double benefit and, as their standard gross margin is more than half the average for all farms [72].

4. Discussion

This section outlines the study's limitations, particularly regarding vertical agrivoltaics, land ownership, and data and methodological issues. The results are compared with other studies assessing the potential and spatial distribution of agrivoltaics. The potential of agrivoltaics over crops other than those investigated in this study and grassland with grazing animals is discussed. The demand for further research regarding water availability under agrivoltaics is outlined. Last, the possible impact of agrivoltaics on landscape and agritourism and the need for stakeholder integration is elaborated. This study analysed only horizontal agrivoltaics, but not vertical agrivoltaics with two bifacial modules, one above the other and up to 3 m high. They are installed 0.2–0.8 m above ground in a north-south direction and placed in rows typically 8–14 m spacing to prevent self-shadowing and enable constant agricultural practices and machine use [54]. As the PV modules face east and west, electricity production peaks occur in the morning and evening. Due to the atypical generation profile, they can achieve higher prices in the electricity market. Vertical agrivoltaics are mainly considered for grassland because the low-growing grass does not shade the modules, and there is less soiling [17,73]. This study did not analyse high-elevated agrivoltaics over grassland with grazing animals due to limited research and data, mainly on sheep and lambs [74–76]. There was no negative impact on forage production and forage quality in semi-arid regions. Vegetation growth and soil erosion control can be better maintained, and animal welfare can be improved by providing shelter [77–79]. In Germany, grassland is under pressure due to decreasing cattle farming and changes in agricultural structures and practices driven by public expectations and diet shifts [80,81]. GM-PV is considered superior for grassland without an agri-economic perspective due to its lower area-specific investments and benefits for biodiversity. The strong competition between agrivoltaics and GM-PV, where GM-PV is mainly the first choice, is also evident in the agrivoltaics country Japan, where 9964 ha and 560 ha of farmland are converted to GM-PV and agrivoltaics respectively, despite the promotion of agrivoltaics to reduce abandoned farmland, which represents 9.4 % of the total farmland area [25]

The data and methodological limitations of this study relate to the poor knowledge of the complex impacts of agrivoltaics under German conditions, which was particularly evident in the lack of peer-reviewed literature on German agrivoltaics studies, so results on the suitability of permanent, moderate shade-tolerant and full shade-tolerant crops were taken from the international literature. In addition, the analysis is greatly influenced by the quality and resolution of the data source used. Data on the spatial distribution of crop type and soil qualities play a crucial role in determining the accuracy of results. While the crop type mapping conducted by Blickensdörfer et al., 2022 [65] provided valuable insights at the national level, it comes with limitations regarding the accuracy and applicability of the maps as satellite data to map crop types across Germany were used. These maps show spatial consistent accuracy at the national level, but discrepancies between the absolute areas in the maps and the statistics for certain crop classes were found. In addition, the 1:1,000,000 scale of the soil quality map may not adequately capture detailed variations in soil properties at smaller spatial scales. Therefore, the results are not absolute and high-precise and applicable for agrivoltaics planning decisions at the local scale as they are subject to uncertainties although only those available were used which have the highest accuracy and reliability.

The methodology developed in this study is compared with the approaches from four other studies on agrivoltaics. Regardless of the agricultural production system, Trommsdorff and Bächle (2022) [82] assessed that in Germany, agrivoltaics can provide around 30 TWh per year by replacing GM-PV planned for around 80,000 ha by 2030. They did not consider the soil quality or the characteristics of crops. However, agrivoltaics should primarily be installed on good soils with high potential for food production and GM-PV on poor agricultural land [3]. Feuerbach et al., 2022 [83] assessed the agrivoltaics potential in Germany based on economies of scale, regional variation in solar irradiation, and farm-specific agronomic effects. Their results show that solar irradiation and investment costs are key determinants, while agronomic costs from crop shading and land losses have a negligible impact on the profitability of agrivoltaics. They concluded that at an electricity price of 8.3 €cents/kWh, 10 % of the most cost-efficient farms could meet 8.8 % of Germany's total electricity demand on about 1 % of arable land, which is mainly located in eastern Germany. Horticulture, wine, and fruit producers were excluded from the study. Elkadeem et al., 2024 [84] developed a GIS multi-criteria-decision approach to identify suitable areas for agrivoltaics in Sweden. The study concluded that about 8.6 % of the Swedish territory is suitable for agrivoltaics, with about 0.2 % and 15 % of this area classified as excellent and very good. Their methodology is similar to the approach applied in this study. It is based on ten restrictions and seven suitability criteria and is differentiated into five suitability classes ranging from excellent to poor. They applied similar constraints and suitability criteria but different thresholds for buffer zones according to Swedish legislation. Besides, they used additional criteria such as agrivoltaics on forests and precipitation, evapotranspiration, and the water stress index. However, their study did not consider the suitability of different crops and soil qualities for agrivoltaics. Willockx et al., 2022 [85] assessed the feasibility of agrivoltaics across Europe by quantifying the Ground PV Coverage Ratio (GCR) of agrivoltaics based on three light requirements of plants: shade-loving, shade-tolerant, and shade-intolerant plants. Their results show that the GCR increased with solar irradiance and crop shade tolerance. They concluded there is more potential in the southern than northern regions due to reduced evapotranspiration and improved space efficiency. Their study indicates that agrivoltaics, combined with potato cultivation, can take up 1 % of agricultural land and increase the capacity of 1290 GWp, ten times the EU's current PV capacity.

The focus of the study is fruit, vegetables, and potatoes grown on 2.8 % of Germany's agricultural land. Major crops such as wheat, maize and beet were not analysed because their yield is determined by solar radiation and they are characterised as shade intolerant. These crops have a higher risk of yield loss, and crop rotation and control of soil-borne pathogens and pests are more challenging [40,86]. Agrivoltaics over these crops can increase crop conversion to non-food crops and decrease regional food supply [25,27]. In addition, the economic return from electricity production is significantly higher than that from agricultural production. For example, a GM-PV system in southern Germany generates around 40,000 €/ha/year based on a remuneration rate of 5.39 €cents/kWh, as determined in the July 2023 EEG tendering round [87]. An agrivoltaic system generates 50–80 % of this yield, i.e., 20,000 to 32,000 €/ha/year [54]. Assuming a 15 % reduction in shading and area loss, the income achievable by winter wheat production (around 1320 €/ha/year) is lower [71]. The economic yield of fruit farming is with 12.000–17.000 €/ha/year higher [72]. Thus there is a risk that agrivoltaics over wheat might be designed to optimise electricity production at the expense of food production.

Landownership is a crucial issue for the implementation of agrivoltaics, but this study did not analyse landownership due to strict data protection rules and the confidentiality and inaccessibility of the information. This is because farmers in Germany do not own all the land they farm, with an average of around 60 % of the land being rented [88]. Farmers are interested in agrivoltaics to have additional income, improve their agricultural production's resilience, and further develop their farms [64]. However, they fear that the landowners want to be the investors, which would impact the farmer's right to unrestricted use of the leased land. A glance at Japan confirms the concerns. Around 60 % of agrivoltaics in Japan are owned by individuals or entities other than farmers, with the risk that agrivoltaics impairs agricultural production due to too low and narrow installations and insufficient sunlight for the crops [29]. Except for permanent crops, there is a risk that half of the crops under agrivoltaics change towards less labour-intensive ones or that farming stops entirely [25]. Another study considered the restriction that the farm must own at least 2.5 ha of arable land, which reduced the number of arable farms suitable for agrivoltaics by approximately 15 % [83]. Integrating landownership would not much change the results of this study as the well-suitable permanent crop area is mainly located in small areas in southern Germany, characterized by small farms which traditionally have a higher share of own land as they are highly specialised and rely on market income from fruit, wine and agritourism. The study differentiates between areas smaller or larger than 2.5 ha to enable farmers to be the investors and beneficiaries of agrivoltaics. The results show that this criterion matches the mainly small-scale German fruit, vine and horticultural business structures well. Increased agrivoltaics size due to economies of scale would change the spatial preferences for agrivoltaics. Besides, small-scale agrivoltaics better allow using the generated electricity within the farm business. The produced electricity can be used on-site to operate autonomous, electrified equipment and other electronic devices to improve labour productivity and reduce the reliance on external electricity supply and seasonal labour for manual tasks such as thinning fruit trees and vineyards and harvesting fruits [66]. Depending on the quality of the mainly well-developed grid infrastructure in rural areas in Germany, agrivoltaics presents an opportunity to improve rural electric vehicle charging infrastructure and provide alternative income for farmers [89].

Agrivoltaics can create a cooler microclimate for both the solar panels and the crops by reducing temperatures, improving water availability and soil moisture, and improving the panel performance, which is a higher total profit in climate change scenarios [35,52]. Agrivoltaics can optimise existing irrigation systems, which will become increasingly important in the future as more frequent and intense heat waves and drier periods lead to water shortages. It can improve water availability in regions with water scarcity and higher irradiation [90], and support the shift from irrigated to rainfed agriculture in regions with groundwater stress [91]. In addition, it can replace nets and plastic covers to prevent damage to fruit and vegetables from hail, frost, and sunburn and can help to adapt to climate change and its impacts by reducing evapotranspiration rates from the soil by 30–40 % and supporting on-site water management [89]. This is particularly relevant for permanent crops, which cannot be changed quickly to climate-tolerant varieties. The further development of the socio-technical GIS model will integrate the spatial distribution of water availability and stress and allow spatial analysis of the energy-food-water nexus by overlapping the crop, soil, and water maps. This will improve the assessment of agrivoltaics' potential for a resilient regional food supply.

To avoid negative attitudes, agrivoltaics are integrated into the landscape as unobtrusively as possible, e.g., by choosing a location that is not easily visible and accessible, planting hedges or replacing existing protective structures such as hail nets [92–94]. The socio-technical criteria of neighbourhood acceptance are translated in this study by restricting significant landscapes and a 200-m buffer zone around residential and commercial areas, as citizens are concerned that agrivoltaics will change the landscape and its recreational value [77,95]. The distance approach to support acceptance applied in this study can be improved by the visual impact assessment, which can identify suitable sites for agrivoltaics and their integration into the landscape [96]. Agrivoltaics impact on the landscape affects agritourism, which needs to be investigated as regions known for fruit and wine production have included agritourism as part of their business model, with activities such as fruit picking and wine tasting. Agrivoltaics over orchards and vineyards could be perceived positively or negatively by agritourists. They may be annoyed and disturbed as they are looking for a quiet rural life, the opportunity to experience nature and get an authentic insight into agricultural practices [97], or attracted by the co-production of fruit, wine, and renewable energy.

The methodology applied in this study can be further developed through the elaboration of key drivers and barriers for agrivoltaics and social constraints for land use conversion to energy infrastructure [98–100]. Given multiple stakeholders and decision-making processes across the agricultural and energy sectors, views on whether, how, and where agrivoltaics is beneficial may vary depending on the agricultural situation, the landscape, and the stakeholders' interests and public expectations [101,102]. The study can be improved by integrating the opinions of stakeholders and citizens to determine the reasonable number and distance of agrivoltaics installations in a region, as even small plants can lead to a perceived negative change in the landscape if there are too many of them in one place or region. Acceptance of agrivoltaics above orchards replacing hail and shade nets can be good due to the benefit-burden ratio and the small changes to the landscape [2]. Nevertheless, resistance can be expected as agrivoltaics moves from niche applications to more widespread and large-scale use [103]. Agrivoltaics should be embedded in the landscape in a co-design process following procedural justice criteria, such as transparency, early and accurate information and participation possibilities [104] and enabling an equitable distribution of benefits and burdens among stakeholders and citizens. Farmers' participation in the co-design of agrivoltaics can help to understand crop varieties and yields' importance and the difference between soil quality and value, which are not always similar [98]. Social acceptance of agrivoltaics as for other renewable energy infrastructure is crucial for the German energy transition. Although agrivoltaics is seen as superior to GM-PV by combining energy and agriculture production and is popular among experts and farmers [64], public support is not given everywhere and at all times, in particular when it comes to the concrete planning of systems [98,99]. Thus, the potential for agrivoltaics must be developed with stakeholders and citizens to understand their values, expectations and concerns, and feelings according to the principle of the NIMBY (not in my backyard) [105,103]. Stakeholder involvement in the socio-technical GIS model would be beneficial in improving mutual understanding within the agricultural community and across disciplines and stakeholders, which are divided on whether agricultural land should be used for GM-PV or agrivoltaics [89]. More comprehensive inter- and transdisciplinary research is needed to analyse the synergies and tradeoffs between agricultural production, the shading, sheltering, and water management functions of agrivoltaics, the on-site use of the produced electricity, and farm income diversification and the benefits and burdens for ecosystem services such as pest and erosion control, soil carbon sequestration, and habitat enhancement to improve pollination services and cultural services such as recreation and human well-being.

5. Conclusions

Agrivoltaics promise benefits regarding dual land use of energy and food production while mitigating land use competition and protecting agriculture from climate change impacts. In Germany, agrivoltaics is still in the research and development stage, and commercial use is lagging behind the rapid growth of GM-PV due to the risk of reduced crop yields, lower solar power system performance, and higher installation costs. In contrast to GM-PV, however, agrivoltaics has a positive perception in the political arena and among farmers and the general public. The German government supports agrivoltaics via the EEG and the Building Act to cover the additional costs of agrivoltiacs and integrate them into small-scale agricultural activities. The results of the study show that further contextualisation of the policy regulation of agrivoltaics could help to better exploit the benefits of the technology. This applies to the investigated crops, which are essential for regional food supply and added value creation but are highly vulnerable to climate change's weather extremes. They are already protected by nets and plastic covers, which could be replaced by agrivoltaics so that no further landscape would be covered and spoilt. The study results show that even considering various restrictions and suitability criteria, agrivoltaics over the investigated crops can significantly contribute to Germany's target for land-based solar energy. In addition, electricity can be better used locally to electrify and automate work processes than it can be for arable crops, which are cultivated with heavy and large agricultural machinery. Long-term inter- and transdisciplinary research is needed to investigate the complex and dynamic interactions of food production characteristics (e.g. yield, food quality, pest control, water management, irrigation, electrification of processes), energy production characteristics (e.g. energy-self-sufficiency, value creation) and public acceptance (e.g. impacts on residential and landscape value, and agritourism). The study shows that the socio-technical GIS model can support decision-making processes for land-based solar energy in Germany and contribute to achieving Germany's climate neutrality target by 2045, while maintaining the acceptance of stakeholders and the general public.

CRediT authorship contribution statement

Rösch C: Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Fakharizadehshirazi E:** GIS-Modelling, Data curation, Visualization, Software, Validation, Writing – review & editing.

Declaration of competing interest

The authors, Christine Rösch and Elham Fakharizadehshirazi, 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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Data availability

Data will be made available on request.

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