Environmental Science & Technology

Article

Cite This: Environ. Sci. Technol. 2018, 52, 7566−7576

pubs.acs.org/est

Examining the Potential for Agricultural Benefits from Pollinator Habitat at Solar Facilities in the United States

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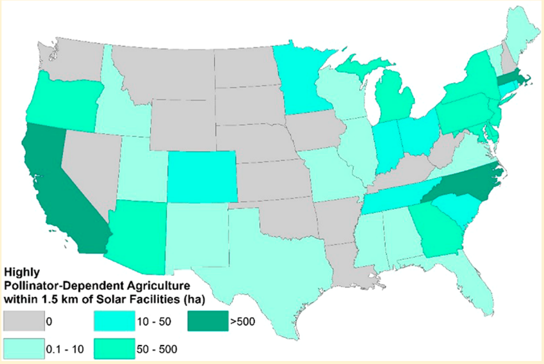
Supporting Information

ABSTRACT: Of the many roles insects serve for ecosystem function, pollination is possibly the most important service directly linked to human well-being. However, land use changes have contributed to the decline of pollinators and their habitats. In agricultural landscapes that also support renewable energy developments such as utility-scale solar energy [USSE] facilities, opportunities may exist to conserve insect pollinators and locally restore their ecosystem services through the implementation of vegetation management approaches that aim to provide and maintain pollinator habitat at USSE facilities. As a first step toward understanding the potential agricultural benefits of solar-pollinator habitat, we identified areas of overlap between USSE facilities and surrounding pollinator-dependent crop types in the United States (U.S.). Using spatial data on solar energy developments and crop types across the U.S., and assuming a pollinator foraging distance of 1.5 km, we identified over 3,500 km^2 of agricultural land near existing and planned USSE facilities that may benefit from increased pollination services through the creation of pollinator habitat at the USSE facilities. The following five pollinator-dependent crop types accounted for over 90% of the agriculture near USSE facilities, and these could benefit most from the creation of pollinator habitat at existing and planned USSE facilities: soybeans, alfalfa, cotton, almonds, and citrus. We discuss how our results may be used to understand potential agro-economic implications of solar-pollinator habitat. Our results show that ecosystem service restoration through the creation of pollinator habitat could improve the sustainability of large-scale renewable energy developments in agricultural landscapes.



INTRODUCTION

Insects are among the most diverse groups of organisms on Earth, with approximately 1 million described species.[1] Of the many roles insects serve for ecosystem function, plant pollination is possibly the most important service directly linked to human well-being.[2,3] Among the services pollinators provide to humans are pollination for food and seed production, and assistance in maintaining biodiversity and ecosystem function.[3] It has been estimated that as much as 8% of global crop production could be lost without insect pollination services,[4] and such a decline could have significant wide-ranging impacts on global agricultural markets, affecting consumer welfare and jeopardizing human health.[3] Recent trends in pollinator abundance, agriculture land uses, and human socio-political activities have highlighted the need to maintain pollinator populations to sustain human food production. Declines in wild and managed insect pollinator populations due to anthropogenic stressors such as habitat loss have raised concerns about a lost pollination service benefit to agricultural production.[2,3] For example, approximately 75% of globally important crop types are at least partially reliant upon animal pollination,[5] and in the U.S., about 23% of agricultural production comes from insect pollinator-dependent crops.[6]

Concerns regarding the conservation of pollinators have risen to the global scale as countries have recognized the severity of pollinator declines and begun developing strategies to sustain pollinator services in the face of a growing human population.[7,8] In many areas, land conversion associated with agricultural intensification has paradoxically contributed to the decline of pollinator populations and their habitats.[9,10] One mechanism to improve pollinator populations and increase agricultural service benefits is through the provision and maintenance of insect pollinator habitat in close proximity to pollinator-dependent agricultural fields. Previous studies have shown how the provision of pollinator habitat around agricultural fields could enhance local pollinator communities.[11] In agricultural landscapes, therefore, land management approaches that focus on providing diverse high-quality

Received: January 3, 2018
Revised: May 25, 2018
Accepted: May 28, 2018
Published: May 28, 2018

DOI: 10.1021/acs.est.8b00020
Environ. Sci. Technol. 2018, 52, 7566−7576

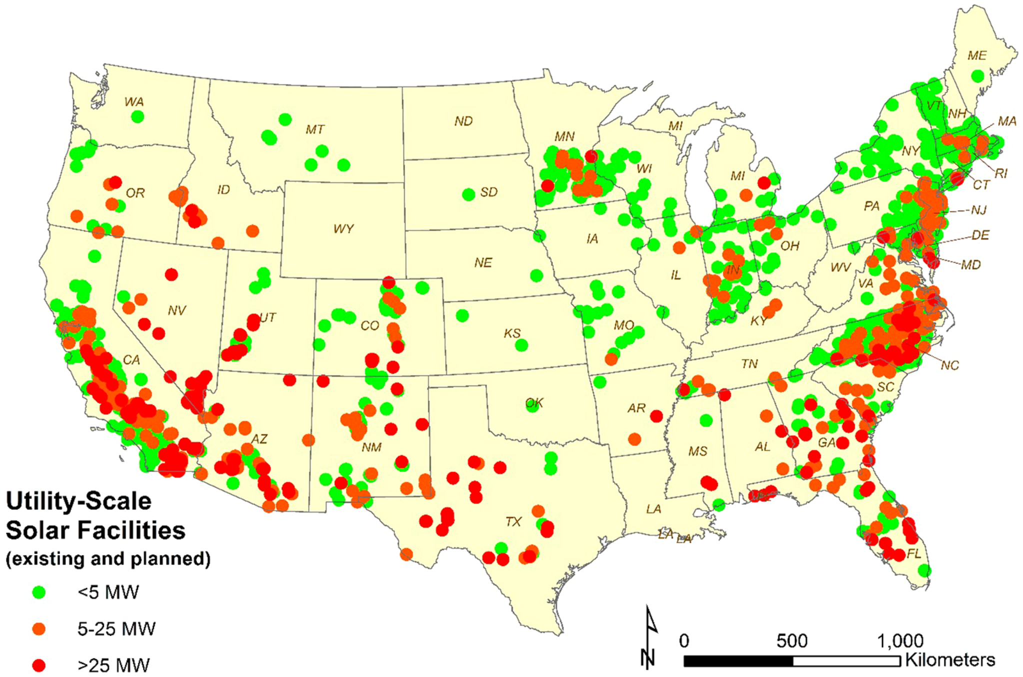


Figure 1. Locations of utility-scale solar energy (USSE) developments in the United States (>1 MW). Data were obtained from the U.S. Energy Information Administration.[17] As of 2016, there were 2,888 existing or proposed solar energy facilities in the U.S., totaling nearly 35 GW of electrical generation capacity.

pollinator habitat may have an important role in safeguarding pollinator populations and the agricultural services they provide.

In addition to agricultural intensification, renewable energy development represents another form of land cover change in rural landscapes across the United States (U.S.).[12,13] Utility-scale solar energy (USSE, ≥1 megawatt [MW]) developments are increasing in agricultural landscapes, due in part to the siting of USSE developments on former agricultural fields.[14,15] The rapid increase in USSE developments is driven in part by economic considerations as well as by concerns about the use and depletion of fossil fuels, global climate change, air and water pollution, and energy security. For example, utility-scale solar development grew at an average rate of 72% per year between 2010 and 2016,[16] and as of the end of 2016, USSE facilities accounted for approximately 22 GW of installed U.S. electricity generation capacity, with an additional 13 GW of planned USSE construction (USEIA 2016) (Figure 1).[17]

Besides the benefits of USSE development as an alternative to fossil fuels, recent work has also indicated several potential adverse consequences associated with solar developments. USSE developments have substantial spatial footprints, with an average total facility area of approximately 3.0−3.6 ha per MW of electric production.[15,18] USSE development in agricultural landscapes has the potential to reduce local agricultural production if farmland or nearby habitat for insect pollinators is converted to USSE development.[19] For example, Hernandez et al.[15] discussed the electricity generation potential of solar development in agricultural areas and brownfield sites in California. Indeed, over 70% of the USSE developments in California are sited in rural areas including shrublands, areas of former agricultural production, and barren lands[12] and some of these areas may contain high quality pollinator habitat.[20] A number of potential adverse impacts have also been indicated with these large-scale developments, including altered hydrologic patterns, habitat loss and fragmentation, impacts to cultural and visual resources, and direct mortality of wildlife.[21−24] Although the total land area projected to be required for solar development through 2030 is less than 0.1% of the contiguous U.S. surface area,[22] there is nonetheless a need to improve the landscape sustainability of large-scale solar developments to avoid or minimize potential impacts to local agriculture and cultural, ecological, and other natural resources.

Recent attention has been placed on USSE developments that integrate measures to conserve habitat, maintain ecosystem function, and support multiple ongoing human land uses in the landscape (hereafter "landscape compatibility"). Opportunities to improve the landscape compatibility of individual USSE facilities in agricultural regions exist through approaches that can reduce impacts of site preparation (i.e., from removal of vegetation, soil compaction, and/or grading), optimize multiple land uses, and restore ecosystem services. For example, the colocation of USSE development and agricultural production (i.e., planting crops among solar infrastructure) could maximize the land-use potential of USSE developments as sites of energy and food production.[13,25−27] In addition, on-site vegetation management approaches could restore ecosystem services such as crop pollination and pest control that may maintain or enhance production on nearby agricultural lands.[11,28] Recent emphasis has been placed on the creation and maintenance of pollinator habitat at USSE facilities (hereafter "solar-pollinator habitat"),[24] which is the concept of planting of seed mixes of regional native plants such as milkweed (*Asclepias* spp.) and other wildflowers, either within the solar infrastructure footprint after construction, such as among solar panels or other reflective surfaces, or in offsite areas adjacent to the solar facility, that attract and support native insect pollinators by providing food sources, refugia, and nesting habitat.

The ecological parameters that constitute pollinator habitat are often species- and region-specific. For example, the creation

DOI: 10.1021/acs.est.8b00020
Environ. Sci. Technol. 2018, 52, 7566−7576

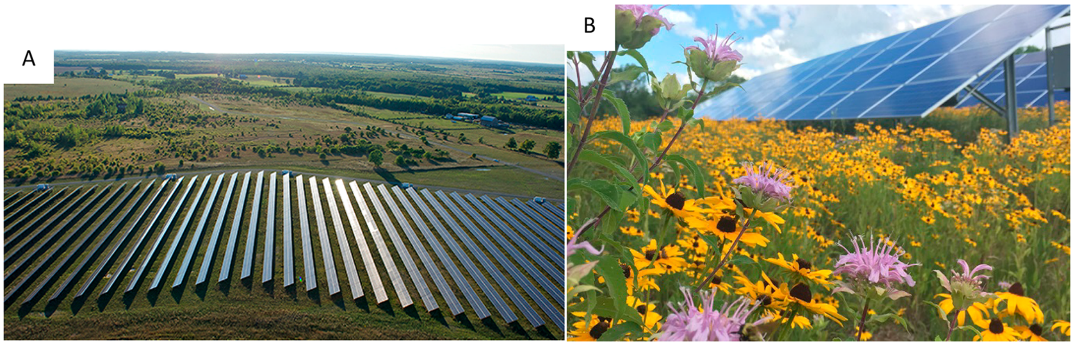


Figure 2. Example opportunities for ecosystem service benefits from solar-pollinator habitat at USSE facilities in agricultural landscapes. (A) A photovoltaic facility in an agricultural landscape (Sandringham Solar Project, Ontario, Canada) (credit: Invenergy, LLC). (B) Solar-pollinator habitat at a solar photovoltaic facility (credit: Rob Davis, Center for Pollinators in Energy/Fresh Energy). By establishing pollinator habitat at solar facilities, local insect pollinator communities may benefit, which in turn could result in increased pollination services to nearby agricultural fields.

of pollinator habitat to support specific native insect species may include the planting of different seed mixes as compared to seed mixes used to establish pollinator habitat to support nonnative Eurasian honey bees (*Apis mellifera*). Despite their ecological differences, all types of solar-pollinator habitat have the potential to improve biodiversity and ecosystem function as compared to conventional USSE vegetation management practices. In general, conventional vegetation management practices, such as placement of gravel, establishment and maintenance of turf grass, mowing, and herbicide application, are intended to minimize or prohibit the growth of vegetation within the facility footprint. Such practices provide little or no habitat suitable for pollinator species, especially if these vegetation management practices occur frequently during operation of the solar facility. In contrast, the provision and maintenance of solar-pollinator habitat and related activities, such as limited mowing and no herbicide or pesticide application, have the potential to provide a variety of ecological benefits for pollinators and nonpollinators alike.[24] Solar energy development policies in Europe have supported pollinator-friendly habitat, and currently two states in the U.S. have incentivized the incorporation of pollinator habitat at solar facilities through voluntary solar-pollinator habitat certification programs (Maryland bill SB1158; Minnesota bill HF 3353).[29,30] It is also possible for many different types of vegetation, including solar-pollinator habitat, to be established with minimal effect on solar energy generation and USSE land use intensity.[25,26]

Depending on the types of vegetation established, the ecological benefits of solar-pollinator habitat may include improved habitat diversity and connectivity for rare or at risk species such as the Karner Blue (*Plebejus samuelis*), Carson Wandering Skipper (*Pseudocopaeodes eudus obscurus*), and monarch butterfly (*Danaus plexippus*); the control of storm-water and carbon storage; and increased pollination and beneficial insect services (Figure 2). More than half of the primary crop types in the U.S. rely, in part, on animal pollination, equal to approximately $14.6 billion USD in agricultural production per year.[31] Therefore, the agro-economic implications for the enhanced pollinator service benefits provided by solar-pollinator habitat could be significant. Solar-pollinator habitat could also provide economic benefits to the solar project through improvements in microclimate conditions underneath the solar arrays, reductions in operations and maintenance costs (e.g., mowing, herbicide use), and the potential for hosting beekeeping operations.[32−34] In addition to ecological benefits, solar-pollinator habitat may increase the social acceptance of USSE facilities by improving the aesthetic value of the managed area.[35]

Despite the potential ecosystem service benefits of solar-pollinator habitat and state-level actions promoting solar-pollinator habitat development, little has been done to quantify the potential for these benefits. Because of the geographic variability in USSE development (Figure 1) and agriculture, the first step toward quantifying the potential agricultural pollinator service benefits of solar-pollinator habitat is to identify the intersection of USSE development and pollinator-dependent agriculture. In this paper, we frame the potential for solar-pollinator habitat service benefits to agricultural production by identifying and quantifying pollinator-dependent crop types in the vicinity of existing and planned USSE facilities in the U.S. We also discuss the crop types (and their locations) that have the greatest potential to receive agricultural pollination service benefits from solar-pollinator habitat.

■ METHODS

The geographic scope of this study is the conterminous 48 states in the U.S. (Figure 1). We obtained data on existing and planned USSE facilities in the U.S. from the U.S. Energy Information Administration Form EIA-860.[17] Form EIA-860 reported data on the status of existing electric generating plants in the U.S. (existing), and those scheduled for initial commercial operation within 5 years (planned). These data included electric capacity (MW), the solar generation technology type, and latitude and longitude information for each of 2,244 operational USSE facilities and 644 planned USEE facilities in the study area. We combined operational and planned USSE facilities (N = 2,888 solar facilities) to estimate total foreseeable USSE buildout and associated pollinator service potential to nearby agricultural fields. On the basis of previously reported land-MW relationships,[15,18] we used a relationship of 3.2 ha of land per MW of electric capacity to estimate the footprint size of each USSE facility. This is a conservative land-use intensity estimate for most solar facilities in the United States, although the land-use intensity for solar electricity generation may be greater in northern latitudes or due to some site-specific designs.[36] We then mapped each facility footprint, sized to represent the total size of the facility, as a circular polygon centered on each USSE location (Figure 3). We included USSE facilities of all technology types in our analysis, including solar photovoltaic (PV) and concentrating solar power technologies.

DOI: 10.1021/acs.est.8b00020
Environ. Sci. Technol. 2018, 52, 7566−7576

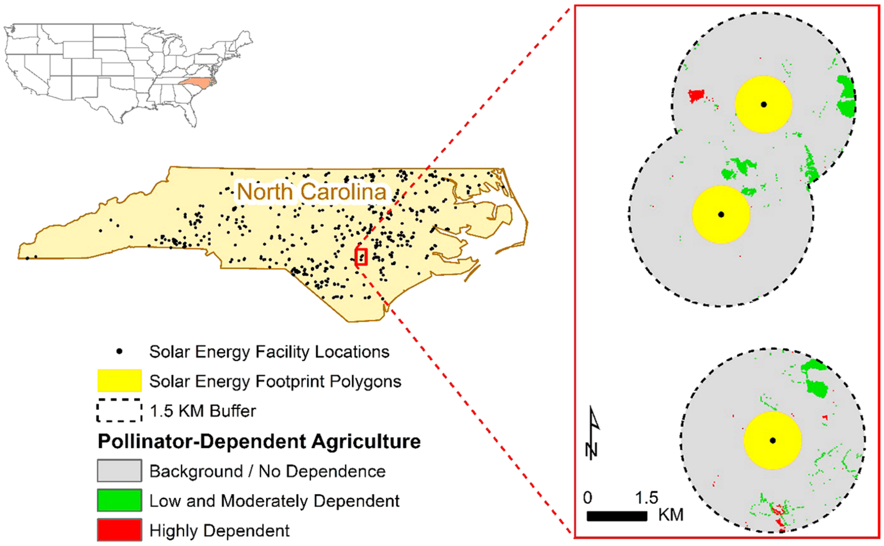


Figure 3. Example 2016 crop data layer (CDL) within 1.5 km of three existing and planned solar energy facilities in North Carolina, USA. The inset shows the areas of different pollinator-dependent crop cover types present in the foraging buffer zone, based on the pollinator-dependence status categories of Aizen et al.,[4] Calderone,[38] and Klein et al.[5] In this example, low and moderately pollinator-dependent crop types include cotton and peanuts (1−40% dependent upon pollinators), whereas the highly pollinator-dependent crops include squash and watermelons (>40% dependent upon pollinators).

We obtained spatial information on the pollinator-dependent crop types in the U.S. from the cropland data layer (CDL) produced by the U.S. Department of Agriculture, National Agricultural Statistic Service (NASS).[37] The CDL is a spatially explicit raster data layer, updated annually, and represents the total agricultural land cover at 30-m resolution across the conterminous U.S. based on classification of satellite imagery by the NASS. The CDL data layer classified 129 land cover types, from which we identified 107 cultivated crop types (SI Table 1). The pollinator dependency of a crop type was defined as the level of total pollination and subsequent total seed production that resulted solely from insect activity rather than from wind or passive (self-driven) pollination. Highly pollinator-dependent plants were those for which a high reduction in seed production would occur if insect pollinators were excluded; in such plants, insect pollination was determined to be essential.[5] For example, if a plant was considered to be 50% pollinator dependent, 50% of its seed production was due to insect pollinators and 50% to other pollination mechanisms. In the complete absence of insect pollinators, successful pollination and subsequent seed production in this plant would be reduced by 50%. For this study, we ranked pollinator dependence of each crop type into one of 5 classifications, based on the classification schemes of Aizen et al.[4] and Calderone:[38] 0 = no benefit from insect pollinators; 1 = >0 but <10% dependence on insect pollinators; 2 = 10−40% dependence on insect pollinators; 3 = 40−90% dependence on insect pollinators; and 4 = >90% dependence on insect pollinators. In a few cases where a CDL crop type was not ranked by Aizen et al.[4] or Calderone,[38] crop dependency values from Klein et al.[5] were used to assign ranks. We ranked crop types based on overall dependence on insect pollinators, including both wild and managed insects such as honey bees. We considered crop types ranked 3 and 4 (i.e., >40% dependence on insect pollinators) as being highly dependent on insect pollinators. To characterize the overlap of pollinator-dependent agriculture with solar electricity resource potential, we summarized the distribution of highly pollinator-dependent agriculture within 10 km regular grids across the 48 states, and displayed these locations with the solar resource potential developed for the 48 states by the National Renewable Energy Laboratory,[39] which modeled solar PV electrical generation potential in terms of kilowatt hours (kWh)/m^2/day.

To identify pollinator-dependent crop types that could benefit from increased insect pollination services provided by solar-pollinator habitat at existing and currently planned USSE facilities, we delineated 1.5 km wide buffers around each USSE facility footprint, based on an approximate maximum foraging distance for native insect pollinators and honeybees originating from the USSE facilities.[11,40,41] We assumed that solar-pollinator habitat established within the USSE footprint or adjacent areas could benefit local insect pollinator communities and thus increase insect visitation and subsequent pollination success in agricultural fields within this 1.5 km foraging zone. We used a geographic information system to calculate, by state and pollinator-dependency ranking, the amount of land area of pollinator-dependent crop cover types within the 1.5 km foraging zones of each of the 2,888 USSEs included in this study (Figure 3). To account for annual crop rotation and errors in classification, we used the CDL raster data to calculate the average area of each crop type within the foraging zone over the most recent three-year period (2014−2016). To avoid overlap of 1.5 km buffers of nearby solar facilities, where applicable, we merged the buffer areas and analysis was conducted on aggregated buffer area and not on an individual USSE basis.

Finally, we estimated the pollinator service value for three crops types to exemplify the potential economic implications of solar-pollinator habitat for agricultural production. We developed simple scenarios to illustrate the potential agro-economic benefit, assuming a hypothetical increase of only 1% in crop production associated with solar-pollinator habitat. The three crop types exemplified were soybeans, almonds, and cranberries because these were among the most abundant pollinator-dependent crop types identified within the 1.5 km pollinator foraging zones around USSE facilities.

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■ RESULTS

The 2,888 existing and planned USSEs across the U.S. represent a combined electrical generation capacity of 35,457 MW, with an average capacity of 12.2 MW (±0.60 SE) per facility. The estimated total USSE footprint size for all installations is approximately 11,346 km^2, based on a relationship of 3.2 ha per MW of electrical generation capacity. Based on the 2016 CDL,[37] approximately 1,300,000 km^2 of the conterminous U.S. is cultivated for crop production, of which approximately 500,000 km^2 are crop types that are at least partly dependent on insect pollination (pollinator dependence ranks 1−4) (SI Table 1). The total aggregated area within the 1.5 km pollinator foraging buffer zones of all USSEs (including all existing and planned projects) was 39,148 km^2, of which approximately 3,528 km^2 (9.0%) include agricultural crop types that could benefit from insect pollination (pollinator dependence ranks 1−4) (SI Table 2). Of this latter area, approximately 363 km^2 (10%) are used for crops that are highly dependent on insect pollinators (>40% dependence; pollinator ranks 3 and 4).

The ten states with the greatest amount of land within 1.5 km of existing and planned USSE facilities account for 78% (2,743 km^2) of all pollinator-dependent agriculture near USSE facilities, and for nearly 98% (355 km^2) of all highly pollinator-dependent agriculture near the facilities (Table 1). California has the greatest amount of existing and planned solar energy capacity (14,562 MW), and also has the greatest amount of land within 1.5 km of solar facilities (8,565 km^2). Other states with at least 2,000 km^2 within 1.5 km of solar facilities include North Carolina, Massachusetts, and New Jersey. See SI Table 3 for a complete summary of the intersection of solar development and pollinator-dependent agriculture in each state.

Overall, there was no detectable geographic relationship between solar PV resource potential and locations of highly pollinator dependent agriculture (Figures 4 and 5). Many areas where solar PV resource potential is high do not currently support large amounts of highly pollinator dependent agriculture, such as the Southwestern U.S. However, there are several areas throughout the U.S., such as the Central Valley of California and along the East Coast, where USSE developments and highly pollinator dependent agriculture occur (Figures 1 and 4).

Over 3,500 km^2 of land within the 1.5 km pollinator foraging zones of existing and planned USSE facilities contain crops that benefit from insect pollinators (>0% pollinator dependent; SI Table 2) and nearly 80% of this cropland (2,742 km^2) occurs within the ten states with the most land area within the USSE foraging zones (Table 1). Within these foraging zones, approximately 363 km^2 of land contain crops that are highly dependent on insect pollinators (>40% pollinator dependent). There are 12 states with at least 5 km^2 of pollinator-dependent cropland within USSE foraging zones (Figure 6A). The three states with the greatest amount of highly pollinator-dependent agriculture near solar facilities are California, North Carolina, and Massachusetts (Table 1; Figure 6B). These three states also have the greatest amount of USSE foraging zone area (Table 1). For the states in which existing or planned USSE facilities are present (n = 43), there was a strong positive correlation between total aggregated foraging area and total area of pollinator-dependent crops within the foraging zones (Pearson Correlation; $r = 0.872$; $p < 0.001$).

Overall, the most abundant crops near USSE facilities that have some level of pollinator-dependence are soybeans, alfalfa, and cotton (Table 2A). These crops have a low to moderate dependence on insect pollinators (1−40% dependence). The following five pollinator-dependent crop types accounted for over 90% of the pollinator-dependent agriculture near USSE facilities: soybeans, alfalfa, cotton, almonds, and citrus (Table 2A,B). The most abundant crops near USSE facilities that are highly dependent on insect pollinators are almonds, cranberries, and melons (Table 2B). Highly pollinator-dependent crops account for nearly 360 km^2 of all crops near USSE facilities that could benefit from insect pollinators.

To exemplify the potential economic implications of solar-pollinator habitat for agricultural production, we estimated the pollinator service value for three crops types known to occur within the 1.5 km foraging zone around USSE facilities. Assuming a hypothetical increase of only 1% in crop production associated with solar-pollinator habitat, agro-economic benefits for soybeans, almonds, and cranberries were estimated as follows:

Soybeans. Although soybeans are considered to be autogamous (self-fertilizing), insect pollinators have been reported to increase yields by up to 18%.[42] Soybeans are the most dominant crop type that we identified near USSE facilities, with nearly 1,500 km^2 of soybean production occurring within 1.5 km of existing and planned solar facilities (Table 2A), which is about 0.45% of the total acreage of U.S. farmland in soybean production in 2016 (335,000 km^2).[43] The total estimated value of U.S. soybean crop was $40 billion USD.[44] On the basis of these figures, we estimate that the 2016 soybean production value in areas within 1.5 km of USSE facilities to be $175 million USD. A 1% increase in soybean yield in these areas from increased pollination services facilitated by solar-pollinator habitat, therefore, could result in an additional $1.75 million USD in soybean crop value.

Almonds. California's almond industry is valued at over $5 billion USD.[44] Almond orchards are largely dependent upon managed honey bees to complete pollination. However, improved pollinator habitat near almond plantations may increase pollination by wild insects and improve the pollination efficiency of both managed and wild pollinators.[45] We identified nearly 300 km^2 of almond orchards within 1.5 km of California USSE facilities (Table 2B), which represents approximately 8% of the total farmland in almond production in California (approximately 3,800 km^2 in 2016).[46] Based on these figures, a 1% increase in almond production in these areas due to increased pollination services from solar-pollinator habitat could result in an approximately $4 million USD increase in almond crop production. Additional economic trade-offs for the almond industry related to solar-pollinator habitat could result from decreased reliance on managed honey bees and associated reductions in honey bee rental fees, which averaged $750 USD per ha to pollinate almond orchards in 2016.[47]

Cranberries. Nearly all cranberry production areas we identified within 1.5 km of USSE facilities were in the state of Massachusetts (Table 2B). The 19 km^2 of cranberry bogs near USSE facilities represent approximately one-third of the total area of cranberry production in the state, which is valued at nearly $70 million USD.[48] Based on these figures, a 1% increase in cranberry production in these areas due to increased pollination services from solar-pollinator habitat could result in an approximate $233,000 USD increase in cranberry production. As with almonds, additional economic benefits

Table 1. Ten States with the Greatest Total Land Area within 1.5 km of Existing and Planned USSE Facilities[a]

State Name	Total Number of USSE Projects[b]	Total USSE Electric Capacity (MW)	Total Area within 1.5 km of Solar Facilities (km^2)[c]	Total Area of Pollinator-Dependent Crops within 1.5 km of Solar Facilities (km^2)	Total Area of Highly Pollinator Dependent Crops within 1.5 km of Solar Facilities (km^2)[d]
California	776 (680 existing, 96 planned)	14,562 (9,861 existing, 4,701 planned)	8,059 (6,301 existing, 2,772 planned)	879.0	322.2
North Carolina	591 (433 existing, 158 planned)	4,027 (2,427 existing, 1,600 planned)	7,572 (5,384 existing, 2,817 planned)	991.7	6.0
Massachusetts	220 (182 existing, 38 planned)	569 (474 existing, 95 planned)	2,238 (1,956 existing, 392 planned)	29.3	20.8
New Jersey	218 (213 existing, 5 planned)	666 (614 exiting, 52 planned)	2,031 (1,964 existing, 83 planned)	109.3	4.0
Arizona	111 (96 existing, 15 planned)	2,528 (1,889 existing, 639 planned)	1,647 (1,331 existing, 506 planned)	172.8	0.7
Texas	42 (19 existing, 23 planned)	2,701 (580 existing, 2,121 planned)	1,456 (529 existing, 927 planned)	58.2	0
Nevada	61 (52 existing, 9 planned)	2,458 (1,598 existing, 860 planned)	1,301 (758 existing, 569 planned)	11.0	0
Florida	40 (24 existing, 16 planned)	1,105 (331 existing, 774 planned)	1,070 (442 existing, 680 planned)	136.6	0.1
Minnesota	168 (53 existing, 115 planned)	489 (255 existing, 234 planned)	1,059 (464 existing, 650 planned)	254.6	0.2
Georgia	39 (37 existing, 2 planned)	1,030 (978 existing, 52 planned)	965 (901 existing, 64 planned)	100.2	1.1
Total	2,266 (1,789 existing, 477 planned)	30,135 MW (19,007 existing, 11,128 planned)	27,298 km^2 (20,030 existing, 9,460 planned)	2,742.7 km^2	355.1 km^2

[a] See Supporting Information (SI Table 3) for a complete summary of the amount solar development and pollinator-dependent agriculture in each state. [b] USSE projects are defined as those >1 MW. Data Source: U.S. Energy Information Administration.[17] [c] The sum of values in parentheses exceeds the total area because there is overlap of 1.5 km buffers for existing and planned USSE facilities. [d] Highly pollinator dependent crop types are considered to be those that are >40% dependent on insect pollinators (pollinator dependence ranks 3 and 4).

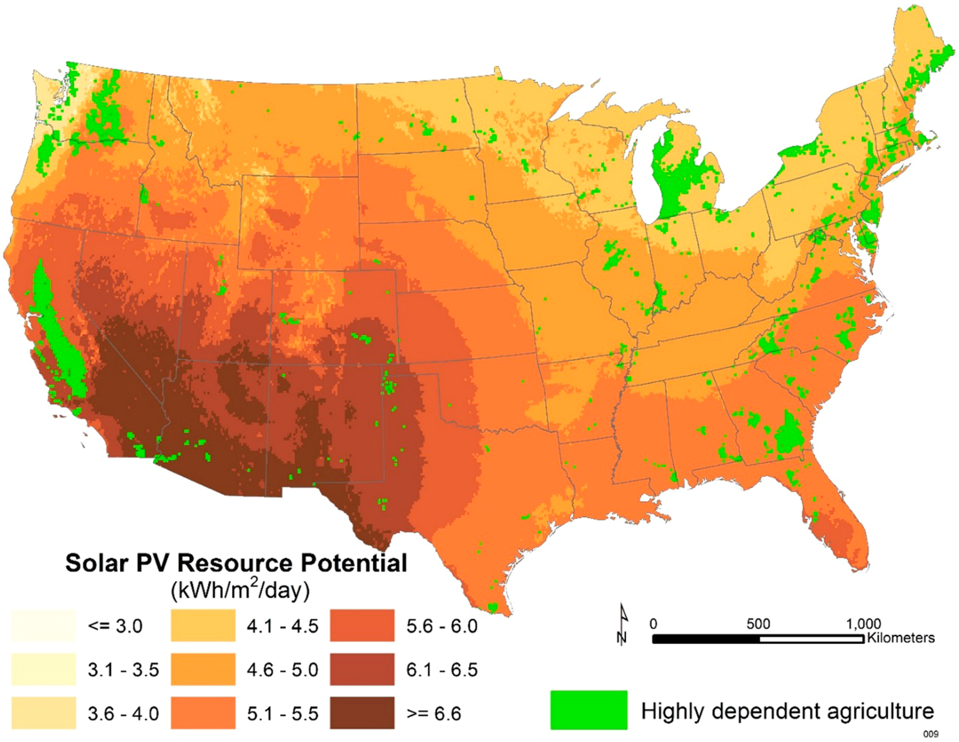

Figure 4. Overlap of solar resource potential (kWh/m^2/day) and highly pollinator dependent agriculture (>40% dependence on insect pollinators).

for the Massachusetts cranberry industry related to solar-pollinator habitat could also result from decreased reliance on managed honey bees and associated reductions in honey bee rental fees, which averaged $417 USD per ha to pollinate cranberry bogs in 2016.[47]

DISCUSSION

A growing body of literature has demonstrated the potential effectiveness of pollinator habitat established in agricultural landscapes in conserving insect pollinators and restoring important ecosystem services they provide.[11,28,35] Our results highlight one such opportunity, namely the development of solar-pollinator habitat to improve the compatibility of USSE facilities in agricultural landscapes. The development of such pollinator habitat at USSE facilities has the potential to increase the biodiversity and abundance of both wild and managed insect pollinators, which in turn can increase pollination services.[49] We identified nearly 7,000 km^2 of cultivated cropland near existing and planned USSE facilities in the U.S. (SI Table 2), with over half of this cropland planted in crops that are at least partially reliant on insect pollination. Though the amount of cropland that could benefit from solar-pollinator habitat represents less than 1% of the total U.S. cropland in production with pollinator-dependent agriculture (approximately 500,000 km^2 in 2016),[37] there may be significant economic benefits at local scales where there is overlap between USSE development and high-value insect pollinator-dependent crops, especially in those areas where insect pollination is essential for production (e.g., for crops with >40% dependence on insect pollinators).

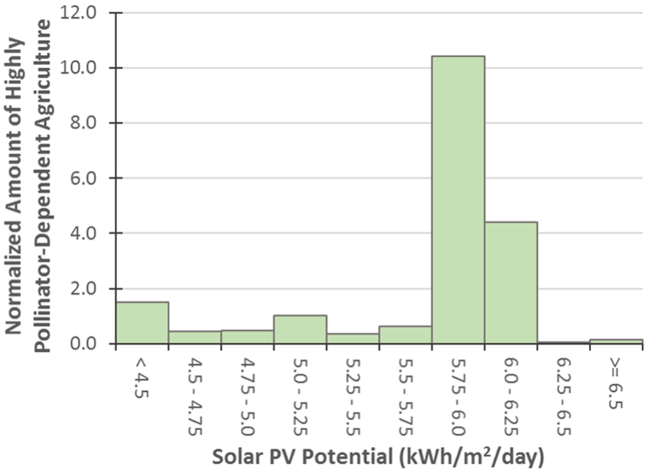

Figure 5. Amount of highly pollinator-dependent agriculture (>40% dependence on insect pollinators) by solar resource potential (kWh/m^2/day). Figures were normalized by dividing the total amount of highly pollinator-dependent agriculture (km^2) by the total land area (km^2) within each solar PV potential category. There was no statistically significant correlation between solar resource potential and amount of highly pollinator-dependent agriculture (Pearson's r = 0.188; p = 0.602).

Our study focused on understanding the potential for agricultural benefits of solar-pollinator habitat by identifying the intersection of USSE development and surrounding agriculture that could benefit from insect pollinators. Our 1.5 km pollinator foraging zones were sized to represent the average foraging activity of native pollinators and honey bees. The planting and maintenance of native pollinator-friendly vegetation at USSE developments in agricultural landscapes could offset local impacts to agricultural production not only through benefits provided by increased pollination services but also through services such as insect pest management and stormwater and erosion control.[24] However, quantifying the actual benefits of solar-pollinator habitat to agricultural production depends on a number of additional factors, such as the specific methods to

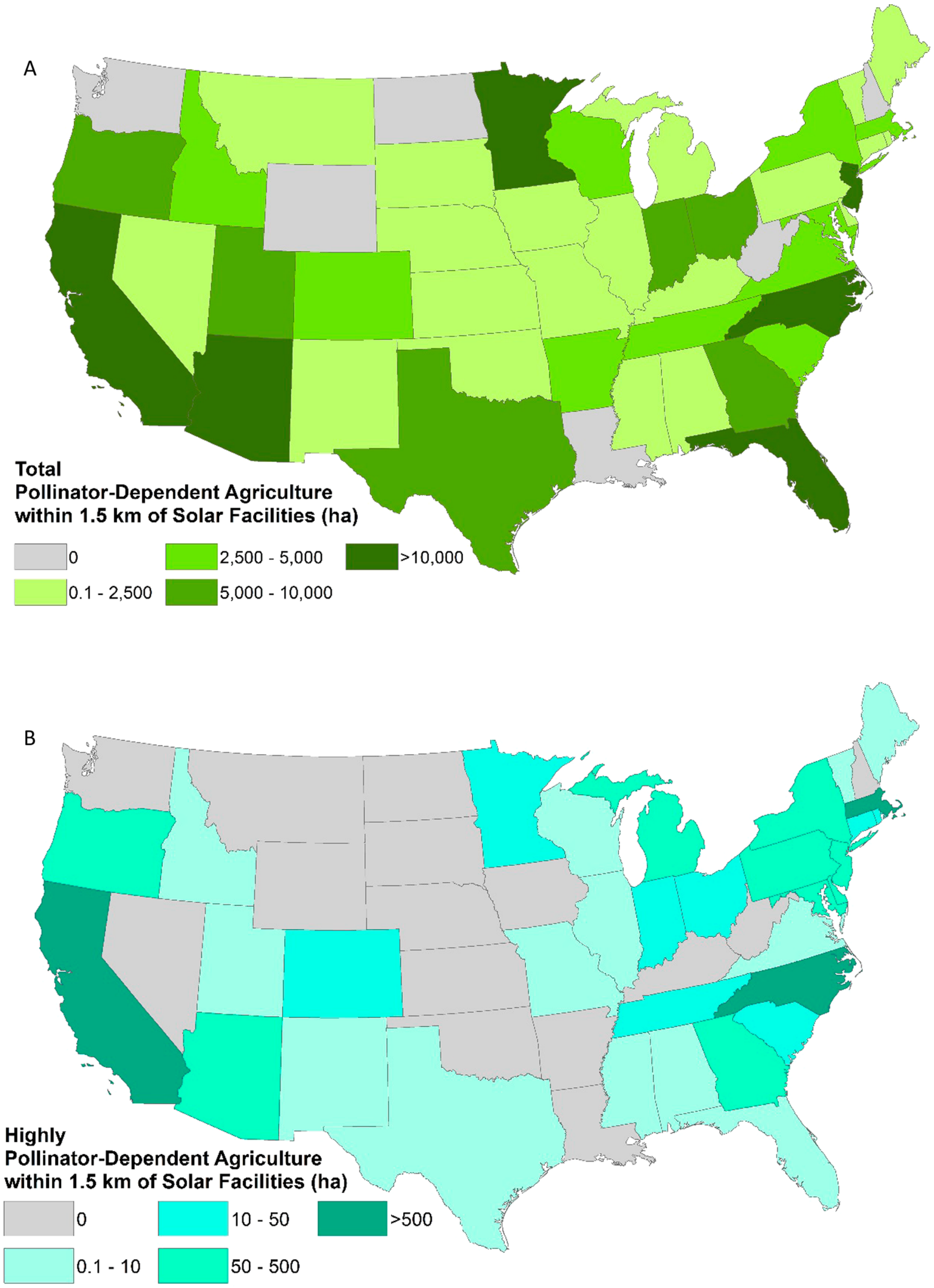

Figure 6. Amount of pollinator-dependent agriculture near existing and planned utility-scale solar energy facilities in the United States. (A) Amount of total pollinator-dependent agriculture (>0% pollinator dependence) within 1.5 km of solar facilities. (B) Amount of highly dependent agriculture (>40% pollinator dependence) within 1.5 km of solar facilities.

establish and maintain solar-pollinator habitat (e.g., seed mixes, soil preparation methods, and habitat management practices), the amount of solar-pollinator habitat provided, and characteristics of the regional pollinator community (e.g., insect diversity, flight distances, pollination efficiency, etc.). For example, some insect species are highly specialized and require uncommon genera of plants for pollen sources that may be difficult to establish within solar facilities. Additional research is needed to understand how these factors could influence the potential agricultural benefits of solar-pollinator habitat. However, our simple extrapolation of the potential economic implications of providing solar-pollinator habitat for three crop types underscores the potential pollination service benefit that solar-pollinator habitat may provide for agricultural production. Almonds, cranberries, and soybeans represent over half of the total pollinator-dependent agriculture currently within the foraging zones at USSE facilities across the U.S. (Table 2). Our hypothetical case studies for these three crop types illustrate the broad geographic potential for solar-pollinator habitat benefits to agricultural production and the economic benefits of solar-pollinator habitat for agricultural production, which could represent millions of dollars (USD).

This study represents the first step toward understanding the potential agro-economic benefits of solar-pollinator habitat.

Table 2. Summary of Pollinator-Dependent Cropland near Existing and Planned USSEs in the United States: (A) Low and Moderately Dependent Crops (1−40% pollinator dependence); (B) Highly Dependent Crop Types (>40% pollinator dependence)[a]

(A) Low and Moderately Pollinator-Dependent Crops

Crop	Insect Pollinator Dependence Rank[b]	Total Hectares of Cropland in USSE Foraging Zones, All States	States with Greatest amount of Croplandwithin USSE Foraging Zones[b]
Soybeans	2	149,364	North Carolina (75,883 ha), Minnesota (21,040 ha), New Jersey (9,747 ha)
Alfalfa	2	78,326	California (27,592 ha), Arizona (15,450 ha), Utah (7,744 ha), Oregon (4,782 ha)
Cotton	2	41,204	North Carolina (18,911 ha), California (6,081 ha), Texas (5,506 ha), Georgia (5,188 ha)
Citrus	1	20,781	Florida (13,400 ha), California (7,377 ha)
Tomatoes	1	10,202	California (10,067 ha)
Peanuts	1	8,573	Georgia (4,022 ha), North Carolina (3,589 ha), South Carolina (717 ha)
Onions	1	3,001	California (1,788 ha), Oregon (1,092 ha), Idaho (81 ha)
Beans	1	1,770	California (460 ha), Oregon (429 ha), Minnesota (238 ha), Idaho (169 ha)
Sunflower	2	340	California (219 ha), Colorado (63 ha)
Strawberries	2	292	California (186 ha), Florida (93 ha)

(B) Highly Pollinator-Dependent Crops

Crop	Insect Pollinator Dependence Rank[b]	Total Hectares of Cropland in USSE Foraging Zones, All States	States with Greatest amount of Croplandwithin USSE Foraging Zonesc
Almonds[d]	3	29,718	California (29,718 ha)
Cranberries	3	1,904	Massachusetts (1,885 ha), New Jersey (11 ha)
Melons (Cantaloupes, Honeydew, Watermelon)	4	1,287	California (1,013 ha), Maryland (106 ha), Arizona (61 ha), North Carolina (36 ha)
Apples	3	867	North Carolina (397 ha), Massachusetts (157 ha), New York (126 ha)
Blueberries	3	521	New Jersey (202 ha), Michigan (93 ha), North Carolina (77 ha), Georgia (44 ha)
Plums	3	477	California (473 ha), New York (2 ha)
Cherries	3	418	California (408 ha), Oregon (5 ha), Michigan (3 ha)
Pumpkins/Squash/Gourds	4	351	New Jersey (115 ha), Massachusetts (106 ha), North Carolina (24 ha)
Peaches	3	189	California (53 ha), Georgia (40 ha), New Jersey (27 ha), North Carolina (22 ha)
Cucumbers	3	100	North Carolina (35 ha), New Jersey (30 ha), Michigan (10 ha)

[a] The ten most abundant crops (in terms of planting acreage) in each pollinator-dependency category within 1.5 km of USSEs are listed in these tables. See Supporting Information for a complete list of the pollinator-dependent crops near USSEs. [b] Insect pollinator dependence rank based on Aizen et al.[4] and Calderone:[38] 1 = >0 but <10% dependence on insect pollinators; 2 = 10−40% dependence on insect pollinators; 3 = 40−90% dependence on insect pollinators; 4 = >90% dependence on insect pollinators. [c] Values in parentheses (ha) represent the amount of land planted with the particular crop within 1.5 km of existing and planned USSEs within that state. [d] Almond pollination is largely accomplished by managed insect pollinators (e.g., honey bees). However, improved habitat near almond orchards may increase pollination by wild insects and improve the pollination efficiency of both managed and wild pollinators.[45]

Our assessment of the possible pollinator service implications for soybeans, almonds, and cranberries not only exemplifies the potential agro-economic value of solar-pollinator habitat, but we also identified several knowledge gaps that need to be addressed to better understand solar-pollinator habitat service values. Because of the geographic variation in insect communities, soil types, vegetation, and agriculture practices, spatially explicit analyses are needed to better understand the benefits of solar-pollinator habitat to nearby agriculture. To be effective, approaches should be developed in an ecosystem services evaluation framework that incorporates economic valuation models that enable the valuations to be based more accurately on crop-specific pollinator dependencies. Additional accuracy in the estimation of benefits could be obtained through utilization of field measurements from before−after solar-pollinator studies, such as changes in insect community abundance and diversity, changes in insect visitation to nearby agricultural fields, and, ultimately, changes in agricultural production.

Pollinator habitat may be established throughout solar facilities (i.e., around and under the solar arrays), in undeveloped areas of the solar facilities, or within adjacent offsite areas. Decisions on the type of pollinator habitat to be created will vary by geographic region, as abiotic processes (e.g., precipitation), native vegetation, and insect pollinator communities also vary geographically. Project developers should consult with regional biologists to identify the appropriate vegetation suitable for the local insect pollinator community that can be feasibly grown among the USSE infrastructure. For example, in Minnesota, where legislation was passed in 2016 to establish a statewide standard for pollinator-friendly solar development,[30] over 930 ha of pollinator habitat has been established at existing solar facilities, consisting of flowering vegetation native to the Midwestern U.S. such as black-eyed susan (*Rudbeckia hirta*), purple prairie clover (*Dalea purpurea*), and partridge pea (*Chamaecrista fasciculate*).[50,51] Similarly, the establishment and maintenance of solar-pollinator habitat should be considered as part of the project design and long-term operations of USSE facilities planned in agricultural landscapes. For example, typical maintenance activities for pollinator habitat include periodic mowing or prescribed burning to remove undesirable weeds and woody vegetation.[52] Though infrequent mowing activities may occur in pollinator habitat established in on-site and offsite locations, prescribed fire might only be an appropriate maintenance activity in offsite habitat locations due to risks of damaging on-site solar infrastructure.

Increased insect pollination services are just one of several ecosystem benefits that could be provided through solar-pollinator habitat. Other ecosystem services resulting from the planting and development of pollinator habitat at USSE facilities may include, but are not limited to, improvements to local biodiversity, water control, and carbon storage. Future ecosystem services evaluation frameworks, therefore, could be expanded to quantify a broader suite of services for not only the solar energy sector but for the wind energy and transmission sectors as well, which could work toward an improved understanding of the landscape compatibility of large-scale energy developments.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.8b00020.

> A detailed summary of results on the amount USSE development and pollinator-dependent agriculture within the 1.5 km foraging zones in each state. Tables summarize for each state: the amount of total 2016 agriculture production, total amount of USSE development and crop area within the 1.5 km foraging zones around USSE facilities, and amount of pollinator-dependent crop types within 1.5 km foraging zones around USSE facilities (PDF)

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Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This work was supported by the U.S. Department of Energy Solar Energy Technologies Office. This paper was created by UChicago Argonne, LLC, Operator of Argonne National Laboratory ("Argonne"). Argonne, a DOE Office of Science laboratory, is operated under Contract No. DE-AC02-06CH11357. The U.S. Government retains for itself, and others acting on its behalf, a paid-up nonexclusive, irrevocable worldwide license in said article to reproduce, prepare derivative works, distribute copies to the public, and perform publicly and display publicly, by or on behalf of the Government. We thank Erin Lieberman (Invenergy, LLC) and Rob Davis (Fresh Energy) for photographs. We also thank C. Negri and other reviewers at Argonne National Laboratory for constructive comments on previous drafts of this paper.

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