Environmental Research Communications

OPEN ACCESS

RECEIVED
25 April 2022

REVISED
4 April 2023

ACCEPTED FOR PUBLICATION
31 May 2023

PUBLISHED
14 June 2023

PAPER

Valuation of pollination services from habitat management: a case study of utility scale solar energy facilities in the United States

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Keywords: valuation of ecosystem services, pollination, food-energy-environment nexus, sustainability

Supplementary material for this article is available online

Abstract

Creating and maintaining pollinator habitats following the ecological infrastructure concept in degraded or unutilized land, such as solar energy facilities, is a practical way to synergistically advance the food, energy, and ecology nexus. Given the large land-use requirements for solar farming—the fastest growing renewable energy technology–considerable attention has been focused on strategies to maximize multiple ecosystem services. In this study, we coupled the principles of agronomy and ecology with economics and integrated national-scale data on crops, pollinators, and solar facilities to identify locations for creating pollinator habitats and estimating the economic value of pollination from the habitats. We examined opportunities for pollination services from pollinator-friendly utility-scale solar facilities adjacent to 42 million hectares of pollination-dependent crops in the conterminous United States at high resolution of 1 ha. We used the net income method to estimate the potential economic value of creating habitat in the land adjacent to solar facilities in the eight states with the greatest number of solar installations. Creating pollinator habitats at the 217 utility-scale solar facilities in these states could support adjacent 80,000 hectares of high pollinator dependent crops, which could potentially generate a pollination value of $120 to $264 million USD. The location-specific information and high-resolution maps generated for the United States demonstrate integration of grey and green infrastructure to support the food, energy, and environment nexus.

1. Introduction

Increasing pressure on land resources for energy and food production and maintenance of ecosystem health has shifted emphasis to maximizing the joint output of multiple ecosystem services from land use. In the past, either scientists focused on the independent understanding of the decline of pollinator populations and dwindling food security [1–4], the land-use change impacts on pollinators [5–7], or they assessed the trade-off between two competing sectors such as food and energy or energy and environment [8, 9]. Earlier studies found that the decline in global pollinator populations is generally attributed to land conversion, loss of natural habitat, infestations and disease, and pesticide use [10]. However, investigation of synergistic pollinators conservation and sustainable energy development using site-specific environmental resources and related innovative technologies is limited [5]. This paper examines the potential inter-sectoral synergy from strategically created ecological infrastructure in pollinator demand-supply gap areas particularly at energy facilities.

Ecological infrastructures are small- to medium-sized natural or seminatural areas (<10 ha) that generate multiple ecosystem services benefits such as improved water quality, climate change regulation, and pollination services [1]. Pollination service is one of the regulating ecosystems services [11] of such ecological infrastructure due to the nesting and floral resources availed for foraging insect pollinators. Managing the land in between solar panels and around solar facilities to maintain natural/seminatural vegetation that supports nesting and foraging needs of insect pollinators is defined as habitats management for pollinators. The pollinators support pollination in pollinator- dependent food crops such as nuts (e.g., almonds), berries, pomes (e.g., apples), melons, vegetables (e.g., cucumbers), and oil seed (e.g., Sunflower) crops [12]. By creating pollinator habitat strategically in a landscape, higher crop yield could be achieved, and more sustainable production would be practiced [13].

Prior studies have demonstrated that the populations of both managed and native pollinators are declining; this poses a substantial threat to food security, human well-being, and the economy [1–4]. The steady decline in the number of wild and managed pollinators has put an estimated 39% of pollinator-dependent crops at risk in the United States [2]. Annual honeybee colony loss within the United States was estimated to be 29%–36% between 2006 and 2010 [9]. Declining pollinators for the past 60 years [1–3] demands an investigation of opportunities to improve their habitats. Earlier research [5–7, 12] has, theoretically and empirically, shown that the high-quality pollination habitat adjacent to cropland can safeguard pollinators and the services they provide. Strategic development of habitat such as at and around energy-generation and distribution facilities, can support the synergistic development of energy without impacting ecosystem health [14].

The contribution of pollinators to human food supply inextricably links them to human well-being [15,16]. More than 75% of global crops rely on animal pollination for yield and/or quality [17]. According to IPBES 2016 [17], while most pollinator species are wild, both the wild pollinators such as flies, butterflies, moths, wasps, beetles, thrips, birds, bats, and wild bees as well as a few species of widely manged honeybees (*Apis mellifera* and *Apis cerana*) perform pollination. Honeybees contribute to the pollination of 90% of global crop types, and recent literature highlights the important roles of other native pollinators [18, 19] in crop pollination. Bees have been credited with contributing to 11% of the U.S. agricultural gross domestic product [19]. The benefits of pollinators for commercial U.S. crops range from $12 to $74 billion (2016 U.S. dollars), with native pollinators accounting for $3 billion of the total [19, 20]. Three million honeybee colonies were used to provide pollination services for pollination-dependent crops in 2016 [21], making the U. S. the world's largest and most active market for honeybee pollination services. Unsuccessful pollinators conservation led to the loss, associated with pollinator-dependent crops that supply nutrients to humans and generate billions of dollars of revenue to farmers.

Strategically created pollinator habitats at USSEs following Blaydes *et al* [14] could address the mounting concerns of declining pollinator populations and resultant food insecurity while enhancing energy security. The management of pollinator habitats around solar facilities is receiving increasing attention as a practical solution to simultaneously address food, energy, and conservation goals [14, 22]. A major environmental concern for USSEs is the impacts of their large spatial footprints (2.5 to 4.0 ha per megawatt of nameplate capacity [23]. Prior studies [9, 24, 25] have examined the constraints that limit the rapid expansion of USSE installations, such as their impacts on land, agriculture, and biodiversity. One study [24] estimated that about 1.42 million ha of land (the size of the state of Connecticut) is needed to install five hundred gigawatts of USSEs—the amount required to reduce nationwide greenhouse gas emissions to 80% of 1990 levels by 2050. In addition, the DOE Solar Futures Study [26] estimated that for meeting the decarbonization goals for the U.S. electricity grid, more than 4 million ha (10 million acres) of land would be needed for USSE development to generate over 1 TW of solar electricity.

Solar energy is the fastest growing renewable energy technology, and it is anticipated to fulfill 14% of the U.S. electricity demand by 2030 [27]. Over the period of 2007–2017, the capacity of USSE facilities operating in the U.S. has increased approximately 60-fold [28]. Given the rise in USSE development over the past decade, there is an increasing need to understand the environmental and socioeconomic impacts of these developments and contextualize them against other forms of land use and energy production. Developing pollinator habitat at USSE sites could potentially transform their spatial footprints into locations for generating ecosystem services. Recognizing these benefits, states such as Minnesota, Maryland, and Massachusetts provide guidelines and incentives that promote the incorporation of pollinator habitat in solar sites, and they have enacted laws to support this goal [29]. Other states have followed suit, including Wisconsin, Iowa, North Dakota, and Vermont [29]. The monetary value of benefits of a pollinator habitat at energy facilities, however, have not been assessed so far.

Earlier work on the economics of pollination has primarily focussed on raising awareness of the impacts of pollination services on global [30], national [19], regional, or state-scale agriculture, valuing pollination by the total value of crops benefiting from insect pollination or the rents paid to beekeepers for pollination services [31, 32]. Earlier studies [19, 20, 33, 34] used the dependency ratio (DR) approach, which is a simple crop production function method to estimate the value of pollination. The DR is the fractional reduction in fruit set due to absence of insect pollinators. The DR approach is based on field research on the impacts of pollination services on yield, and Klein *et al* [16] has reviewed such field work. Lautenbach [35] used the DR approach to identify locations where spending on conservation would be beneficial at a global scale at a resolution of 100 km^2. However, the DR approach leads to inflated values for pollination services because the variable costs of

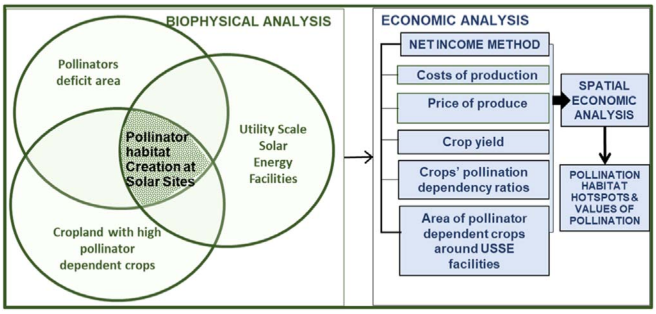

Figure 1. Integrated assessment framework.

production is not in the calculation [36–38]. For the detailed discussion on the biases in estimated value of pollination associated with DR approach, please refer Winfree *et al* [39]. Allsopp [40] and the U.S. Department of Agriculture (USDA) [21] used the replacement cost approach, which uses the costs of renting the pollinators as the proxy for the value of pollination services. Winfree [39] combined various approaches, developed a net income method that is free from biases of the DR approach, and used it for the valuation of pollination for watermelon crops in New Jersey and Pennsylvania. Earlier studies [41–43] used spatially explicit ecosystem services modelling of crop pollination. We did not find any prior work that evaluated the pollination benefits from habitat created at each solar energy facilities across the conterminous U.S. at a high spatial granularity. A spatially explicit approach to estimate site specific value of pollination from creating pollinator habitat applicable for a national scale assessment is clearly a gap that needs to be addressed.

The purpose of this paper is to develop a framework and to generate spatially explicit information on the strategic placement of ecological infrastructure (or pollinator habitat management) at energy facilities for pollinator conservation. We developed an integrated assessment framework that couples ecological, economic, and spatial analysis to identify the areas that can benefit from pollinator habitat management across the U.S. Our demonstration of the framework is applied to utility-scale solar energy (USSE) facilities. This framework builds upon previous research [44] that examined the potential interactions between USSEs and pollinator-dependent crops that could benefit from pollinator habitat restoration at USSE facilities at the state level. We used the framework to estimate the economic value of creating pollinator habitats at USSEs in areas with pollinator-supply and demand gaps. We generated spatially explicit information for: (a) the distribution and pollination DR of major crops that depend on insects for more than 10% of their pollination; (b) the location that could benefit from pollinator habitat management, including around USSE sites; and (c) the potential value of pollination from creating habitat at USSEs sites. Our findings using this approach demonstrate the integration of grey and green infrastructure to support the food, energy, and ecology nexus.

2. Methods

The integrated assessment framework includes biophysical and economic aspects of the system [38, 39]. The biophysical analysis component includes agronomic, ecological, and geospatial analyses to characterize [1] the spatial distribution of pollinator-dependent U.S. crops, [2] levels of pollinator abundance in areas adjacent to the pollinator-dependent crops area, and [3] locations of existing USSEs near a low pollinator abundance area and pollinator dependent crops (figure 1). We coupled the spatial analysis with the net income method developed by Winfree *et al* [39] to estimate the economic value of pollination from creating habitat at the USSE facilities. The net income method uses the avoided loss in value of crop production attributed to pollination and the changes in the variable costs of production to estimate the value of pollination. The detail on the net income method follows (section 2.3).

2.1. Data sources

We collected data on agronomic, ecological, and economic variables that were available at various spatial scales (for e.g., 30 m × 30 m, at county, state, and regional scales) for the U.S. The database includes geospatial data as well as market-based information. The croplands data and land-use data were raster data available at 30 m × 30 m resolution obtained from the USDA's National Agricultural Statistical Service [45]. Although we used the best data available for a large-scale study at the given spatial granularity, the maps generated are subject to inaccuracies due to the misclassification errors of Landsat imagery; these errors ranged from 2% to 14% in some crops [46]. We corrected the data on crop area for these errors prior to their use in further analyses. We collected pollination dependency ratio data through a review of literature [16, 47, 48] and used the most up-to-date DR values for the analyses.

We collected data and information on yield and price for each crop from 2012 through 2016 from the USDA [49]. Data for these variables are available at state level and variable costs of crops production for each state from Land Grant university websites (supplementary material). We use the variable costs data from adjacent states or national averages for the crops, where state-specific variable costs of crop production were not available.

We assigned each pixel (30 m × 30 m) of the pollinator-dependent crops in the cropland data layer with their respective dependency ratios, yield, price, and variable costs of production using the ArcGIS platform for the spatial economic analysis.

2.2. Spatial analysis of biophysical characteristics of pollinators and habitat management opportunities

2.2.1. Pollinator-dependent crops in the United States

Pollination-dependent food crops include nuts (e.g., almonds), berries, pomes (e.g., apples), melons, vegetables (e.g., cucumber), and oilseed (e.g., Sunflower) crops in the U.S. Two data sets were used to map the spatial distribution of crops with varying ratios of pollination dependency across the U.S.: [1] data on crops that depend upon insect pollination and their levels of dependence on pollinators (figure S1) [16, 47, 48], and [2] spatial information on crops from the USDA Crop Land Data Layer [45]. The pollination dependency of crops, or the percentage loss of crops in the absence of pollinators, can be categorized into the following four categories [16]: essential (production reduction by ⩾91% without animal pollinators), great (production reduction by 41%–90% without animal pollinators), modest (production reduction by 10%–40% without animal pollinators), and little (⩽ 9% reduction without pollinators). The remaining (per cent) crop pollination, for each category, occurs via means other than animal pollinators, such as air or water. The cropland data layer is the raster data of 30 m resolution were used in further analyses. Using the cropland data layer data on crop distribution at 30 m grids and the respective DRs, we prepared a map (shape files) of pollinator-dependent crops in ArcGIS.

2.2.2. Pollinator supply-demand discrepancy (PSDD) area

Notte *et al*, [13] introduced the concept of ecosystem service unmet demand by showing how creating pollinator habitats in areas where there is a mismatch between pollination supply and demand can benefit crop production. Here we call them pollinator supply demand discrepancy (PSDD) areas, which must meet these criteria: [1] the pollinator population abundance (or supply) is low, and [2] demand for pollination services is high.

2.2.2.1. Pollinator supply

We used information on bee abundance in the U.S. [3, 50] as the measure of pollinator supply. Koh *et al* [3] used nesting suitability (ground, cavity, stem, and wood for nesting guild) and floral resource availability for 3 major foraging seasons (spring, summer, and fall) for forty-five representative land-cover types (32 crops and 13 non crops) data to parameterize 4 different bee nesting guilds using experts' estimates. The authors [3] predicted the wild bee abundance index using the probability distributions for nesting suitability and floral resources as the input parameters in the Lonsdorf model [49] and validated the model results using field data of wild bee abundance. Pollinator abundance ranges from 0 to 0.4 for the U.S. [3], where 0.21 to 0.4 are high abundance areas such as chaparral and desert shrublands, forests, grasslands and rangelands, and low abundance area (< 0.2) were mostly agricultural land. We used the low-pollinator-abundance areas as pollinators supply deficit area in our further analyses (figure 2(B)).

Pollinator demand: We follow Notte [13] for quantifying the demand for crop pollination as the extent of high pollinator-dependent crops. We used the top three categories of pollination-dependent crops, the crops losing more than 10% of their yield without pollinators from the map of pollinator-dependent crops for the PSDD map (figure 2(C)).

2.2.2.2. PSDD area

We used ArcGIS to process the raster images (maps) to identify the PSDD area as the location where the high-pollination-dependent crops area intersects the low pollinator abundance area. Creating pollinator habitat in such PSDD area increase pollinator population and as a result the pollination services increases. By filling in the PSDD landscape with pollinator habitat(s), higher crop yield would be practiced. Pollination benefits to crops from a pollinator habitat are local because most pollinator species have limited foraging distances. Several studies [3, 6, 51] have found an average foraging distance for pollinators as 0.67 to 3.0 km. We use the distance up to 3.0 km around pollinator habitats as the area receiving pollination services in the PSDD area in our analysis.

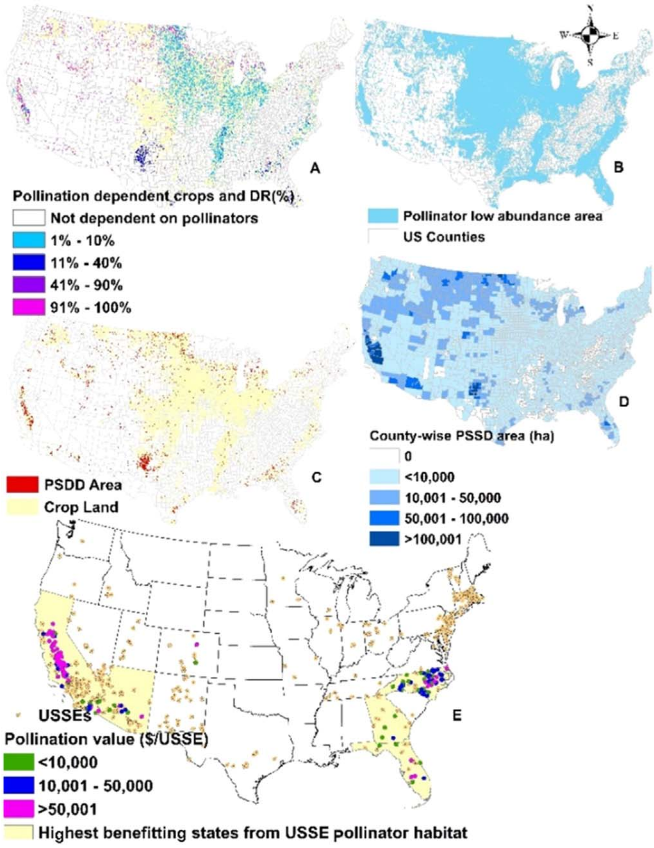

Figure 2. (A). Pollinator- dependent crops in the United States and their dependency ratio (DR)s. (B). Low-pollinator-abundance area in the United States. (C). Pollinator supply demand discrepancy (PSDD) areas in the United States. (D). Counties with different concentrations of PSDD area. (E). Estimated potential average annual pollination value per USSE facility by creating pollinator habitats at USSE facilities.

2.2.3. Identifying potential USSEs sites for creating pollinator habitat

We used the PSDD map and data on USSE sites to identify the locations for creating pollinator habitat at USSE facilities. We collected the USSE locations and nameplate capacities data (1986–2016) from the U.S. Energy Information Administration (EIA) [52]. For our analysis, we created a circular buffer zone around each USSE based on the area of the USSE and foraging distance of pollinators 1.5 to 3.0 km. We calculated the area of pollinator dependent crops in PSDD area within the buffer zone of each USSE facility using ArcGIS. We assigned each parcel of each crop in each USSE the yield, price, variable costs for the crop in the location and their respective dependency ratios using spatial join function in ArcGIS platform. We estimated the value of pollination for each parcel of 1 ha and aggregated for each USSE site using the pollination services valuation method in ArcGIS platform. Our analysis is limited to the estimation of value of pollination from creating the habitat at USSEs as compared to the land/vegetation management under current practice. Assessment of prior land use and associated environmental impacts are outside of the scope of this paper.

2.3. Pollination services valuation method

The value of ecosystem services provided by insect pollinators includes both market and nonmarket value. The nonmarket value of pollinators includes the existence value of pollinators and the use value, such as the utility derived from seeing pollinators or simply from knowing their existence. This paper focuses on the market value of pollination as the first step in demonstrating the framework for identification of USSEs for creating pollinator habitat. We estimated the market value of pollinators as the incremental value of the crops due to change in quantity and quality of crop produced attributed to pollination services.

We applied the net income method following Winfree *et al* [39]. The estimate of the potential value of pollination from a habitat created at a solar facility is:

$$V_{\Delta pol} = \sum_{i=1}^{I} (P_i * Y_i - VC_i)(D_i * A_{ij})$$

$$\text{S.T. } A_{ij} \leqslant \pi r_j^2$$

where P_i is the price of crop i;Y_i is the yield; A_{ij} is the area around of crop i within a foraging distance of the habitat created at the USSE site j; VC_i is the variable cost of production of crop i; and D_i is the pollinator dependence of crop i.

While the principle of net income method remains intact in our approach by including the variable cost in the equation, we modified the method to accommodate the estimation of the value for the pollination from creating habitat at USSEs. We used an average foraging distance (r) for pollinators of 1.5 to 3.0 km [3, 6, 51] to construct a buffer area (πr_j^2) around the potential habitat development site at each USSE. The buffer is a constraint in the net income method that limits the area for the foraging from the habitat created by the USSE and we used only the high pollinator dependent crops i within the area for calculation. Although insect pollinators can travel much farther than 3.0 km, our estimates are conservative, assuming the concentrated visits by pollinators are within 3.0 km of their colony based on [51]. We calculated the number of hectares of pollinator dependent crop i within 3.0 km that could potentially benefit from the pollinator habitat. We used the equation to calculate the value of pollination for each pollinator dependent crop in the buffer area delineated for each USSE site and aggregated the values as the potential value of pollination due to creating habitat at that USSE. The method developed here provides a flexibility to aggregate the value of pollination estimated at grid level to county, state, and national scales as well as for the number of crops of interest.

The USSE sites located within the PSDD regions are the only facilities where development of pollinator habitat and/or management of honeybees can create additional pollination benefits. We did not calculate the value of pollination by habitats created at USSE sites at pollinator-abundant (non PSDD) areas because (a) the method is much more complex and requires field level data, and (b) the additional value of pollination from new habitat in already pollinator-abundant areas may not be significant. Hence, we identified USSE sites located at PSDD areas (the pollinator-scarce area with high demand for pollinators) and estimated the value of pollination at those sites only.

In addition to pollination ecosystem services, the pollinator habitats created at USSEs can provide additional ecosystem services such as climate regulation and water regulation as defined by MEA report [11]. The ecological infrastructure created by growing native grasses and wildflowers captures carbon dioxide from atmosphere and sequesters in soil that supports climate regulation [53]. Similarly, the vegetation retains the sediments and nutrients thereby regulating downstream water quality [54]. While a comprehensive assessment of each of these ecosystem services would provide a holistic picture, such assessment is outside of the scope of this work. Creating pollinator habitat at additional USSE sites may become economically attractive by evaluating and aggregating other ecosystem services, such as the values of climate and water regulation into the total benefit of such habitats. This work is the first step in developing a framework and assessing one of the benefits i.e., value of pollution from creating pollinator habitat/ecological infrastructure at one type of energy sites i.e., USSEs.

3. Results

3.1. Pollinator habitat development opportunities

We identified pollinator-dependent crops across the United States. Of the major U.S. crops, 16 were ⩾90% dependent on insect pollination; 19 were 40%–90% dependent; and 12 were 10%–40% dependent. Crops that lose >40% of their production without insect pollination will benefit significantly from increased pollinator populations. These crops include macadamia, kiwifruit, almonds, apples, apricots, nectarines, peaches, plums, cherries, avocados, berries, cucumbers, squash, melons, and pumpkins (figure S1). Among the selected crops, grapes, citrus, peanuts, beans, and sugar beets lose less than 10% of production; however, the large area used for these crops may accrue higher pollination benefits at some locations. The pollination-dependency analysis shows that in the Midwest, crops with less than 10% or greater than 90% dependency on insect pollinators are prevalent (figure 2(A)). However, patches of crops in Texas are 10%–40% pollinator dependent. On the west coast, high-pollination-dependent crops are concentrated in the Central Valley of California.

We mapped areas with low pollinator abundance and identified PSDDs. Low-pollinator-abundance areas in the U.S. are concentrated in the cropland areas in the Midwest, Florida, the eastern half of Georgia, North Carolina, and South Carolina, and Central Valley of California (figure 2(B)). We identified about 15 million ha of area as PSDD area, where the economic benefit of developing pollinator habitat could be the highest (figure 2(C)). Of about 1,400 counties identified to have more than 1,000 ha of PSDDs, 426 counties have more than 10,000 ha. The twenty counties with the largest amount of PSDD land (80,000 to 180,000 ha) are in California, North Dakota, and Texas. The states of Texas, Montana, North Dakota, Wisconsin, Idaho, Georgia, Minnesota, California, and Michigan have twenty or more counties with more than 10,000 ha under PSDD (figure 2(D)). About twenty-nine states have more than 100,000 ha of PSDD area each (table S2). While the smaller patches of PSDD areas are distributed throughout other states, concentrated patches exist in the Central

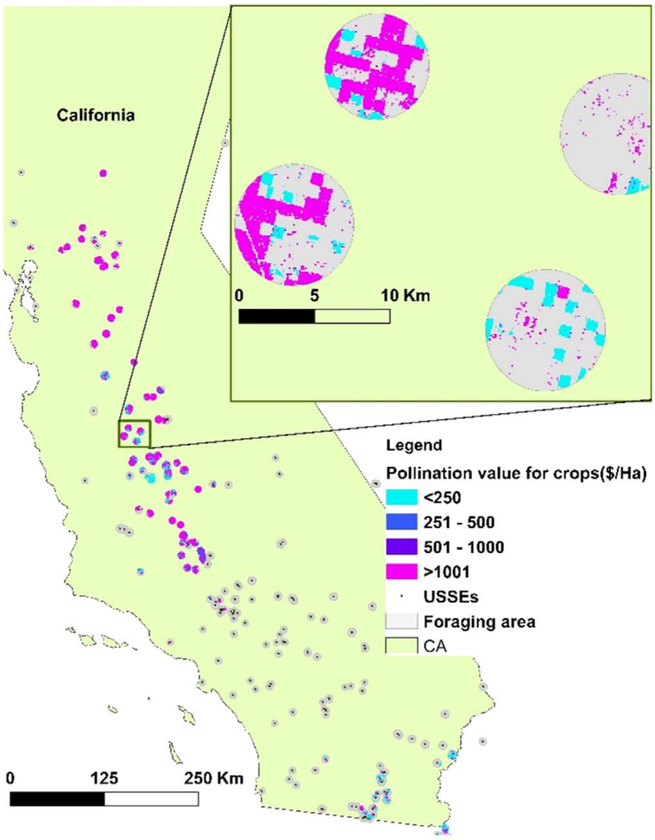

Figure 3. USSE facilities, mapped foraging areas around the potential habitat at USSE facilities, and the value of pollination services ($/ha of pollinator dependent crops) at the foraging areas in central and southern California [Box shows magnified buffer zones around USSE facilities and pollination value per ha. The crops with low or no pollination benefits are eliminated from the calculation of foraging areas around USSE facilities].

Valley area of California, north-western Texas, central Florida, south-western Georgia, north-eastern North Carolina, the Dakotas, Minnesota, Wisconsin, Michigan, and along the lower Mississippi River. Although the management of pollinator habitat adjacent to areas with low pollinator abundance is necessary to maintain the ecosystem, habitat management close to the PSDD patches could lead to higher benefits for crops.

3.2. Value of pollination from pollinator habitat at USSE facilities

The estimated land area covered by USSEs in the United States is nearly 113,800 ha (table S3). The top eight states of California, North Carolina, Arizona, Nevada, Georgia, Texas, Utah, and Florida share 84% of the total solar capacity of the United States (table S3). We dropped many USSEs from our analysis for potential pollinator-habitat development sites because either they were too far away from pollinator-dependent cropland or pollinator abundance is high within the facilities' pollination buffer zones. We identified 217 solar facilities that could potentially benefit the cropland in the vicinity.

The potential value of pollination services provided to high-pollination-dependent croplands around the selected 217 USSEs is aggregated and ranges from $120—$264 million (table S4). The USSEs with the potential to benefit the adjacent croplands from creating habitats at the sites are in figure 2(E). Specific crops are identified that could benefit from the siting of USSEs. We found that the total potential benefit of pollinator habitat management at USSEs is the highest for almonds, walnuts, melons, Sunflower, and pears. The value of pollination services is the highest for the states of California, Arizona, North Carolina, Florida, and Georgia. For illustration, we created a map for the state of California (figure 3) that illustrates the foraging buffer area around USSE sites and potential value of pollination services for crops within the buffer area.

4. Discussion and conclusions

Strategically placed ecological infrastructures over the agricultural landscape support and increase pollinators and provide ecosystem services [1, 55, 56]. Plots of land in and around energy infrastructure, such as USSEs and right-of-way corridors, in the vicinity of arable land could potentially be used to create ecological infrastructure capable of generating multiple ecosystem services, including pollination services as well as water regulation and climate regulation. The increasing growth rate of USSEs may further exacerbate the competition between land for solar energy generation and land for food production [52, 57, 58]. Whereas, creating ecological infrastructure at USSEs could provide habitat, nesting and floral resources to bees that increase pollinator population[14] and pollination services, reduce soil degradation, and support the sustainability of the food, energy, and environment nexus. This work demonstrates a framework and analysis to support improvements in food, energy, and conservation through the management of ecological infrastructure at various energy facilities such as USSEs.

We examined opportunities for habitat management at existing USSEs facilities of the United States, coupling economic analysis with agronomic, ecological, and geospatial analyses in an integrated assessment framework. We evaluated the pollination services provided when pollinator habitats are created at USSE facilities and the USSE facilities are sited in agricultural landscapes with PSDD. The total value of pollination services provided to 80,000 ha cropland adjacent to 217 USSE facilities within the PSDD regions ranged from $120 to $264 million/year. Previous work identified more than 350,000 ha of agriculture near existing and planned USSE facilities that may benefit from increased pollination services through the establishment of pollinator habitat at USSEs [44]. Our analysis does not include all the existing USSE facilities; we had to drop the USSEs from our analysis as potential pollinator-habitat development sites, which were either far away from the pollinator-dependent cropland or pollinator abundance was high within the facilities' pollination buffer zones. DOE Solar Futures Study [26] estimated that to meet decarbonization goals for the U.S. electricity grid, more than 4 million ha (10 million acres) of land would be needed for USSE development to generate over 1 TW of solar electricity. Consideration of habitat management in USSE facilities could make significant contributions towards conservation of pollinators.

Understanding the value of pollination, costs of habitat management, and associated trade-offs can support dialogue between the solar industry and nearby agricultural landowners to optimize environmental co-benefits of energy and food production. There are costs associated with creating pollinator habitat and/or managing honeybees at solar installation sites. It is known that the solar industry incurs costs for vegetation management such as turf management. On the other hand, farmers paid $140 to $351 per acre in 2016 for leasing managed bees for pollination services for alfalfa, blueberries, raspberries, cranberries, oranges, avocados, almonds, and kiwis [21]. Farmers spend $280 million to pollinate 393,000 ha of almonds [21]. Pollination services to 10% of the state's almond crop can be provided by strategic placement of pollinator habitat at USSE facilities in California. Detailed benefit cost analyses of pollinator habitat can be useful in initiating dialogues on 'possibilities for creating pollinator habitat locally' with the stakeholders including the solar developers as well as the farmers. This paper's focus is to develop a framework for estimation of benefits and calculating the value of pollination attributed to each habitat site. Such information on benefit cost analysis could be useful to safeguard pollination services, should exogenous factors such as COVID-19 disturb the transportation of pollinators from other parts of the country to California.

Some caveats in this study are worth noting. The scope of the study is limited to estimating the potential value of pollination to support the value proposition for integrating green and grey infrastructure and we illustrated that using pollinator habitat management at USSE facilities. Such ecological infrastructure generates other ecosystem services such as water regulation and climate regulation in addition to pollination services and the scope of this paper is limited to the assessment of pollination services. Estimation of all the ecosystem service stock and ecosystem service flow would provide the total monetary value of such ecological infrastructure. The assessment of one ecosystem flow—the pollination services—remains an underestimation of the total monetary benefits from the ecological infrastructure. There are either the vegetation management costs at solar facilities such as mowing once or twice a month or pollinator habitat creation costs. The vegetation management costs vary depending upon the initial land use condition, method for vegetation management, and other site specific characteristics. For example artificial turf material is $60/m^2 [59], vegetation mowing and management is $961/acre [60], gravel installation cost (100 ft X 40 ft strip with 10 inches gravel cost $3000 [61]. According to Xerces Society's bee habitat cost estimator [62], habitat creation for bees with native flowering plants around the year cost $9 to $91/acre depending upon the location, irrigation need, and initial condition of the site. However, the costs are not subtracted in our analysis; the benefits calculated here is the total revenue and not the net profit. A detailed benefit - cost analysis of the site-specific USSE facility pollinator habitat management should be conducted in subsequent studies to determine the payoff of switching current vegetation management to create pollinator habitat. Thus, this study looks at the societal revenue rather than the benefit costs analysis of a USSE site. Additionally, we were unable to estimate the value of crops, including avocado, macadamia, pecan, kiwi, and some berries, which are important economically as well as from pollinator benefits standpoints. There is a lack of information about these crops such as their updated pollinator DRs, information on variable costs of production, and missing cropland classification in the USDA NASS CDL. These issues made it difficult to estimate the value of pollination services for these crops.

We used high - resolution spatial data on high-pollination-dependent crops, pollinator abundance, and existing USSEs with the economic valuation to identify and quantify potential pollination benefits. The framework developed in this study can support identifying hotspots for creating pollinator habitats around other energy generation and distribution sites, including wind farms and right-of-way corridors for estimating the economic value of pollination services. Furthermore, this framework paves the way toward valuation of pollination services at high resolution.

A sustainable landscape requires the coexistence of food, energy, and biodiversity [63] While turning scientific knowledge into action remains a fundamental challenge at the local to the global scale [64], information on the economic benefits provided by solar pollinator habitat may foster dialogues toward thoughtful placement of habitat at USSEs located at PSDD area. This study contributes to finding innovative ways of creating green ecological infrastructure around various grey infrastructure projects to support sustainable and resilient landscapes.

Acknowledgments

Funding

This work is supported by the U.S. Department of Energy Solar Energy Technologies Office under Contract No. DE-AC02-06CH11357. Sandia National Laboratories and Argonne National Laboratory created the manuscript. Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.

Author contributions

SKM designed the research. SKM and MZ collected and analysed data. All authors contributed to preparing the manuscript. We are extremely grateful to the two anonymous reviewers, whose comments helped significantly in improving this work.

Data availability statement

All data, code, and materials used in the analysis will be made available for researchers upon request for their purposes of reproducing or extending the analysis. The data that support the findings of this study are obtained from publicly available data sources such as https://doi.org/EIA: https://www.eia.gov/electricity/data/eia860/ and CropScape: https://nassgeodata.gmu.edu/CropScape/.

Competing interests

Authors declare no competing interests.

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