Current Opinion in Insect Science

A stitch in time: integrating energy infrastructure into the fabric of conservation habitats

--Manuscript Draft--

Short Title:	Energy infrastructure as conservation habitat
Keywords:	pollinators; insect conservation; habitat; energy; solar farm
Corresponding Author:	Adam Dolezal University of Illinois Urbana-Champaign UNITED STATES
Corresponding Author's Institution:	University of Illinois Urbana-Champaign
Corresponding Author E-Mail:	adolezal@illinois.edu
First Author:	Tristan A. Barley
Order of Authors:	Tristan A. Barley
	Hollie Blaydes
	Adam Dolezal
Abstract:	Insect communities are declining globally as a result of multiple, interacting drivers, including habitat loss due to agricultural intensification and urbanization. Biodiversity losses necessitate immediate conservation efforts, including the creation of new habitats, but it can be challenging to find suitable spaces in which to implement such mitigation actions. However, energy infrastructure, including solar farms and rights-of-way, presents opportunities to enhance insect conservation efforts by adding to the existing patchwork of habitats across working landscapes. While research has already demonstrated the potential for new habitats in homogenous, resource-poor landscapes, pairing these habitats with energy infrastructure has not been fully explored or utilized, although the evidence base is growing. Here, we examine the challenges of finding opportunities to establish insect habitats in working landscapes, discuss the potential for energy infrastructure as spaces for habitats, and propose solutions to move this potential new means of insect conservation forward.
Author Comments:	

ILLINOIS

COLLEGE OF LIBERAL ARTS & SCIENCES

Department of Entomology
320 Morrill Hall, MC-118
505 S. Goodwin Ave.
Urbana, IL 61801-3750

February 13, 2025

Dear Editors,

On behalf of my co-authors, I am pleased to resubmit our revised manuscript "**A stitch in time: integrating energy infrastructure into the fabric of conservation habitats**" for consideration in *Current Opinion in Insect Science*.

We sincerely appreciate the comments from both reviewers. As documented in our "response to reviewers" document, we have addressed the majority of these revisions by making changes as suggested, resulting in an improved manuscript.

Thank you for your consideration.

Sincerely yours,

Adam G. Dolezal
Assistant Professor
Department of Entomology
College of Liberal Arts and Sciences Administration
University of Illinois at Urbana-Champaign
505 S Goodwin Ave
320 Morrill Hall | M/C 118
Urbana, IL 61801
217.300.6762 | adolezal@illinois.edu

COINSCI-D-24-00091: Response to reviewers

We thank the reviewers for taking the time to review the manuscript and for providing constructive comments. They have helped us to enrich the manuscript, and we have addressed their feedback. Below, we provide responses to the editor's and each of the reviewers' comments. For ease, the comments are in standard type and our responses are in italics.

Best wishes,

The authors

Editor

1. P7L6: replace 'it is monitor' with 'monitoring'

   We have made this change.

2. P8L59: insert 'infrastructure development' after 'energy'.

   We have made this change.

Reviewer 1

1. "Rapid development of this industry necessitates swift action to leverage this growth": consider rephrasing to not include "this" twice in one sentence.

   We thank the reviewer for this suggestion and have reworded this sentence to read "Rapid development of this industry necessitates swift action to leverage growth".

2. "Success will require planning, monitoring, and communication": While I know space is limiting in this section, add descriptive words for each verb would be helpful (e.g. site-specific planning, plant and pollinator monitoring, and open communication)

   We have made these changes.

3. I really appreciate that the authors included examples of the impacts of land use change on pollinators not only from North America and Europe, but also Africa, Asia, and South America in the introduction! Nonetheless, I believe that the authors could broaden the phrasing/restructure some of the sentences from P1L16-27 so that these examples don't seem like a laundry list but instead encapsulate the broader patterns (for example, provide phrasing that broadly encapsulates patterns across continents, as all of the examples provided are not unique to any given continent, while citing all the sources currently provided).

We have taken the reviewer's feedback on board and have restructured the suggested sentences to provide more detail: "Similar drivers of insect decline have been reported in South America, where deforestation and agricultural expansion (in combination with other factors), are likely to have led to reductions in populations [24]. The loss and fragmentation of habitats has also affected insects in Africa, with impacts on species diversity and assemblages reported [25]."

4. P1L41 briefly mention what CRP is before describing what it can accomplish, similar to what you have for B-lines after.
   We thank the reviewer for this suggestion and now include additional details about CRP land: "The CRP pays farmers to remove environmentally sensitive land from agricultural production and manage it in a way that improves environmental health, which can also benefit insects." We have also restructured the Introduction to better highlight examples of practices undertaken through the CRP.

5. P2L11 can you rephrase "grow and decline over time" to some other phrasing that better describes temporal patterns of governmental programs (e.g. how they vary in duration and how the uncertainty associated with how long they will be around can make long term conservation planning/management challenging)
   We have amended this section, which now reads: "Whilst it is encouraging that initiatives exist to increase the amount, quality and connectedness of insect habitat within working landscapes and beyond, such programs can have their limits. For example, there is often uncertainty around the duration of schemes, which can make long term conservation planning and management challenging."

6. After mentioning enrollment can you specify whether funding available through CRP stayed constant or was similarly reduced (and thus may have been the cause)?
   We have specified that the 2008 and 2014 Farm Bills reduced the CRP enrollment cap, leading to the declines in CRP across the US.

7. P2L20 you had used the term "novel systems" at the end of the previous sentence, consider rephrasing
   We thank the reviewer for this suggestion and have reworded this section, so that "novel systems" is not repeated.

8. Header "Solar infrastructure and ROW as insect habitat": have not yet defined rights of way. Replace with "Solar infrastructure and Rights Of Way as insect habitat"
We have made this change.

9. P2L58 before moving to ROW, can you give a few examples of habitat creation in solar facilities not from Europe and US (i.e. from Asia, Africa, and/or Latin America)?
As far as we are aware, there are no examples of habitat creation within solar facilities outside of Europe or the US. However, we now state this is the manuscript and include an example of solar infrastructure providing a microclimatic refuge for insects in Chile: "As far as we know, there are currently few studies that focus on insect response to solar developments in other continents, such as Asia or Africa, but one study from Chile indicates that shaded conditions provided by solar farm infrastructure could provide a refuge for insects."

10. P4L5 Replace "it is monitor" to "monitoring"
We have made this change.

11. P4L7 incur a cost or incur costs
We have made this change.

12. Figure 1. A few modifications would strengthen this figure. It is unclear what the symbol of the sun with the hands of the clock represents. Reading the figure caption, I gather it must be the limited window of time, but I don't think this clearly comes across. A change may be appropriate (i.e. either removing entirely, or using a sand timer that better expresses limited time). Adding one more level in the gradient of conventional management to habitat co-creation would strengthen this figure: on the left could be from no grass and no pollinators (a new section), then the small amounts of grass in the current section to the left (which would now be in the center) with a few icons of honey bees, and finally on the right the habitat co creation with multiple species of plants with icons of multiple species of bees, flies, and butterflies. It will be important also to raise the panels and/or lower the height of the vegetation as this would appear to be shading the panels, which is a problem that site operators have to deal with. Because "monitoring" is such a broad term can you specify monitoring of plant establishment and insect diversity or whatever you want to emphasize?
We thank the reviewer for these suggestions and have amended Figure 1 in response. Specifically, we have: (i) removed the sun with the hands, (ii) added another level of management in between

conventional management and insect habitat co-location, (iii) lowered the height of vegetation so it is no longer shading the panels and (iv) amended the accompanying text within the Figure. We hope these edits make the Figure clearer.

Reviewer 2

1. I think that the title does not really match the content. In general, I like puns in paper titles, but as a non-native English speaker this can also be challenging. Here, I do not really get the "A stich in time" part of the title. Perhaps more importantly, I think that the second part of the title, specifically "the fabric of conservation habitats" a bit misleading. Sure, the authors discuss how habitat creation in solar energy park san d rights-of-way complement conservation in other parts of the landscape, but my expectation of the paper when only reading the title was that the focus would be on landscape linkages and habitat connectivity.

While we appreciate the concern of the reviewer, we have chosen to retain our original title, as we feel it does evoke the appropriate metaphor. If this falls outside of the journal's guidelines, we are happy to reconsider.

2. I found that the strength of the paper was the recommendations for monitoring habitats and biodiversity. The paragraph on "Habitat creation and management" was a bit weak and disappointing. I had expected more specific recommendations here. On the other hand, there are other recent review papers that make such recommendations. I was missing two recent reviews: Sturchio & Knapp. 2023: https://doi.org/10.1038/s41559-023-02174-x Gómes-Catasus et al. 2024. https://doi.org/10.1111/conl.13025 I believe that the "Habitat creation and management" paragraph could be strengthened by relating to these two (and other) reviews.
   We thank the reviewer for this suggestion and have included some examples of specific management actions in the "Habitat creation and management" section: "Recommendations include providing foraging and reproductive resources for insects within solar farms, which can be achieved by sowing or encouraging nectar and pollen rich plant species or increasing the diversity of habitats within the site [44, 63]. This can be achieved through considered habitat management, such as grazing or cutting at low intensity and late in the season, rotational management of habitats (i.e. leaving areas uncut to create diversity in vegetation structure) and minimizing the use of agrochemicals [44, 63]. At present, published recommendations focus on habitat creation and management in temperate ecosystems, so consideration may be required if being adapted to

other ecosystem types.". We have also made sure to cite the literature suggested and have expanded on how solar farm design could be used as a tool: "Solar farm design options can vary depending on the type of panels used, the configuration of arrays (e.g. north-south or east-west facing), whether the panels move (e.g. fixed axis panel arrays or tracking arrays), spacing between panels and other factors, which are likely to influence habitats within the site. However, habitat creation and management could be considered during solar farm design and be used as a tool to restore, maintain and enhance habitats, with implications for insects [59]. For example, spacing of panel rows could be adjusted depending on target levels of shading, which can impact plant [60] and insects [61] within these developments."

3. I believe that the use of acronyms (like ROW, AES, BLM, CRP etc.) should be kept at a minimum. Most of them are mentioned just once or a few times, and do not add anything to the readability of the text.

   We have made efforts to significantly reduce the use of acronyms throughout the manuscript.

A stitch in time: integrating energy infrastructure into the fabric of conservation habitats

Authors: Tristan A. Barley[a], Hollie Blaydes[b], Adam G. Dolezal[a*]

[a]University of Illinois, Department of Entomology, Urbana, Illinois, United States

[b]Lancaster University, Lancaster Environment Centre, Lancaster, United Kingdom

[*]Corresponding Author

Abstract

Insect communities are declining globally as a result of multiple, interacting drivers, including habitat loss due to agricultural intensification and urbanization. Biodiversity losses necessitate immediate conservation efforts, including the creation of new habitats, but it can be challenging to find suitable spaces in which to implement such mitigation actions. However, energy infrastructure, including solar farms and rights-of-way, presents opportunities to enhance insect conservation efforts by adding to the existing patchwork of habitats across working landscapes. While research has already demonstrated the potential for new habitats in homogenous, resource-poor landscapes, pairing these habitats with energy infrastructure has not been fully explored or utilized, although the evidence base is growing. Here, we examine the challenges of finding opportunities to establish insect habitats in working landscapes, discuss the potential for energy infrastructure as spaces for habitats, and propose solutions to move this potential new means of insect conservation forward.

Highlights

- Energy infrastructure could provide opportunities for insect conservation habitat
- Rapid development of this industry necessitates swift action to leverage growth
- We can fold existing knowledge of conservation practices into this novel system
- Success will require site-specific planning, plant and pollinator monitoring, and open communication

Introduction

Insect losses are a global concern, with abundance decreasing by 1-2% each year and many species facing extinction [1]. Declines in insect biodiversity are driven by multiple, interacting factors [2, 3], but a common challenge across regions is loss of habitat [4]. While public and scientific interest in habitat loss has focused on pollinators like honey bees [5, 6], bumble bees [7], and butterflies [8], declines in many insect taxa have been documented [9, 10] across many different ecosystems [11, 12*]. The causes and effects of habitat loss can vary by region, but reduction in habitat presence or quality are often linked to agricultural intensification [13, 14, 15], which can result in landscape simplification and reduced resource availability [16]. For example, in areas of the United States where native insect habitat has been replaced by agriculture [16, 17], and urban development [18], many pollinating insects have been reduced or extirpated [19, 20]. Agricultural change presents similar effects in Europe, negatively affecting specialist species which are dependent upon diverse habitats [21]. In Australia, habitat loss and fragmentation are compounded by the introduction of invasive weeds, resulting in a loss in food resources for native insect species [22]. Habitat loss is also affecting insects in Asia, for example, some migratory insect species that are beneficial to agricultural production have been found to be declining in northeastern China, potentially due to a loss of habitat in the region [23]. Similar drivers of insect decline have been reported in South America, where deforestation and agricultural expansion (in combination with other factors), are likely to have led to reductions in populations [24]. The loss and fragmentation of habitats has also affected insects in Africa, with impacts on species diversity and assemblages reported [25].

To address these challenges, multiple approaches have been developed to increase habitat availability, and many are practiced in working landscapes (i.e. those managed predominantly for human uses such as agriculture or forestry), which can present few opportunities for insect conservation. However, even in intensively managed landscapes, high quality habitat can be created to offset insect declines. For example, native habitat spaces can increase the abundance of local pollinators [26] and predaceous beetles [27], while habitat restorations can lead to similar communities as those found in remnant habitats [28]. Given these benefits, programs that encourage the creation of new habitat, such as the United States Department of Agriculture's Conservation Reserve Program (CRP), can be potent tools of insect conservation. The CRP pays farmers to remove environmentally sensitive land from agricultural production and manage it in a way that improves environmental health, which can also benefit insects. CRP land is vital in diversifying United States' landscapes, reducing soil erosion, and increasing regional diversities [29]. For example, CP43 "Prairie Strips" places strips of prairie habitat strategically within corn and soybean fields [30], which can increase the diversity and abundance of beneficial insects [26, 27] and provide refugia from pesticides for pollinators [31]. Similar initiatives exist in the Europe, where governmental support is provided through agri-environment schemes [32] and initiatives also exist that focus on increasing habitat connectivity for insects at a national scale. For example, in the United Kingdom, B-Lines (strips of flower-rich habitat used to connect larger habitat patches) aim to connect important insect habitats across the country [33].

Whilst it is encouraging that initiatives exist to increase the amount, quality and connectedness of insect habitat within working landscapes and beyond, such programs can have their limits. For example, there is often uncertainty around the duration of schemes, which can make long term conservation planning and management challenging. The amount of funding available for such schemes can also change over time and this has been the case for CRP land in the United States. Participation in CRP peaked in 2006 but has dropped precipitously since the Farm Bill reduced the enrollment cap in 2008 and 2014, declining approximately 38% from ~15M to ~9M hectares [17, 34, 35]. So, while publicly funded programs can help to address insect losses in these agriculturally dominated areas, finding more land and funds to deploy these practices remains difficult. We therefore argue that one of the major barriers to facilitating insect conservation in working landscapes is not a lack of knowledge, but rather the implementation of practices.

Meeting conservations goals may require new initiatives, such as harnessing novel land uses that are beginning to appear within working landscapes. Although research will continue to tune and improve conservation and habitat management practices across the globe, there is now an established evidence base to inform insect conservation in these landscapes [36, 37*], i.e., co-locating vital, high-quality insect habitat within landscapes primarily used by humans, or "land sharing", to simultaneously meet human production needs and conservation goals [38]. We believe that such learnings can be applied to novel land uses within these systems and here we highlight the potential opportunities and challenges surrounding rapidly emerging land use changes related to solar energy and infrastructural rights-of-way.

Solar infrastructure and rights-of-way as insect habitat

Solar energy infrastructure is expanding rapidly around the globe in response to decreasing technology costs and climate change targets [39**], creating new areas that could be utilized in working landscapes to create insect habitats. For example, the United States of America Bureau of Land Management has proposed expanding solar energy production by creating ~9M hectares of new solar infrastructure on public lands to meet net-zero carbon goals [40], and in the United Kingdom, new government targets aim to more than triple solar energy production by 2030 [41]. Similarly, the European Union has seen increased initiatives to expand renewable energy, particularly solar energy capacity, to meet emissions targets [42]. Most solar infrastructure is deployed as ground-mounted "solar farms", arrays of solar panels mounted on metal supports embedded into the soil. Characteristics of solar farms differ across nations, varying in technology type and configurations, but typically the infrastructure itself occupies land that could also be used for habitat creation [43*]. There is a growing body of evidence to suggest that creating insect habitats within these developments is both possible and effective, depending on the ecoregion. For example, in temperate systems, there are many opportunities for solar farms to support insect pollinators through the provision of foraging and reproductive resources, increasing landscape heterogeneity and connectivity and through the creation of microclimatic variation [44]. Evidence from the United Kingdom indicates that solar farms managed to provide more resources that can support a greater abundance [45*] and diversity [46] of insects, though responses are moderated by the surrounding landscape. Studies from the United States indicate that planting native flora within solar arrays can increase local insect diversity and abundance, potentially helping to offset habitat losses brought about by declines in CRP enrollment [35, 47]. The benefits of targeted management could also support other ecosystem services, such as carbon storage and water retention [48] and could increase local pollination services to nearby pollinator-dependent crops [49, 50**]. However, in arid or dryland systems, solar developments can disturb insect communities, resulting in a loss of diversity and abundance [51, 52]. There are currently few studies that focus on insect response to solar developments in other continents, such as Asia or Africa [53], but one study from Chile indicates that shaded conditions provided by solar farm infrastructure could provide a refuge for insects [54].

Another related system increasingly being explored for this purpose are rights-of-way, which includes railroads, powerlines, highways, and waterways. Co-locating habitat in these spaces can help to facilitate insect diversity [55] and support a high diversity of pollinating insects when properly maintained [56]. In Europe, powerlines can also positively affect local insect diversity [57]. In both solar and rights-of-way systems, results can vary across ecoregions, making it difficult to build consensus practices and highlighting the importance of integrating existing knowledge of restoration from ecosystems across the globe.

Developing methods for habitat creation, management, and monitoring

Whilst opportunities to support insect conservation in energy infrastructure exist and evidence of insect response to these developments is emerging, further work is required to better understand how to (i) create and manage habitats in these specific contexts to optimize insect biodiversity gains and (ii) monitor biodiversity response to interventions. However, the rapid expansion of renewable energy infrastructure presents a significant challenge - waiting for more research to fully explore different potential practices may miss a critical window of as solar facilities are created *en masse* across many landscapes. Instead, guidelines need to be developed and implemented side-by-side with new research, leveraging existing expertise in conservation and working to integrate this knowledge into the realities of energy infrastructure construction and operations (Figure 1).

Habitat creation and management

Guidelines for developing and managing habitats within solar farms are beginning to be developed, with a bill recently presented to the United States of America Senate which would require new solar developments to include habitat creation in their design [58]. Solar farm design options can vary depending on the type of panels used, the configuration of arrays (e.g. north-south or east-west facing), whether the panels move (e.g. fixed axis panel arrays or tracking arrays), spacing between panels and other factors, which are likely to influence habitats within the site. However, habitat creation and management could be considered during solar farm design and be used as a tool to restore, maintain and enhance habitats, with implications for insects [59]. For example, spacing of panel rows could be adjusted depending on target levels of shading, which can impact plant [60] and insects [61] within these developments. Once operational, the management of habitats within solar farms is critical and can affect insect biodiversity [45]. In the United Kingdom, the National Capital Best Practice Guidance, developed by the trade body for the solar industry, provides a resource to developers and managers aiming to integrate habitat within their sites [62], and pollinator specific management recommendations have also been published [63]. Recommendations include providing foraging and reproductive resources for insects within solar farms, which can be achieved by sowing or encouraging nectar and pollen rich plant species or increasing the diversity of habitats within the site [44, 63]. This can be achieved through considered habitat management, such as grazing or cutting at low intensity and late in the season, rotational management of habitats (i.e. leaving areas uncut to create diversity in vegetation structure) and minimizing the use of agrochemicals [44, 63]. At present, published recommendations focus on habitat creation and management in temperate ecosystems, so consideration may be required if being adapted to other ecosystem types. Unfortunately, such resources are currently harder to find for rights-of-way projects aiming to incorporate conservation habitat.

Even where specific guidance for managing habitats within energy infrastructures is not yet available, existing methods and knowledge from other systems could be applied and adapted to the unique constraints of each land use. That said, it is paramount that these recommendations be written with key stakeholders in mind. Private companies, such as solar developers and operators, may lack expertise in restoration sciences, making them dependent upon the recommendations of experts that might not fully understand solar infrastructure. Production targets in energy facilities still need to be met, so such guidance needs to be nuanced and tailored to create habitat that is consistent with the day-to-day needs of a solar production facility. Without practical guidance from researchers and conservation groups, solar developers may default to simply laying down seeds and operating sites as they would any other, likely resulting in the habitat not establishing properly, or avoiding incorporating insect habitat altogether in site design. This can result in a loss for conservation efforts and local landowners interested in requiring insect habitat in leasing agreements.

Monitoring habitats and biodiversity

Once insect habitats have been established in solar farms, rights-of-way, or other energy infrastructure, monitoring the habitat and response by target insect species will be critical. Creation of these habitats will incur an economic cost, so ensuring habitats are developing as expected is paramount to realize gains from this front-end investment. Unsuccessful habitat establishment may deter site owners and managers from incorporating insect habitats into other existing sites or future developments, hindering conservation efforts. Monitoring habitats over time can also help to identify potential problems before they arise. For example, common challenges in temperate grassland systems include a dominance of competitive agricultural grass species and/or a decline in floral diversity, in which case habitats might need reseeding every few years [64]. Monitoring will also become increasingly important if habitat implementation becomes regulated, i.e., being required or strongly encouraged as part of new developments [65, 66].

While some solar farms have begun to undertake monitoring, there are challenges with standardization. Indeed, monitoring is commonly undertaken by consultants, who may only monitor an individual site or a few sites, and approaches across companies can be diverse. As monitoring is often not compulsory or strictly regulated, data are collected based on clients' needs and budget. Sites are therefore not always monitored in the same way, making it challenging to pool data across sites and assess broader trends. Standardizing data collection when monitoring these developments would allow data amalgamation and if adopted at enough sites, the analysis of national level trends and better understanding of insect (and wider biodiversity) response to energy infrastructure. To address challenges associated with monitoring and allow the collection of standardized data, monitoring approaches could be based on existing methods [e.g. 67] or methods could be adapted especially for energy infrastructures. For example, a standardized monitoring protocol especially for solar farms has been developed in the UK [68, 69] which has been adopted by more than 100 sites (~10% of the UK solar farm portfolio) over two years and has allowed exploration of insect response to solar farm interventions [70, 71]. Using standardized protocols in research would also allow better comparison of results collected across studies and different contexts [53].

Conclusion: Re-thinking conservation

The framework required to co-locate habitat in novel spaces, such as energy infrastructure and rights-of-way, has been established through restoration research efforts in many simplified landscapes. Creating diverse habitats in resource-limited spaces can be successful at increasing landscape heterogeneity [72] and facilitating insect conservation [73**]. While there are knowledge gaps on co-locating habitat with infrastructure, these mainly revolve around the applicability of practices across ecoregions and the magnitude of conservation benefits that can be accrued. Industry will not wait for these nuances to be resolved before building new facilities; as such, researchers should begin tailoring guidelines, best practices, and recommendations sooner rather than later. Solar energy in particular has emerged as a highly competitive source of energy, and, just as insect declines are occurring worldwide [1], solar energy will likely continue to rapidly expand globally. While energy is propelled into the future, insect conservation has the potential to be left behind as new projects either avoid co-locating habitat with infrastructure due to the perceived complexities or cut corners in creating said habitat. Pairing habitat with infrastructure has the potential to meet energy infrastructure development needs while simultaneously meeting conservation goals, a win-win scenario that will only be met by having open discussions between key stakeholder groups, including local landowners, government agencies, private companies, conservation groups, and researchers. However, without swift action, co-benefits could quickly evaporate if stakeholders become disillusioned with blindly attempting to make such a system work. Entomologists must pair research with policy and practicality to push conservation into the future.

Declaration of Interest: No authors have any financial or personal relationships with other people or organizations that could inappropriately influence (bias) their work

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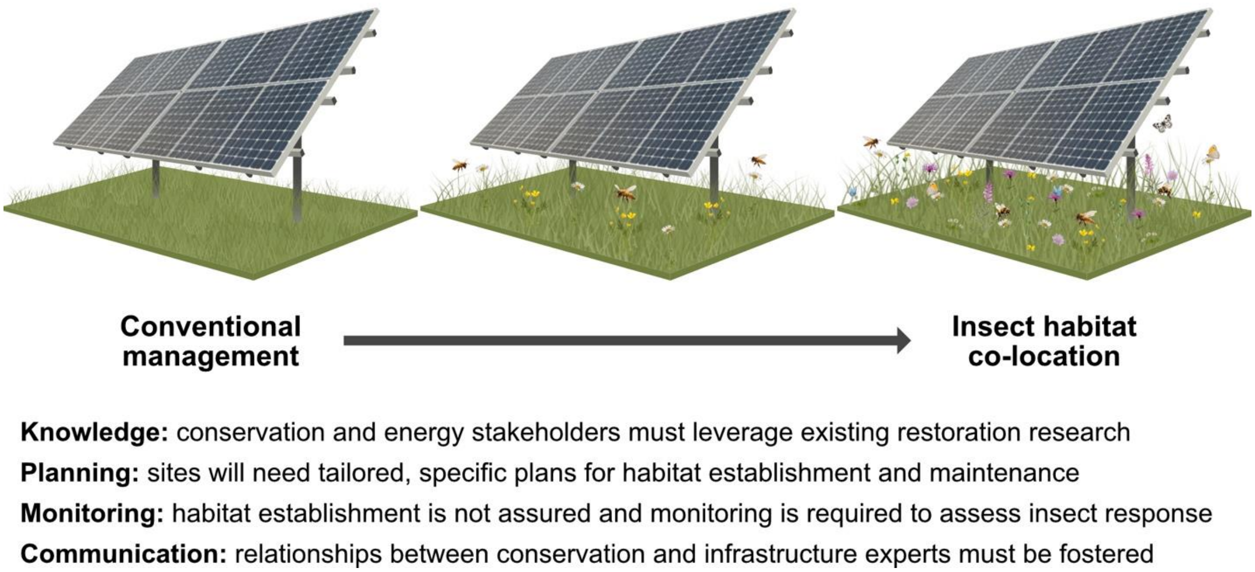
This worldwide meta-analysis shows that landscape heterogeneity can improve biodiversity, highlighting the need and potential for practices that increase this type of heterogeneity.

Figure legends

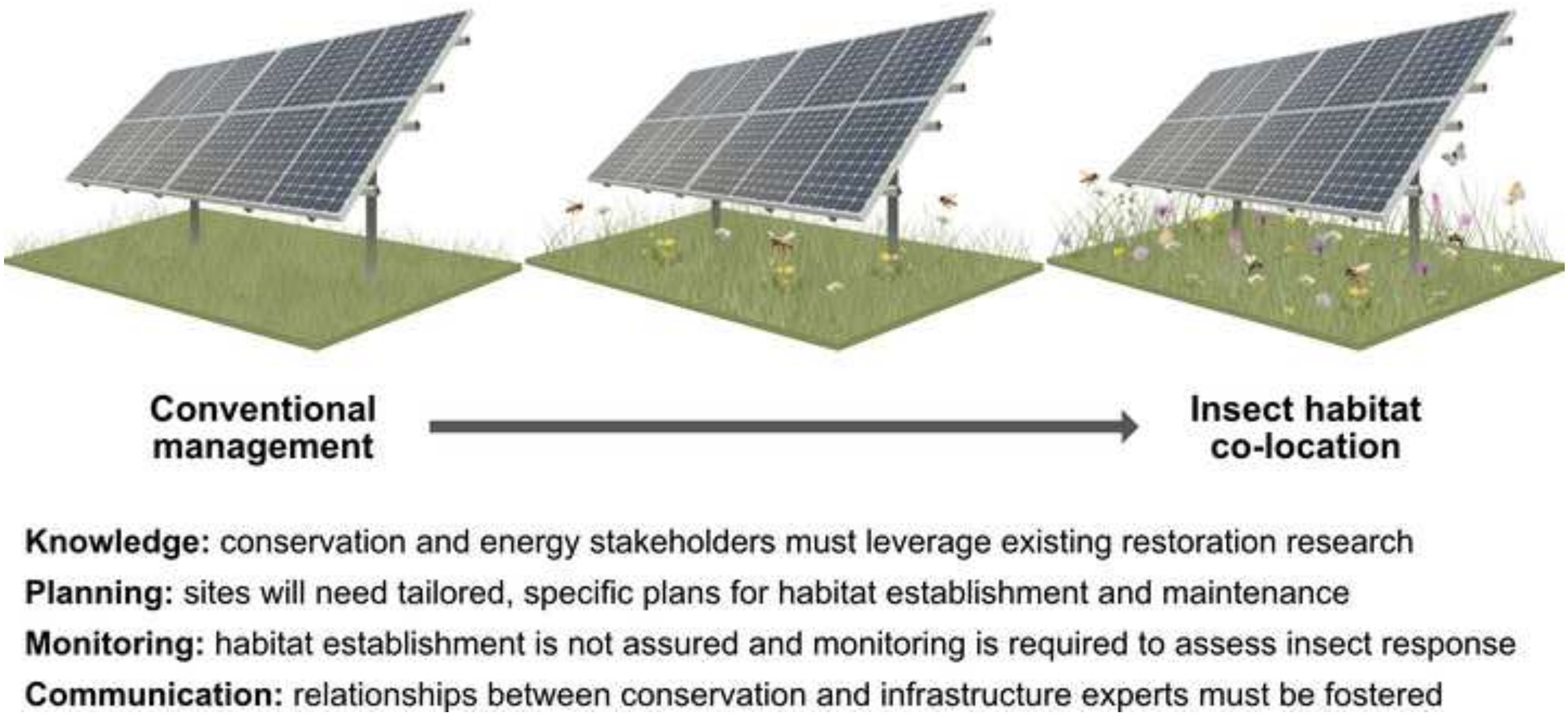
Figure 1: Rapid expansion of solar and rights-of-way infrastructure creates a limited time window to leverage new land use. Because solar and rights-of-way infrastructure is expanding quickly in many regions, utilizing them for conservation gains may best be achieved in the near future. However, there are important challenges to achieving these goals. While infrastructure-specific research would be ideal, existing knowledge of restoration/conservation practices can

and should be used to create recommendations side-by-side with ongoing research. Using this knowledge, site plans will need to be tailored to the ecoregion and local conditions, and long-term monitoring to ensure the habitat is established successfully will be critical. Perhaps most importantly, new relationships will need to be developed and fostered between experts in conservation and infrastructure to bridge gaps and identify problems before they become intractable.



Declaration of Interest: No authors have any financial or personal relationships with other people or organizations that could inappropriately influence (bias) their work

Figure 1


Conventional management
Insect habitat co-location
Knowledge: conservation and energy stakeholders must leverage existing restoration research
Planning: sites will need tailored, specific plans for habitat establishment and maintenance
Monitoring: habitat establishment is not assured and monitoring is required to assess insect response
Communication: relationships between conservation and infrastructure experts must be fostered

A stitch in time: integrating energy infrastructure into the fabric of conservation habitats

Authors: Tristan A. Barley[a], Hollie Blaydes[b], Adam G. Dolezal[a*]

[a]University of Illinois, Department of Entomology, Urbana, Illinois, United States

[b]Lancaster University, Lancaster Environment Centre, Lancaster, United Kingdom

[*]Corresponding Author