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Ecosystem Services Conceptual Model Application

Bureau of Land Management Solar Energy Development

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SUMMARY

Interest in using ecosystem services to integrate considerations of people and the environment continues to grow in federal agencies. One method that can help agencies incorporate ecosystem services into decision making is the use of ecosystem services conceptual models, which link changes in biophysical systems caused by an intervention to human well-being outcomes. Evidence-based ecosystem services conceptual models can provide efficiency and consistency in application, transitioning ecosystem services from an interesting concept to an actionable approach for natural resource management.

Despite the potential usefulness of these models, there are few examples available to build from and little published detail on how to implement them. We provide an example ecosystem services conceptual model for solar energy development on lands administered by the Bureau of Land Management, which wants to facilitate solar energy development on suitable land in the southwestern United States while minimizing negative impacts on social, cultural, and ecological systems. With agency staff, we developed a model that captures the potential outcomes of the installation and operation of solar energy facilities on Bureau of Land Management-managed land. An accompanying evidence library provides a summary of the currently available evidence for each relationship in the model and an assessment of the strength of that evidence. Agency staff think that ecosystem services conceptual models could improve and help to streamline environmental assessments and help the agency achieve its socio-economic strategy.

INTRODUCTION

The southwestern United States has high potential for solar energy development, and the 100 million acres of land managed by the Bureau of Land Management (BLM) in that region are no exception. Thirty-seven utility-scale solar projects representing a total of 10,000+ MW of potential energy output have been approved on BLM-managed land since 2009 (M. Hildner, personal communication, December 4, 2017). This clean energy powers homes, businesses, and industry, helping to reduce their contributions to climate change. However, the land use and infrastructure required by solar energy facilities can affect a range of ecological, cultural, and social resources, even in the remote and largely untouched arid and semi-arid ecosystems of the southwestern United States. BLM is taking steps to minimize the impacts of new solar energy projects on the land it manages through its authorization process for utility-scale solar development, which was formalized by its Solar Energy Program (BLM 2012).

The Solar Energy Program is a Department of the Interior initiative to facilitate solar energy development on public lands administered by BLM while minimizing adverse effects on ecological, cultural, and recreational resources. The program designated 19 solar energy zones (SEZs) within which utility-scale solar energy production is the priority land use and project authorization is streamlined. Collectively, the SEZs include more than 298,000 acres in Arizona, Colorado, New Mexico, California, Nevada, and Utah. SEZs represent areas of high solar energy potential in which solar energy development will have relatively low ecological and cultural impacts. The Solar Energy Program also designated exclusion zones, which are ecologically and culturally sensitive areas where solar energy development will not be permitted, and variance areas, including all BLM-administered lands that are not part of a SEZ or an exclusion zone, in which solar energy development can be permitted on a case-by-case basis. BLM is in the process of creating monitoring and adaptive management strategies for each of the SEZs that will simplify the process of measuring the impacts of solar energy projects and of assessing the success of project design features and mitigation measures to minimize those impacts. The authorization process for individual projects in SEZs includes a site-specific environmental assessment; projects can be required to use best management practices or implement compensatory mitigation.

Decision makers, including those at BLM, are increasingly looking to consider socio-ecological systems and to better integrate ecological and social outcomes (BLM 2013). One way to do both is to include ecosystem services, which link ecological changes to their social effects on people. This strategy allows outcomes arising from changes to ecological systems to be considered alongside those that result directly from the planned development (NESP 2016). Ecosystem services conceptual models (ESCMs) represent a possible starting point for incorporating ecosystem services into decisions. These models illustrate the way that a management intervention cascades through an ecological system and results in ecosystem service and other human welfare impacts. They can provide a foundation for understanding and communicating ecosystem services to audiences not familiar with the ecosystem services concept. ESCMs can also be used to establish common socio-ecological metrics and even to form the basis for quantitative models (Olander et al. 2018b). Perhaps the most valuable feature of ESCMs for agency implementation is that they can be developed into a transferable and consistent project assessment resource. Models can be developed for a specific site or for a general type of intervention across sites. Given a constrained set of management interventions and a fixed number of effects such interventions can have on the environment and people, it appears possible to establish a reference set of ESCMs that can be adapted for a particular project. A single general model developed for solar installations can be a useful platform for any solar installation across the region. Agency staff suggest that this model could help to streamline environmental assessments, reducing the time, resources, and expertise needed for each assessment and increasing the consistency of the assessment and review process.

In partnership with BLM, we have developed an example ESCM and evidence library for utility-scale solar development that could provide a starting point for systematic and transparent assessments, facilitate communication with stakeholders during planning and permitting processes, and identify strengths and weaknesses in the evidence for solar energy development-related impacts to ecosystem services. The general conceptual model is not tied to a specific project or location, but it includes the potential ecosystem services outcomes resulting from any solar energy development on BLM-managed lands in the southwestern United States. This general model can then be adapted to any specific development to provide a consistent and credible foundation for building site-specific reviews.

This model and evidence library are meant to demonstrate a new decision support resource, allowing its uses and design to be further assessed and tailored to decision makers' needs. The general model can be adapted for particular uses. If this tool is of value to the BLM or other users, additional models and libraries can be developed for other applications.

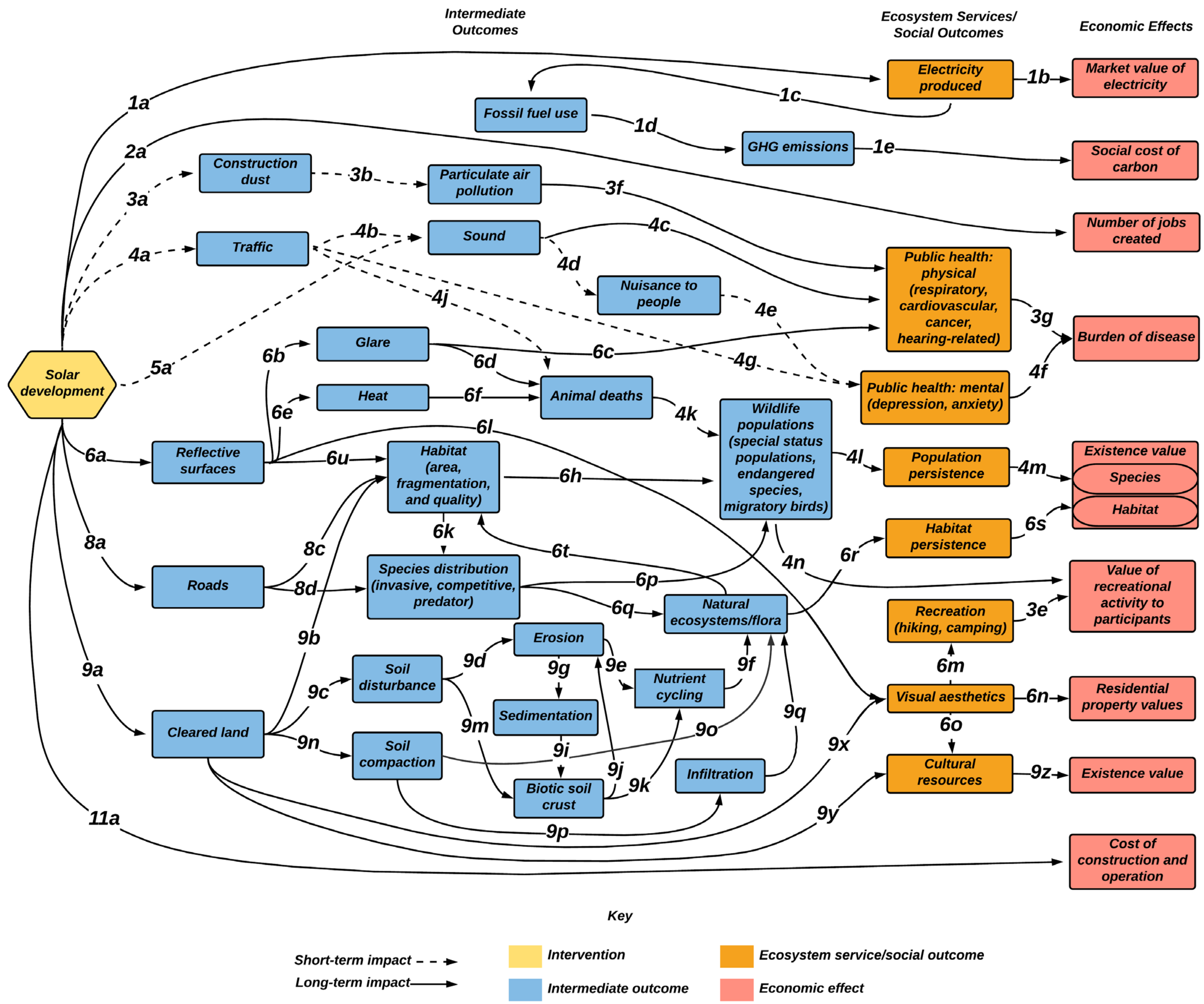
GENERAL SOLAR ENERGY DEVELOPMENT MODEL

Conceptual Model

The conceptual model was initially drafted from several articles synthesizing the social, economic, and environmental impacts from utility-scale solar energy development (Aman et al. 2015; Hernandez et al. 2014; Kreuter et al. 2016; Tsoutsos et al. 2005; and Turney and Fthenakis 2011).[1] After BLM staff reviewed the initial model, evidence for each of the hypothesized relationships represented in the model was examined. The conceptual model was continually revised on the basis of information gathered in the evidence collection process and feedback from expert reviewers (Figure 1). The final components in each chain in the conceptual model are outcomes that are directly relevant to people, including ecosystem services (orange boxes) and their associated values (red boxes).

[1] Parts of this section were adapted from Olander et al. (2018b).

Figure 1. Simplified general conceptual model for solar energy development on BLM lands



Note: This figure is a simplified version of the general conceptual model. It presents no negligible links. The full model with negligible links included is in Appendix I. The economic effects (red boxes) do not all measure the same thing and cannot be added together or directly compared to one another.

Model Notes and Considerations

Ecosystem Service and Social Outcome Endpoints

This model is not only meant to be general, but also inclusive. The ecosystem service and social outcome endpoints (orange boxes in Figure 1) represent a wide array of possible outcomes resulting from solar energy development. These endpoints are meant to align with the concept of benefit-relevant indicators (BRIs), which reflect changes in ecological condition that are relevant to people (NESP 2016; Olander et al. 2018a). Although the endpoints presented here are not BRIs, they represent categories of services or benefits that could be specified to BRIs that are relevant to a particular site.

Economic Effects

If economic effects of ecosystem and social services are important, the model can be extended to include these values (red boxes in Figure 1). The values shown in Figure 1 represent options for economic metrics, but other methods for valuation of ecosystem services exist. Economic effects are not always required. Stopping at benefit relevant indicators may be sufficient for many decisions.

Outcome Comparisons

One potential use of ESCMs is to compare the outcomes of multiple interventions. For example, the outcomes of the installation of a utility-scale solar energy facility could be compared with the outcomes of the installation of a coal power plant. To make such a comparison, a separate conceptual model should be created for each intervention (e.g., solar and coal). It may appear easier to make comparisons across interventions within a single conceptual model (e.g., to express the amount of water used in solar energy development as the amount of water saved by replacing a coal power plant with a solar energy facility). However, this shortcut can lead to inaccurate comparisons because the outcomes of the second intervention are not fully investigated. Therefore, comparisons with other energy sources are not included in this conceptual model, with one exception. Links 1c, 1d, and 1e capture the greenhouse gas (GHG) emissions effects of replacing fossil fuels with solar energy, and they contain comparisons of GHG emissions from various energy sources. These links were retained because decreasing fossil fuel emissions is one of the primary goals of solar energy development.

Spatial and Temporal Considerations

ESCMs are a conceptual schematic to help decision makers think through the logic of a change in a system, but they do not depict all important aspects of these changes. The models can sometimes include a simplified indication of the temporal dimensions of change, such as short-term temporary changes versus long-term persistent changes, but often the temporal dimension is missing. In the solar energy development model, short-term effects (those not expected to persist after the construction of a facility is complete) are indicated with dashed arrows, and long-term effects (those expected to continue even after construction is complete) are indicated with solid arrows (Figure 1). These models do not show the very important spatial dimensions of system dynamics, and they are not designed to capture system feedbacks, but they can provide a starting place for considering such feedbacks (see below). However, both spatial and temporal considerations are addressed in the evidence library, often included in the "other factors" section.

Feedback Loops

Many biophysical and social feedback loops are not represented visually in this model diagram, for example, the negative feedbacks of some recreational activities on wildlife populations. Feedback loops are instead addressed in the text of the evidence library to simplify the model image and keep the focus on the predominant flows or cascades between the ecological aspects and social aspects of the arid and semi-arid ecosystems in which most BLM solar energy projects are installed. Feedback loops could be incorporated into an ESCM if the user requires their inclusion.

External Drivers

This model includes only aspects of the socio-ecological system that are affected directly or indirectly by the intervention of focus, in this case, installation of a new solar energy plant. Many external drivers also influence the socio-ecological outcomes but are not represented graphically in the model. Many of these drivers, such as climate change, land use change, invasive species, and storms, are addressed where applicable in the "other factors" sections of the evidence library. If a conceptual model is specified to a site and turned into a quantitative model, external drivers will have to be incorporated to accurately model the system.

Evidence Collection

Evidence was collected to support each link (arrow) in the model through a search of online academic databases and Google Scholar using key words from each link. To assess the current level of understanding, generalizability of evidence, and consistency of effects for each relationship, the search emphasized meta-analyses, research syntheses, and review articles. Other types of evidence, including individual research studies, technical reports, computer models, and interviews, were also considered. The literature search for each link was not exhaustive, but it was reasonably extensive and should be sufficient for a general sense of the available evidence. Further work could be done to refine and update the evidence.

Through the process of evidence collection, some of the links and nodes were determined to be inconsequential for solar energy development in general or on BLM land specifically. These links and nodes are excluded from the simplified general conceptual model presented in the main body of this report (Figure 1), but a full version of the conceptual model is included in Appendix I, along with the evidence collected for the excluded links. Links were categorized as potentially negligible according to these criteria:

> ***at least one source stated that the relationship is unimportant*** for solar energy development in general or in the southwestern United States specifically, and no other sources indicated that the relationship was important,
>
> ***or***
>
> the available evidence suggests that ***the magnitude of the effect resulting from the solar installation is likely very small*** due to facility location characteristics (nearby population, climate, land cover, and so on), ***and the relationship has no potential to affect human health and will not contribute to cumulative effects*** if several solar energy facilities are built in the same area.[2]

Links that were retained in the general model due to their potential to contribute to human health effects or to cumulative effects are identified in the evidence library.

Evidence Library

Evidence collected for each link was entered into an evidence library. The evidence library is organized by link number (see Figure 1), with each link entry describing the relationship between two nodes in the conceptual model. All link entries contain the information described in Table 1.

Table 1. Description of the contents of the evidence library

Evidence library contents for each link	Description
Description of the relationship	Description of the relationship between the starting and ending node (when possible, the direction and magnitude of change are stated)
Summary of evidence	Discussion of the relationship between the two nodes and the supporting evidence for the relationship
Strength of evidence	Evidence grade for the strength of the relationship, determined using an evidence matrix (see Table 2)
Other factors	List of other factors that may influence the relationship between the two nodes

Although most entries contain information pertaining to a single link, some entries in the library contain evidence that combines multiple links—but only in cases in which applicable evidence encompasses more than one link, as in research studies directly relating length of time a photovoltaic panel is left exposed to atmospheric dust and reduction in the amount of electricity produced. This combined information from links 3h and 3i is listed with the link number 3hi. This

[2] Due to importance of human health effects, links contributing to these effects were retained even when they are likely to be insignificant, and due to the potential for multiple solar energy facilities to be placed near one another in a solar energy zone, links that may contribute to cumulative effects were retained even when the effect of one solar energy facility is expected to be small relative to the scale of the system.

combination link does not have an evidence grade because it does not appear in the model diagram; it is included in the library to provide additional support for the relationships described in each of the individual links it replaces.

Kinds of Information

Two kinds of information are included in these libraries: evidence and examples. Evidence included in the library describes general or site-specific relationships between nodes and can include individual research studies, models, calculators, and meta-analysis results. Individual research studies can provide evidence for the existence of a relationship, but they are usually low-quality evidence for contexts other than the one in which the study was conducted (see "strength of evidence assessment" below).

For links with missing or weak evidence, examples of site-specific studies that could be done at a site or for a particular intervention to fill an evidence gap for this library are provided. In many cases, the example studies are individual research studies conducted in other contexts that are considered part of the body of evidence for the relationship but that also illustrate how the relationship could be assessed in the focal context. In a few cases, the example studies are essentially general methods papers that describe an approach but that do not contribute to the evidence for the relationship.

Strength of Evidence Assessment

The strength of evidence available for each link was assessed on the basis of the four criteria in Table 2. Evidence was assessed using this method; examples were not. Evidence must score "high" for each of the four criteria to receive a "high" strength-of-evidence rating. If the evidence for a link does not receive the same rating for all criteria, the overall strength of evidence for the link is determined by the evaluator, taking into account each of the individual ratings.

Table 2. Strength of evidence assessment rubric

	Criteria			
Confidence level	**Types of evidence**	**Consistency of results**	**Methods**	**Applicability**
High	Multiple	Direction and magnitude of effects are consistent across sources, types of evidence, and contexts	Well documented and accepted	High
Moderate	Several	Some consistency	Some documentation, not fully accepted	Some
Fair	A few	Limited consistency	Limited documentation, emerging methods	Limited
Low	Limited, extrapolations	Inconsistent	Poor documentation or untested	Limited to none
None	None	N/A	N/A	N/A

Source: This table was adapted from the Bridge Collaborative Practitioner's Guide: Principles and Guidance for Cross-sector Action Planning and Evidence Evaluation.
Note: N/A = not applicable.

Types of evidence can include individual research studies (experimental or observational), meta-analysis or synthesis studies, tools, models, expert opinion, and local knowledge. Consistency of results takes into account the direction and magnitude of effects shown in the evidence. Methods include level of documentation, whether methods are supported by other literature and appropriate for the study objective, and whether limitations of the methods are discussed. Applicability refers to the relevance of the evidence to the relationship, including the geographic, social, and biophysical contexts of the evidence relative to the relationship in question.

Evidence Considerations

Assessing the available evidence for a particular link requires consideration of two distinct aspects of the evidence: ***existence*** and ***predictability.***[3] The first consideration is ***existence*** of a relationship between the two nodes involved—does a change in one node lead to some change in the other? The second aspect, which is dependent on the first, is ***predictability*** of that change. Do we have evidence to show ***how*** one node will change with the other? Is this information generalizable to all scenarios, or is it context specific? When collecting evidence for a general model, consideration of the generalizability of predictive capability becomes especially important. Our evidence libraries focus on the evidence for ***existence*** of a relationship, and where possible we highlight the ***predictability*** of the relationship.

Strength of evidence also needs to take "other factors" into consideration. Consider the hypothetical relationship between nodes A and B. A large body of evidence may describe the existence of the relationship between A and B, but other factors may also influence B. Those other factors might not appear in the conceptual model diagram (because they are not affected by the intervention), but they may be important in the estimation of an outcome in node B. The existence of these other factors will likely lower the evidence grade because they reduce the applicability and consistency of the evidence that links A and B. Alternatively, those other factors can be added to the ESCM and the strength of evidence for their influence on intervention effects can be directly considered.

Evidence collection for generalized conceptual models has limitations. Certain nodes in a general model are purposefully left vague or general, and they will need to be specified once a local site is chosen. For example, the "wildlife populations" node is general, and specific wildlife species will have to be selected when applying the general model at a local site. These generalizations limit gathering of applicable evidence in some cases. Although it may be possible to gather evidence for linkages between various nodes and the general "wildlife population" node, it is impossible to gather relevant evidence for all species. Due to the general nature of that node and our inability to make definitive statements about the connection between other nodes and general "wildlife populations," the evidence grade for those links in the general model will often suffer. In many cases, the nodes will include lists of example studies (rather than evidence) to illustrate how this linkage might be assessed once a more specific node is selected for a local site.

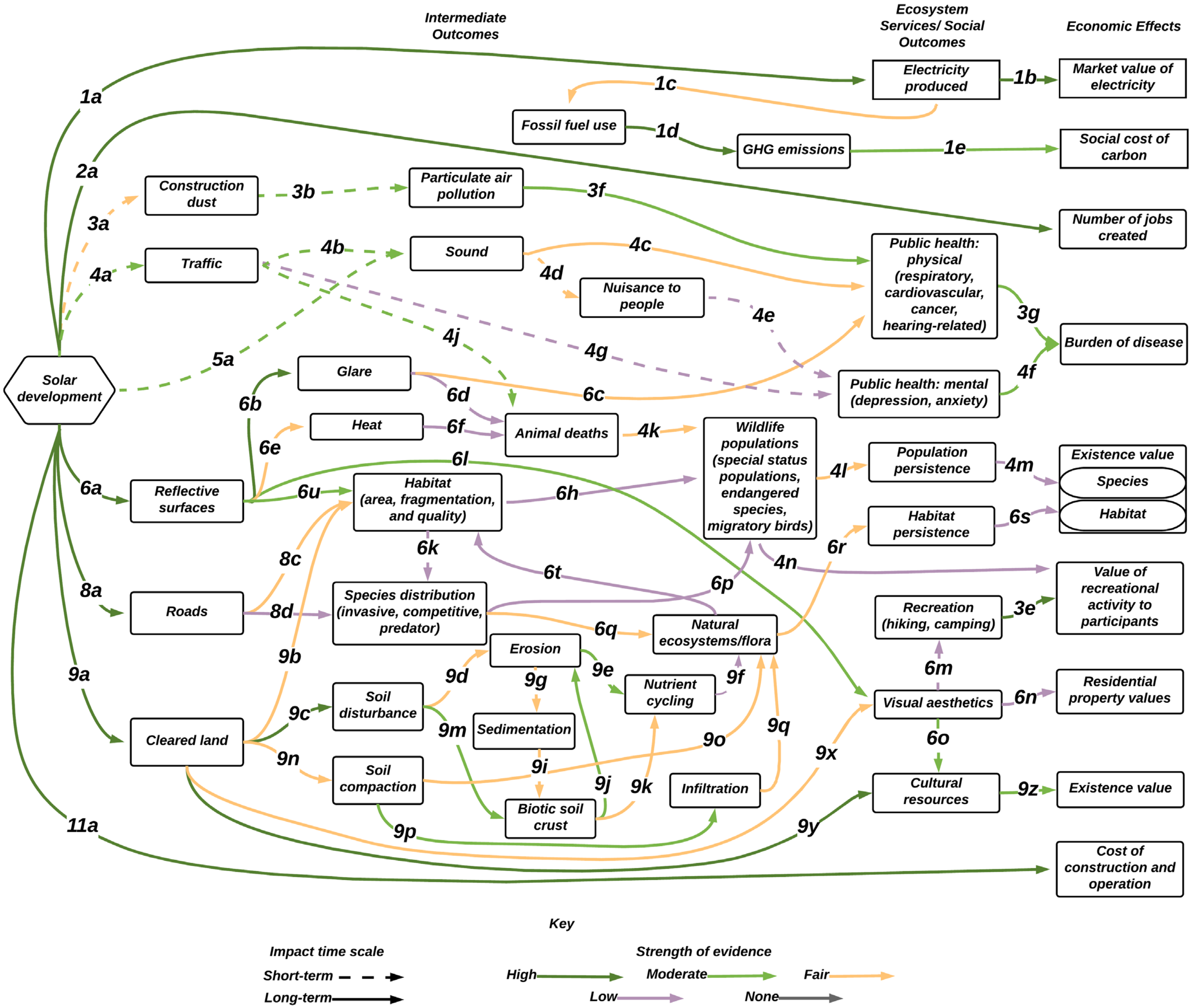
Strength of Evidence Map

Once evidence has been evaluated using some confidence rubric, the confidence in each link can be expressed visually in the ESCM. Many researchers use what they call "evidence gap maps" to provide a visual summary of the number of studies done to test a broad suite of interventions and a broad suite of targeted outcomes. A number of examples have been developed by The International Initiative for Impact Evaluation (3ie) (Snilstveit et al. 2017) and others. However, for an evidence review focused on a single or a few interventions for which we want to include details on intermediate outcomes as well as final outcomes, we suggest the expression of confidence within the ESCM be displayed using the conceptual model framework. The conceptual model can be used as the template, with arrows colored to represent the grade that the evidence received. We call these "strength of evidence maps" (Figure 2).

A strength of evidence map for solar energy development allows for a quick visual assessment of how well connections between solar energy development and outcomes that matter to people (ecosystem services, social outcomes, and economic effects) are supported by currently available evidence (Figure 2). These maps can also be used to inform research priorities because they identify research gaps and provide context for gaps that might be the most important in addressing significant uncertainties or risks for decision makers.

[3] This section was adapted from Olander et al. (2018b).

Figure 2. Simplified general conceptual model (negligible links not included) showing the strength of evidence for each link



Sources

Aman, M.M., K.H. Solangi, M.S. Hossain, A. Badarudin, G.B. Jasmon, H. Mokhlis, A.H.A. Baker, and S.N. Kazi. 2015. "A Review of Safety, Health, and Environmental (SHE) Issues of Solar Energy System." *Renewable and Sustainable Energy Reviews* 41: 1190–1204.

BLM (Bureau of Land Management). n.d. "Solar Energy Data." https://www.blm.gov/programs/energy-and-minerals/renewable-energy/solar-energy/data.

———. 2012. "Approved Resource Management Plan Amendments/Record of Decision (ROD) for Solar Energy Development in Six Southwestern States." http://blmsolar.anl.gov/documents/docs/peis/Solar_PEIS_ROD.pdf.

———. 2013. "Bureau of Land Management Socioeconomics Strategic Plan 2012–2022." Division of Decision Support, Planning, and NEPA, Washington, D.C. https://www.blm.gov/sites/blm.gov/files/BLMSocioeconomicStrategicPlan2012-2022.pdf.

Hernandez, R.R., S.B. Easter, M.L. Murphy-Mariscal, F.T. Maestre, M. Tavassoli, E.B. Allen, … and M.F. Allen. 2014. "Environmental Impacts of Utility-scale Solar Energy." *Renewable and Sustainable Energy Reviews* 29: 766–779.

Kreuter, U.P., A.D. Iwaasa, G.L. Theodori, R.J. Ansley, R.B. Jackson, L.H. Fraser, … and E.G. Moya. 2016. "State of Knowledge about Energy Development Impacts on North American Rangelands: An Integrative Approach." *Journal of Environmental Management* 180:1–9.

NESP (National Ecosystem Services Partnership). 2016. *Federal Resource Management and Ecosystem Services Guidebook*. 2nd ed. Durham: National Ecosystem Services Partnership, Duke University, https://nespguidebook.com.

Olander, L.P., R.J. Johnston, H. Tallis, J. Kagan, L. A. Maguire, S. Polasky, D. Urban, J. Boyd, L. Wainger, and M. Palmer. 2018a. "Benefit Relevant Indicators: Ecosystem Services Measures That Link Ecological and Social Outcomes." *Ecological Indicators* 85:1262–72.

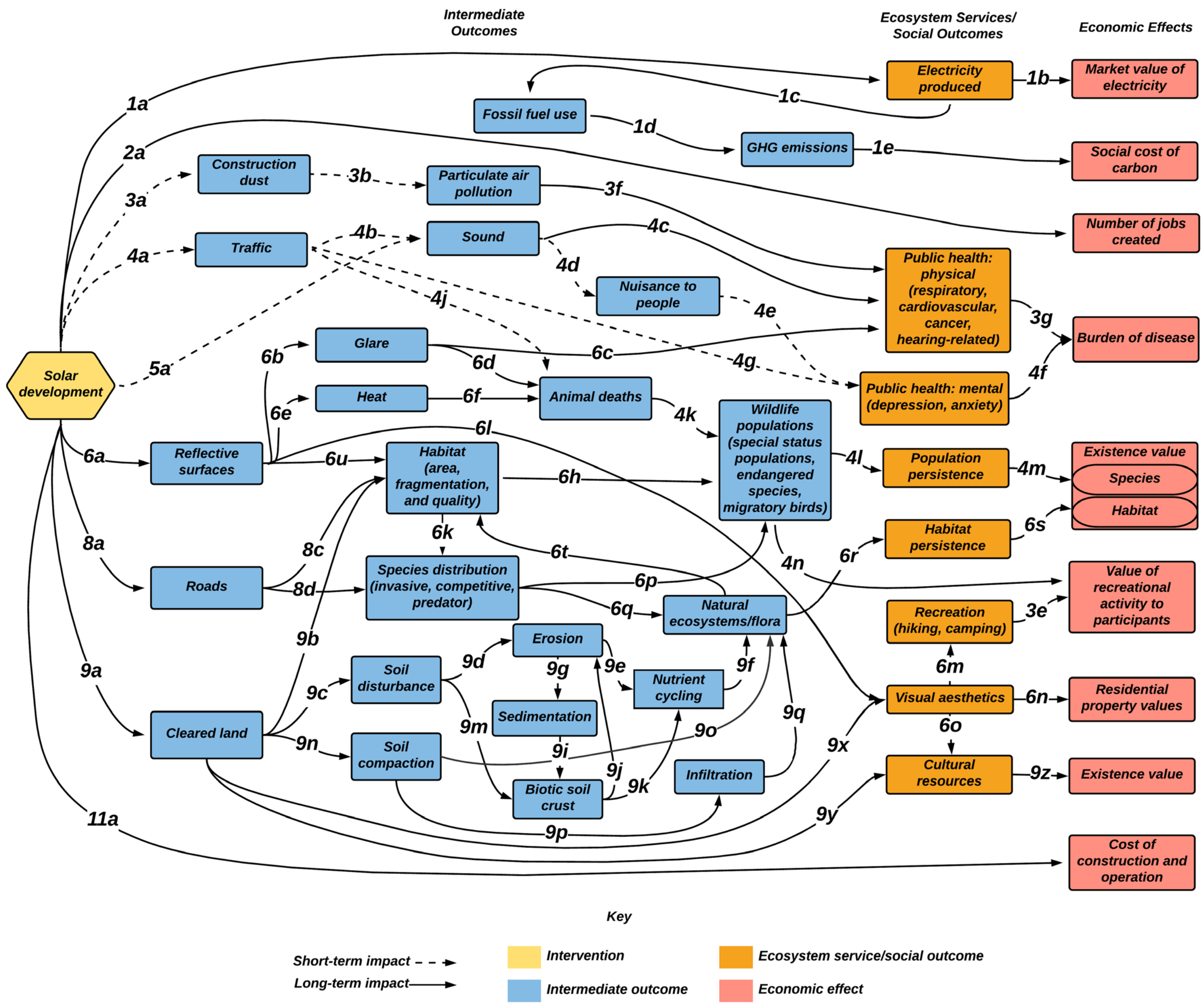
Olander, L., S. Mason, K. Warnell and H. Tallis. 2018b. "Building Ecosystem Services Conceptual Models." National Ecosystem Services Partnership Conceptual Models Series no. 1. Durham, NC: Duke University, Nicholas Institute for Environmental Policy Solutions. URL TO COME

Snilstveit, B., R. Bhatia, K. Rankin, and B. Leach. 2017. "3ie Evidence Gap Maps: A Starting Point for Strategic Evidence Production and Use." 3ie Working Paper 28. New Delhi: International Initiative for Impact Evaluation (3ie). http://www.3ieimpact.org/media/filer_public/2017/02/28/wp28-egm.pdf.

Tsoutsos, T., N. Frantzeskaki, and V. Gekas. 2005. "Environmental Impacts from the Solar Energy Technologies." *Energy Policy* 33: 289–296.

Turney, D. and V. Fthenakis. 2011. "Environmental Impacts from the Installation and Operation of Large-scale Solar Power Plants." *Renewable and Sustainable Energy Reviews* 15: 3261–3270.

Figure 3. Evidence library table of contents



EVIDENCE LIBRARY FOR SOLAR ENERGY DEVELOPMENT MODEL

1a: Solar Development → Electricity Produced

Description of Relationship

Approximately 0.75 kilowatt hours (kWh) of electricity is produced each day per square meter of photovoltaic panels, assuming that the panels have 15% efficiency and receive 5 kWh/m^2/day of solar radiation.

Summary of Evidence

Solar facilities can produce electricity in several ways, including direct conversion of solar energy through photovoltaic panels and traditional turbine generation by heating water or other heat exchange fluids. The amount of electricity produced depends the amount of solar energy, or insolation, reaching the facility—an amount that varies by location (see "Other Factors")—and the facility's efficiency. The efficiency of a solar technology is the percentage of solar energy falling onto the module that is converted to electricity. A survey of completed large (>20 MW) solar photovoltaic projects in the United States found module efficiencies of 9%–19%; efficiencies for proposed large PV projects range up to 29% (Ong et al. 2013). Various concentrating solar power technologies have efficiencies of 8%–35% (IEA 2010).

The System Advisor Model can predict the performance of solar photovoltaic systems and four types of concentrating solar power systems: parabolic trough, power tower, linear Fresnel, and dish-Stirling (Blair et al. 2014).

Strength of Evidence

High: Electricity production is the main purpose of a solar energy facility. Several types of evidence, including a tool (System Advisor Model), a research study of completed solar PV projects, and industry reports, provide a consistent picture of the range of efficiencies of solar technologies currently in use in the United States.

Predictability: The amount of energy production expected from a solar facility can be calculated from technical parameters of the system and physical features of the site.

Other Factors

Location

Solar insolation in the continental United States ranges from 3.4 kWh/m^2/day (Northeast, Pacific Northwest) to 5.4 kWh/m^2/day (Southern California, Arizona) (Energy.gov). Larger or higher-efficiency solar installations would be needed in lower-insolation areas to generate the same amount of electricity as smaller solar installations in high-insolation areas.

Technology

PV systems with 1- and 2-axis tracking systems, which allow the panels to change angles to follow the sun, generate more energy than those with fixed systems. A simulation of energy generation by different tracking systems in locations across the United States found that 1-axis systems provide a 12%–22% increase in energy yield compared to fixed systems, and 2-axis systems provide a 3%–44% increase in energy yield compared to fixed systems. The most efficient type of PV tracking system depends on the location of the solar installation (Ong et al. 2013).

Of the four types of concentrating solar power technologies currently in use, linear Fresnel systems have the lowest efficiency (8%–10%), followed by parabolic troughs (15%), towers (20%, but up to 35% under development), and parabolic dishes (25%–30%) (IEA 2010).

Other

Temperature affects PV panel efficiency; a temperature rise of 1°C causes a drop in efficiency of 0.1%–0.5%. The temperature of a PV panel is affected by panel material, solar irradiance, ambient temperature, and wind velocity (Du et al. 2016).

Sources

Blair, N., A.P. Dobos, J. Freeman, T. Neises, and M. Wagner. 2014. System Advisor Model, SAM 2014.1.14: General description. National Renewable Energy Laboratory NREL/TP-6A20-61019. http://www.nrel.gov/docs/fy14osti/61019.pdf.

Du, Y., C.J. Fell, B. Duck, D. Chen, K. Liffman, Y. Zhang, M. Gu, and Y. Zhu. 2016. "Evaluation of Photovoltaic Panel Temperature in Realistic Scenarios." *Energy Conversion and Management* 108: 60–67. https://doi.org/10.1016/j.enconman.2015.10.065.

Energy.gov. Solar Energy Potential. https://energy.gov/maps/solar-energy-potential.

IEA (International Energy Agency). 2010. Technology Roadmap: Concentrating Solar Power. https://www.iea.org/publications/freepublications/publication/csp_roadmap.pdf.

Ong, S., C. Campbell, P. Denholm, R. Margolis, and G. Heath. 2013. Land-use Requirements for Solar-powered Plants in the United States. National Renewable Energy Laboratory NREL/TP-6A20-56290. http://www.nrel.gov/docs/fy13osti/56290.pdf.

1b: Electricity Produced → Market Value of Electricity

Description of Relationship

Electricity from new utility-scale PV solar plants has a value of about $30–$50/MWh on the wholesale power market. Electricity from existing concentrating solar power (CSP) plants is selling at $120–$190/MWh due to higher production costs when contracts were signed (2009–2011), but no new CSP contracts have been signed since 2011 (Bolinger et al. 2017).

Summary of Evidence

Electricity generated by a utility-scale solar energy facility is sold on the wholesale power market through a power purchase agreement (PPA) that sets the price. PPAs represent the revenue to the solar energy facility owner from electricity sales. A 2017 study of utility-scale (>5 MW) PV projects in the United States found that most PPAs finalized in 2016 were priced at or below $50/MWh, with a mean of $35/MWh (Bolinger et al. 2017). These values do not include solar energy facilities that are owned by utilities, which sell the electricity produced directly to consumers rather than on the wholesale market; nor do they include PPAs that did not result from negotiations or a competitive bids process. One study found that no new PPAs for concentrating solar power systems have been finalized since 2011, likely because the cost to build and operate CSP systems has not remained competitive with large-scale PV systems. For CSP PPAs finalized between 2009 and 2011, prices ranged from $120/MWh to $190/MWh (Bolinger et al. 2017). All prices are reported as 2016 U.S. dollars.

Strength of Evidence

High: The electricity prices listed here are from regulatory filings for a large sample of utility-scale PV power plants and the complete population of CSP plants in the United States, providing direct and highly applicable evidence for this relationship.

Predictability: Although past electricity prices can be used as a guide to predict future prices, prices have been changing rapidly. The market value for electricity from future solar energy facilities is likely to be lower than for electricity from existing facilities. In addition, the prices listed here do not account for electricity prices resulting from certain regulatory programs that prevent competitive pricing.

Other Factors

Location

For PV solar energy facilities, PPA prices are lower in California, the Southwest, and Texas than in the Midwest or Northeast. This discrepancy reflects the additional resources required to generate the same amount of electricity from solar power plants in the Midwest and Northeast due to their relatively lower solar energy resources (Bolinger and Seel 2016).

The Public Utility Regulatory Policies Act (PURPA) requires power utilities to purchase power generated by certain renewable energy sources, which can include solar power plants, at predetermined prices regardless of the utilities' need for the electricity. Individual states determine the requirements for qualification, prices, and length of these "avoided-cost contracts." As the cost to produce solar energy has fallen, some solar developers have been using these requirements to sell their electricity at prices above the market rate (Bolinger and Seel 2015). As noted above, PPAs from avoided-cost contracts are not included in the 2017 Bolinger et al. study or the relationship described here, but they can result in higher prices for electricity from solar energy in certain areas. States can change their avoided cost calculations, so this effect may not be consistent in the long term.

Technology

As described above, electricity from CSP systems is being sold at a higher price than electricity from PV systems. The price difference reflects the higher cost of producing electricity with CSP, which is not currently competitive with PV systems. For that reason, no new CSP plants have been planned since 2011, and many previously planned CSP projects have been changed to PV projects or canceled entirely (Bolinger and Seel 2016).

Sources

Bolinger, M., and J. Seel. 2015. *Utility-scale Solar 2014: An Empirical Analysis of Project Cost, Performance, and Pricing Trends in the United States.* Lawrence Berkeley National Laboratory. https://emp.lbl.gov/sites/all/files/lbnl-1000917.pdf.

———. 2016. *Utility-scale Solar 2015: An Empirical Analysis of Project Cost, Performance, and Pricing Trends in the United States.* Lawrence Berkeley National Laboratory. https://emp.lbl.gov/sites/default/files/lbnl-1006037_report.pdf.

Bolinger, M., J. Seel, and K.H. LaCommare. 2017. *Utility-scale Solar 2016: An Empirical Analysis of Project Cost, Performance, and Pricing Trends in the United States.* Lawrence Berkeley National Laboratory. https://emp.lbl.gov/sites/default/files/utility-scale_solar_2016_report.pdf.

1c: Electricity Produced → Fossil Fuel Use

Description of Relationship

A 1-kWh increase in solar energy generation causes a decrease in fossil fuel energy generation of 1 kWh.

Summary of Evidence

A 1:1 relationship between increased renewable energy generation (including solar energy) and decreased fossil fuel energy generation is assumed by most energy analysts and the Intergovernmental Panel on Climate Change (IPCC) (York 2012). However, one analysis of energy sources over the past 50 years found that a 1-kWh increase in electricity production from renewable energy sources was associated with a 0.08-kWh–0.09-kWh decrease in electricity production from nonrenewable sources. This relationship is likely due in part to the existing energy grid's design, which does not accommodate the inherent variability of solar energy; electricity storage or backup generation sources are required to allow solar energy to be widely adopted as a replacement for fossil fuels (York 2012; Kroposki et al. 2017).

Since the early 2000s, the use of coal to generate electricity has dropped while the use of renewable energy sources (including solar) and natural gas has increased. According to the Energy Information Administration's (EIA) *Annual Energy Outlook 2017,* the use of coal will continue to fall and natural gas and renewables to rise. Cheaper solar power technologies combined with government subsidies may help to shift electricity generation from coal and natural gas to solar.

Strength of Evidence

Fair: A 1:1 relationship is assumed in many energy analyses conducted by reputable sources, but there is some evidence that this assumption is not valid in all cases (York 2012).

Other Factors

Location

The location of a new solar energy facility and the other electricity-generating facilities nearby may influence this relationship (e.g., when a solar energy facility is built to replace a fossil fuel plant).

Technology

Technology has no effect on the relationship.

Sources

EIA (Energy Information Administration). 2017. *Annual Energy Outlook 2017*. U.S. Energy Information Administration. www.eia.gov/aeo.

Kroposki, B., B. Johnson, Y. Zhang, V. Gevorgian, P. Denholm, B.-M. Hodge, and B. Hannegan. 2017. "Achieving a 100% Renewable Grid: Operating Electric Power Systems with Extremely High Levels of Variable Renewable Energy." *IEEE Power and Energy Magazine* March/April 2017: 61–73.

York, R. 2012. "Do Alternative Energy Sources Displace Fossil Fuels? *Nature Climate Change* 2(6): 441–443.

1d: Fossil Fuel Use → GHG Emissions

Description of Relationship

The replacement of 1 MWh of electricity generation from fossil fuels with solar power results in a carbon dioxide (CO_2) emissions reduction of 168–906 kg, depending on the solar technology and fossil fuel plant type (Hertwich et al. 2015).

Summary of Evidence

Greenhouse gas (GHG) emissions from electricity production have been estimated for various energy sources through life-cycle analysis. One study that directly compared emissions from solar energy to other energy sources found that GHG emissions were 16–57 kg CO_2-eq/MWh (depending on panel type) from solar PV systems, 33 kg/MWh from CSP tower systems, and 23 kg/MWh from concentrating solar power trough systems. GHG emissions from fossil fuels were 791–922 kg CO_2-eq /MWh from plants with no carbon capture and storage (CCS) system and 201–527 kg/MWh from plants with carbon capture and storage (CCS) systems (Hertwich et al. 2015). Therefore, the maximum reduction in GHG emissions from replacing electricity generation from fossil fuels with solar power—906 kg CO_2-eq/MWh—would be expected if a solar PV system replaces a fossil fuel plant with no CCS. The minimum reduction in GHG emissions from replacing electricity generation from fossil fuels with solar power—168 kg CO_2-eq/MWh—would be expected if a CSP tower system replaces a fossil fuel plant with CCS.

The life-cycle GHG emissions from fossil fuel electricity production estimated by Hertwich et al. (2015) are generally consistent with another life-cycle analysis that found emissions ranging from 700 kg to 1100 kg CO2-eq/MWh for non-CCS fossil fuel systems, depending on the specific fuel type, and that CCS systems can decrease emissions by 60%–80% (Schreiber et al. 2012). A meta-analysis of life-cycle GHG emissions for solar photovoltaics found a mean of 49.9 kg CO_2-eq/MWh, which is within the range reported by Hertwich et al. (Nugent and Sovacool 2014).

However, these estimates of emissions from fossil fuel plants do not take into account the difference between marginal and average emissions factors. Marginal power generators, the last ones needed to meet power demands, are the generators that will be displaced due to an increase in electricity production from solar energy (Siler-Evans et al. 2012). Often, these marginal sources are older and have higher GHG emissions than the average source, so reductions in GHG emissions from replacing these sources with solar energy facilities are greater than would be suggested by the differences in average values for GHG emissions. Only one study was found that calculated marginal GHG emissions from electricity production; it used data from the Environmental Protection Agency's (EPA) Continuous Emissions Monitoring Program for fossil fuel power plants, which includes emissions from only the power generation portion of the life cycle (Siler-Evans et al. 2012). It also estimated CO_2 emissions, not CO_2-equivalent emissions (which include other greenhouse gases). For these reasons, the emissions values from this study are an underestimate of total life-cycle GHG emissions from marginal power sources and cannot be directly compared with the above-noted life-cycle emissions for solar energy. However, this study does suggest that the initial reduction in greenhouse gases would be greater in areas with a higher proportion of older power plants, which tend to be less efficient and have higher emissions than newer plants.

The AVoided Emissions and geneRation Tool (AVERT) developed by the Environmental Protection Agency can estimate the reductions in greenhouse gas (CO_2, sulfur dioxide or SO_2, and nitrogen oxides or NO_X) emissions resulting from various energy efficiency and renewable energy programs, including an increase in utility-scale solar PV capacity (EPA 2017). The tool is based on historical power generation, emissions, and demand data on a regional scale; regions correspond to electricity market modules. Although not intended for fine-scale or long-term analyses, AVERT can provide a quick estimate of the GHG emissions reductions expected from a new utility-scale solar PV facility.

Strength of Evidence

High: Multiple life-cycle analyses using well-documented and accepted methods provide fairly consistent GHG emissions values for solar and fossil fuel energy sources in the United States (Hertwich et al. 2015; Schreiber et al. 2012; Nugent and Sovacool 2014), and GHG emissions from solar energy are consistently lower than from fossil fuel sources.

Predictability: The AVERT tool can estimate the GHG emissions reductions associated with an increase in utility-scale PV capacity, and the emissions estimates from life-cycle analyses can be used to get an idea of the magnitude of GHG emissions reductions that might be expected from the replacement of a given fossil fuel technology with solar energy. However, the estimated fossil fuel GHG emissions in life-cycle analyses do not represent the marginal emissions, which are emissions from the fossil fuel plants that will actually be replaced by increased solar energy production.

Other Factors

Location

No matter the region, a solar PV plant will contribute a fraction of the GHG emissions compared to a fossil fuel plant. However, the specific avoided emissions will depend on the marginal fuel sources and their associated emissions factors in each region. For example, solar developments in the Midwest region could result in up to 40% more avoided CO_2 emissions than in the West region, simply because the primary marginal fuel source in the Midwest is coal, which has higher emissions than gas, the primary marginal fuel source in the West. Table 3 shows the marginal fuel sources for the eight U.S. North American Electric Reliability Corporation (NERC) regions as of 2012. Although the marginal fuel sources may have shifted since then, the regional differences shown here likely persist. As power generation shifts toward more renewable sources, the marginal emissions factors will change, and the GHG emissions benefits from replacing fossil fuel plants with solar energy plants will shift. No studies have been found that show changes in marginal emissions factors as power generation shifts to renewable sources.

Table 3. Percent marginal fuel source for eight NERC regions

NERC regions	Coal	Gas	Oil
FRCC – Florida	17	71	12
MRD – Midwest	79	20	0
NPCC – Northeast	8	81	11
RFC – Mid-Atlantic	70	29	0
SERC – Southeast	55	45	0
SPP – Southwest	35	65	0
TRE – Texas	16	84	0
WECC - West	14	86	0

Source: Siler-Evans et al. (2012).

Technology

Because the primary source of CO_2 emissions associated with solar energy production is manufacturing, the different materials and manufacturing techniques used for different types of solar technology result in different amounts of CO_2 emissions.

Sources

Hertwich, E.G., T. Gibon, E.A. Bouman, A. Arvesen, S. Suh, G.A. Heath, J.D. Bergesen, A. Ramirez, M.I. Vega, and L. Shi. 2015. “Integrated Life-cycle Assessment of Electricity-supply Scenarios Confirms Global Environmental Benefit of Low-carbon Technologies.” *PNAS* 112(20): 6277–6282.

Nugent, D., and B.K. Sovacool. 2014. “Assessing the Lifecycle Greenhouse Gas Emissions from Solar PV and Wind Energy: A Critical Meta-survey.” *Energy Policy* 65: 229–244.

Schreiber, A., P. Zapp, and J. Marx. 2012. “Meta-analysis of Life Cycle Assessment Studies on Electricity Generation with Carbon Capture and Storage.” *Journal of Industrial Ecology*16(S1): S155–S168.

Siler-Evans, K., I.L. Azevedo, and M.G. Morgan. 2012. “Marginal Emissions Factors for the U.S. Electricity System.” *Environmental Science and Technology* 46: 4742–4748. DOI: 10.1021/es300145v.

U.S. EPA (Environmental Protection Agency). 2017. Avoided Emissions and geneRation Tool (AVERT) User Manual, version 1.6. https://www.epa.gov/sites/production/files/2017-07/documents/avert_user_manual_07-31-17_508.pdf.

1e: GHG Emissions → Social Cost of Carbon

Description of Relationship

The emission of one metric ton of CO_2 in 2020 has a social cost of approximately $42 (2007 dollars, at a 3% discount rate).

Summary of Evidence

The social cost of carbon, expressed as the economic value of impacts caused by the emission of an additional metric ton of CO_2 in a given year, can be estimated through modeling. A variety of models have been used to estimate the social cost of carbon; a range of values results from differences in model structure and input parameters. The U.S. Interagency Working Group (IWG) on the Social Cost of Greenhouse Gases developed a widely used estimate by integrating three models (FUND, DICE, and PAGE) based on economics and climate science; the models were weighted equally to develop the final social cost of carbon estimates (Table 3) (IWG 2016; NASEM 2017).

Table 4. Social cost (2007 $) of emitting 1 metric ton of CO_2, by year of emission and discount rate

	Discount rate		
Year	5%	3%	2.5%
2015	$11	$36	$56
2020	$12	$42	$62
2025	$14	$46	$68
2030	$16	$50	$73
2035	$18	$55	$78
2040	$21	$60	$84
2045	$23	$64	$89
2050	$26	$69	$95

Source: IWG (2016).

A recent study that updated the DICE model gave results within 10% of the IWG estimates (Nordhaus 2014).

Strength of Evidence

Moderate: The IWG's social cost of carbon estimates are based on integrated assessment models that are generally accepted, but the specific cost projections vary among the models, and some of the assumptions and techniques used in these estimates have been identified as being inaccurate or in need of improvement (NASEM 2017).

Sources

IWG (Interagency Working Group on Social Cost of Greenhouse Gases). 2016. Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis. https://19january2017snapshot.epa.gov/sites/production/files/2016-12/documents/sc_co2_tsd_august_2016.pdf.

NASEM (National Academies of Sciences, Engineering, and Medicine). 2017. *Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide.* Washington, DC: The National Academies Press.

Nordhaus, W. 2014. "Estimates of the Social Cost of Carbon: Concepts and Results from the DICE-2013R Model and Alternative Approaches." *Journal of the Association of Environmental and Resource Economists* 1(1/2): 273–312.

2a: Solar Development → Number of Jobs Created

Description of Relationship

Each gigawatt hour (GWh) of electricity generated by solar PV energy creates approximately 0.87 job-years (0.58 from construction, installation, and manufacturing and 0.28 from operation and maintenance), and each GWh of electricity generated by solar thermal energy creates 0.23 job-years (0.08 from construction, installation, and manufacturing and 0.15 from operation and maintenance) (Wei, Patadia, and Kammen 2010).

Summary of Evidence

The employment estimates listed above are from a synthesis of renewable energy job creation studies and include jobs related to manufacturing, construction, installation, operations, and maintenance (Wei, Patadia, and Kammen 2010). According to a 2016 survey of 3,888 solar energy companies in the United States conducted by The Solar Foundation, solar energy had the second-highest employment among energy sectors, behind only oil/petroleum, even though solar energy only accounted for 1.3% of all U.S. energy production.

Strength of Evidence

High: The relationship between the installation and operation of a solar energy facility and job creation is clear and straightforward, as shown by the employment estimates generated from a synthesis of several studies of job creation from renewable energy sources in the United States.

Predictability: The synthesis study of employment in renewable energy industries can be used to get a sense of the magnitude of job creation by solar energy development. The methods used for the synthesis were well-documented and appropriate, but the number of included studies was small (three each for solar photovoltaics and solar thermal energy), and there was a wide range of employment values among the included studies, especially for photovoltaics (Wei, Patadia, and Kammen 2010). In addition, while the employment estimates for solar thermal systems are by necessity for utility-scale systems, the estimates for photovoltaic systems include jobs related to small-scale residential and commercial installations as well as larger utility-scale systems. The small-scale PV systems are less efficient to install than utility-scale systems are, so the reported value is likely higher than the actual employment generated by utility-scale systems.

Other Factors

Location

Because many solar jobs are localized (especially installation/maintenance), net employment gains or losses due to shifts from non-renewable energies to solar energy will vary by region (Wei, Patadia, and Kammen 2010). However, solar energy production is possible throughout the United States; the top 20 states in terms of solar jobs include northeastern and midwestern states (e.g., Massachusetts, New York, Michigan, and Illinois) as well as southwestern states (e.g., California, Nevada, and Arizona) (The Solar Foundation 2017).

Technology

As stated in the "Description of Relationship," solar facilities using PV technology are expected to create more job-years per GWh of electricity generated than solar facilities using thermal technology (Wei, Patadia, and Kammen 2010).

Sources

The Solar Foundation. 2017. National Solar Jobs Census 2016. http://www.thesolarfoundation.org/solar-jobs-census/.

Wei, M., S. Patadia, and D.M. Kammen. 2010. "Putting Renewables and Energy Efficiency to Work: How Many Jobs Can the Clean Energy Industry Generate in the US?" *Energy Policy* 38(2): 919–931. https://doi.org/10.1016/j.enpol.2009.10.044.

3a: Solar Development → Construction Dust

Description of Relationship

The construction of a solar facility in the Southwest United States generates particulate matter (PM)—approximately 0.11 tons of PM10/acre/month and 0.011 tons of PM2.5/acre/month (Chang et al. 2016).

Temporary link: This link is temporary because dust is only created during the construction of a solar energy facility.

Summary of Evidence

Site preparation and solar plant construction requires grading and excavation (California Energy Commission, California Department of Fish and Wildlife, U.S. Bureau of Land Management, and U.S. Fish and Wildlife Service 2014). These activities disrupt the soil surface, facilitating wind erosion and creating dust. The PM emissions factors listed in "Description of Relationship" are for moderate- to high-impact construction activities; solar development likely requires lower-impact activities, so the emissions factors may overestimate dust creation from solar development (Chang et al. 2016).

Likely negligible link: This link is likely to be negligible due to the relatively low-impact construction required for solar energy installations and the temporary nature of PM emissions. However, this link has been retained in the simplified model due to possible human health effects (see link 3f).

Strength of Evidence

Fair: No meta-analyses or studies of dust generation specifically from solar development were found, but the potential for dust generation is often considered during the planning process for solar energy development (Chang et al. 2016).

Predictability: Generally accepted PM emissions factors for construction activities can be used to estimate the amount of generated dust, but as noted above, these emissions factors are for higher-impact activities and may overestimate the dust created by solar energy construction.

Other Factors

Location

Climate factors and soil types associated with certain locations affect the amount of dust created and how far it spreads. Dust creation is positively correlated with soil silt content and negatively correlated with soil moisture content (U.S. EPA 1995).

Technology

Different types of solar technology require different site preparation and construction activities, therefore producing different amounts of dust. No studies have been found that examine differences in dust creation associated with different solar technologies.

Other

Dust creation from construction is positively correlated with average vehicle speed and weight (U.S. EPA 1995).

The percentage of vegetation removed during construction and the dust suppression strategies used will influence the amount of dust produced (Chang et al. 2016).

Sources

Chang, Y.-S., R. Kotamarthi, H.M. Hartmann, T. Patton, and M. Finster. 2016. Modeling of Dust Levels Associated with Potential Utility-scale Solar Development in the San Luis Valley-Taos Plateau Study Area. Environmental Science Division, Argonne National Laboratory.

California Energy Commission, California Department of Fish and Wildlife, U.S. Bureau of Land Management, and U.S. Fish and Wildlife Service. 2014. Draft Desert Renewable Energy Conservation Plan (DRECP) and Environmental Impact Report/Environmental Impact Statement. California Energy Commission, California Department of Fish and Wildlife, U.S. Bureau of Land Management, U.S. Fish and Wildlife Service.

U.S. EPA (Environmental Protection Agency). 1995. "Heavy Construction Operations." In *AP-42 Compilation of Air Pollutant Emission Factors,* 5th edition. Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency. https://www3.epa.gov/ttn/chief/ap42/ch13/final/c13s02-3.pdf.

———. 2003. AERMOD: Latest Features and Evaluation Results. U.S. EPA Office of Air Quality Planning and Standards. https://www3.epa.gov/ttn/scram/7thconf/aermod/aermod_mep.pdf.

3b: Construction Dust → Particulate Air Pollution

Description of Relationship

The dust created by the construction of a solar energy site is dispersed in the atmosphere, creating particulate air pollution. Computer models can be used to predict the location and magnitude of air quality effects from particulate emissions.

Temporary link: This link is temporary because it results from a temporary link (see link 3a).

Summary of Evidence

Dust produced from the construction of solar developments includes particulate matter (PM10 and PM2.5) that can cause air quality concerns for people in surrounding areas. Fine particles can travel from hundreds to thousands of kilometers; coarser particles from <1–10s of kilometers (Chang et al. 2016). To determine where and to what extent PM emissions will affect air quality, a computer model can be used. An EPA model (AERMOD) is widely used to simulate the dispersion of dust from construction projects; evaluation of the latest version of AERMOD with primary datasets shows that it performs better than the older ISC3 model, which it replaced (U.S. EPA 2003).

Recent PM modeling of potential solar projects in solar energy zones (SEZs) in Colorado and New Mexico predicted the following air quality effects due to the construction of a 3,000-acre solar development over one year: a maximum increase in 24-hour PM10 ranging from 374–569 $\mu g/m^3$ at the development site and 81–230 $\mu g/m^3$ about one mile from the site and an increase in 24-hour PM2.5 concentrations of 26–40 $\mu g/m^3$ at the development site and 3.8–15 $\mu g/m^3$ about one mile from the site. Annual PM-2.5 concentrations were predicted to increase 6–10 $\mu g/m^3$ at the development site and ~2 $\mu g/m^3$

about one mile from the site. This modeling was conservative and represents a worst-case scenario for these areas (Chang et al. 2016).

Likely negligible link: This link is likely to be negligible due to the relatively low-impact construction required for solar energy installations and the temporary nature of PM emissions. However, this link has been retained in the simplified model due to possible human health effects (see link 3f).

Strength of Evidence

Moderate: Although no studies were found that measured actual PM air pollution during the construction of a solar facility, any particulate matter created during construction will change the air quality for at least a short time where it is emitted. Impact assessments for solar energy development projects consider potential effects on particulate matter concentrations (Chang et al. 2016).

Predictability: Sophisticated dust models allow the amount of particulate air pollution created by a specific solar development project to be predicted, taking into account the project location, local climate and meteorological conditions, transport and deposition of particulate matter, and dust control measures (Chang et al. 2016).

Other Factors

Location

As noted in link 3a, the amount of particulate matter produced will depend on the predominant soils in the area and the exposure to erosive wind forces.

Technology

As noted in link 3a, the different site preparation and construction activities required by different types of solar technology are likely to create different amounts of particulate matter. No studies have been found that examine differences in PM emissions associated with different solar technologies.

Sources

Chang, Y.S., R. Kotamarthi, H.M. Hartmann, T. Patton, and M. Finster. 2016. Modeling of Dust Levels Associated with Potential Utility-Scale Solar Development in the San Luis Valley-Taos Plateau Study Area. Environmental Science Division, Argonne National Laboratory. Prepared for the Bureau of Land Management.

U.S. EPA (Environmental Protection Agency). 2003. AERMOD: Latest Features and Evaluation Results.

U.S. EPA Office of Air Quality Planning and Standards. https://www3.epa.gov/ttn/scram/7thconf/aermod/aermod_mep.pdf.

3e: Recreation → Value of Recreational Activity to Participants

Description of Relationship

Each day of "general recreation" has an average consumer surplus value of $40.66–$126.54, depending on location (U.S. region). Values of more specific types of recreation (hiking, camping, hunting, fishing) can be estimated with meta-regression calculators from the U.S. Geological Survey's (USGS) Benefit Transfer Toolkit or with unit value transfers from previous studies.

Summary of Evidence

The USGS Benefit Transfer Toolkit provides several options for estimating economic value for a variety of recreational activities within the United States. The toolkit is based on a database of more than 2,000 individual nonmarket valuation estimates. The most useful tools are the meta-regression calculators for values of fishing, hunting, trail use, and wildlife viewing. These calculators take into account the region, type of wildlife species involved, and land ownership type. They can be used to estimate the value of a day of recreation in a certain location. All values are in 2014 dollars.

For recreation types for which no meta-regression is available, a unit value transfer (using results from a primary study at one site to estimate benefits at another site) provides an alternate approach. These estimates may be the best approach available, but users need to be aware that a unit value transfer can introduce significant uncertainty and that using meta-regressions (described above) or developing site- and context-specific estimates is a better approach if those estimates are an important component in a decision (Wainger et al. 2016). If a study exists within the USGS Nonmarket Valuation Database that closely matches the recreation type and site being evaluated, it can be used for a point estimate benefit transfer. Average values for studies in a particular geographic region can also be used for a benefit transfer if no individual study is a good match. Table 5 lists average values for several types of recreational activities in the Intermountain and Pacific Coast regions.

Table 5. Average values for recreational activities in the Intermountain and Pacific Coast regions

Activity	Intermountain	Pacific Coast
Hiking	$95.96	$50.30
Camping	$22.11	$29.11
Fishing (freshwater)	$78.83	$71.35
Hunting (big game / small game)	$87.07 / $64.90	$83.80 / $183.65
Off-highway vehicle	$61.80	$43.90
Wildlife viewing	$66.13	$94.02

Source: USGS Benefit Transfer Toolkit

The Recreation Use Values Database (RUVD) is another compilation of valuation studies for recreation; it includes studies conducted across North America and was last updated in 2016 (RUVD 2016).

Strength of Evidence

High: Many individual valuation studies for recreation have been conducted across the United States, including the southwest; these show that participants in a wide variety of recreational activities do place value on those activities.

Predictability: As described above, data from the online databases and associated meta-regressions can be used to estimate the value of certain recreational activities. The USGS Benefit Transfer Toolkit database appears to be fairly complete, but it is unclear how recently it has been updated; some more recent valuation studies may not be included. The RUVD was recently updated and can be used for unit value transfers, but it does not include meta-regressions. Application of meta-regressions can be better than use of average and point estimates (Wainger et al. 2016). The similarity between the site in which the study was conducted and the target site influences which benefit transfer method is most appropriate and how accurate the transfer will be (Bateman et al. 2011).

Other Factors

Location

As described above, values for certain recreational activities vary by region, likely due to differences in quality of recreational experiences and costs of living across regions.

Recreational Activity

As shown in Table 4, values vary greatly by type of recreational activity.

Sources

Bateman, I.J., R. Brouwer, S. Ferrini, M. Schaafsma, D.N. Barton, A. Dubgaard, …, and D. Seméniené. 2011. "Making Benefit Transfers Work: Deriving and Testing Principles for Value Transfers for Similar and Dissimilar Sites Using a Case Study of the Non-market Benefits of Water Quality Improvements across Europe." *Environmental Resource Economics* 50: 365–387.

RUVD (Recreation Use Values Database). 2016. Corvallis, OR: Oregon State University, College of Forestry. http://recvaluation.forestry.oregonstate.edu/. Accessed Nov. 2, 2017.

Wainger, L.A., R.J. Johnston, K.J. Bagstad, C.F. Casey, and T. Vegh. 2016. "Benefit Assessment: Monetary Valuation." In *Federal Resource Management and Ecosystem Services Guidebook,* 2nd ed. Durham: National Ecosystem Services Partnership, Duke University. https://nespguidebook.com/assessment-framework/monetary-valuation/.

USGS. (United States Geological Survey). N.d. Benefit Transfer Toolkit. https://my.usgs.gov/benefit-transfer/.

3f: Particulate Air Pollution → Public Health: Physical

Description of Relationship

Short-term 10-μg/m^3 increases in PM2.5 exposure have been associated with all-cause mortality increases of 0.8%–2.14% (Kim et al. 2015; Shi et al. 2016). Long-term 10-μg/m^3 increases in PM2.5 exposure have been associated with all-cause mortality increases of 1.5%–7.52% (Schwartz et al. 2002; Shi et al. 2016). Long-term 10 μg/m^3 increases in PM2.5 exposure have also been linked to increases in cardiovascular and cardiopulmonary mortality of 9%–76% and increases in respiratory mortality of 1.68%–2.2% (Anderson et al. 2012).

Short-term 10-μg/m^3 increases in PM10 exposure have been associated with all-cause mortality increases of 0.5%–0.6% (Anderson et al. 2012; Kim et al. 2015) as well as increases in cardiopulmonary mortality of 0.7% (Anderson et al. 2012). Long-term 10 μg/m^3 increases in PM10 exposure have been linked to increases in respiratory mortality of 0.6%–1.3% (Anderson et al. 2012).

Summary of Evidence

The size of a particle determines where it can travel within the human body, and therefore what health effects it can cause. Particles less than 10 μm in diameter can enter the respiratory tract; particles 5–10 μm are most likely to be deposited in the tracheobronchial tree and particles 1–5μm in the respiratory bronchioles and alveoli. Depending on their location, particles can interfere with gas exchange and penetrate the lungs before moving into the bloodstream (Kim et al. 2015). A review of epidemiologic research of PM health effects found that exposure to particulate air pollution has been associated with respiratory diseases, including asthma, reduced lung function, and lung cancer, as well as cardiovascular diseases, including myocardial infarction and congestive heart failure (Kim et al. 2015). A second review found that many individual studies demonstrate a relationship between long-term exposure to high PM levels and elevated risks of mortality from lung cancer, cardiopulmonary disease, and congestive heart failure. Short-term exposure to high PM levels has been associated with increased hospital admissions and cardiopulmonary mortality. High PM levels have been found to increase the incidence of bronchitis and asthma symptoms, use of rescue inhalers, and lung function (Anderson et al. 2012).

Many studies that assessed the shape of a dose-response relationship for particulate matter have found evidence for a linear or near-linear relationship between PM exposure and human health effects, suggesting that there is no threshold PM2.5 concentration (within the concentration ranges studied) below which no health impacts are observed (U.S. EPA 2011; Schwartz et al. 2002). Most experts on the health effects of particulate matter believe that there is no threshold in the relationship between PM2.5 concentration and mortality at the population level, and the EPA uses a no-threshold model for PM2.5 health effects (U.S. EPA 2010). This means that any increase in PM concentrations is expected to have adverse human health effects. A recent large-scale study of PM2.5-related mortality in New England found that short-term (two-day) and long-term (one-year) exposure to PM2.5 was associated with increases in all-cause mortality even at concentrations far below the EPA standards, which were 12 μg/m^3 annual average PM2.5 and 35 μg/m^3 daily PM2.5 as of 2016 (Shi et al. 2016).

Likely negligible link: This link is likely to be negligible due to the relatively low-impact construction required for solar energy installations (see link 3a), the temporary nature of PM emissions, and the rural context of BLM solar installations. However, this link has been retained in the simplified model due to possible human health effects.

Strength of Evidence

Moderate: No meta-analyses determining specific dose-response relationships between PM levels and human disease incidence exist, but large-scale epidemiologic studies have assessed the dose-response relationship and found little evidence for a threshold. In addition, many individual studies using established epidemiological methods demonstrate a relationship between exposure to particulate matter and adverse human health outcomes. Two reviews of the research found that there is consistent evidence of adverse health effects from PM exposure.

Other Factors

Location

The exact location of the installation will determine who is affected by particulate matter; a geographically specific analysis incorporating air quality modeling can be used to identify the affected population.

Technology

The technology has no effect.

Other

Health effects from PM air pollution are especially pronounced in high-risk populations (e.g., the elderly, children, people with asthma or COPD) (Anderson et al. 2012).

Sources

Anderson, J.O., J.G. Thundiyil, and A. Stolbach. 2012. "Clearing the Air: A Review of the Effects of Particulate Matter Air Pollution on Human Health." *Journal of Medical Toxicology* 8(2): 166–175.

Chang, Y.S., R. Kotamarthi, H.M. Hartmann, T. Patton, and M. Finster. 2016. "Modeling of Dust Levels Associated with Potential Utility-Scale Solar Development in the San Luis Valley-Taos Plateau Study Area." Environmental Science Division, Argonne National Laboratory. Prepared for Bureau of Land Management.

Kim, K.-H., E. Kabir, and S. Kabir. 2016. "A Review of the Human Health Impact of Airborne Particulate Matter." *Environment International* 74: 136–143.

Lovich, J.E., and J.R. Ennen. 2011. "Wildlife Conservation and Solar Energy Development in the Desert Southwest, United States." *Bioscience* 61: 982–992. doi:10.1525/bio.2011.61.12.8.

Pope, C.A. III, M. Ezzati, and D.W. Dockery. 2009. "Fine-particulate Air Pollution and Life Expectancy in the United States." *The New England Journal of Medicine* 360: 376–386.

Schwartz, J., F. Laden, and A. Zanobetti. 2002. "The Concentration-Response Relation between PM2.5 and Daily Deaths." *Environmental Health Perspectives* 110(10): 1025–1029.

Shi, L., A. Zanobetti, I. Kloog, B.A. Coull, P. Koutrakis, S.J. Melly, and J.D. Schwartz. 2016. "Low-concentration PM2.5 and Mortality: Estimating Acute and Chronic Effects in a Population-based Study." *Environmental Health Perspectives* 124(1): 46–52.

Sullivan, R., J. Abplanalp, E. Zvolanek, and J. Brown. 2016. Visual Resource Analysis for Solar Energy Zones in the San Luis Valley. Environmental Science Division, Argonne National Laboratory. Prepared for Bureau of Land Management.

U.S. EPA (Environmental Protection Agency). 2010. Summary of Expert Opinions on the Existence of a Threshold in the Concentration-Response Function for $PM_{2.5}$-related Mortality. Office of Air Quality Planning and Standards. https://www3.epa.gov/ttnecas1/regdata/Benefits/thresholdstsd.pdf.

———. 2011. Policy Assessment for the Review of the Particulate Matter National Ambient Air Quality Standards. EPA 452/R-11-003. Office of Air Quality Planning and Standards. https://www3.epa.gov/ttn/naaqs/standards/pm/data/20110419pmpafinal.pdf.

3g: Public Health: Physical → Burden of Disease

Description of Relationship

The societal effect of adverse physical health outcomes is captured by the burden of disease, which can be quantified using non-monetary indicators, such as disability-adjusted life years (DALY) and monetary valuation, including value of statistical life and cost of illness estimates.

Summary of Evidence

The DALY metric of the environmental burden of disease is widely used by governmental and non-governmental organizations as a policy evaluation tool. Required data to calculate DALYs lost due to a particular cause include population exposure to the cause, an exposure-response relationship for each outcome, an estimate of the proportion of disease that is attributable to the cause, an estimate of the prevalence of each outcome, and a disability weight value for each outcome (Theakston et al. 2011). The equations used to calculate DALYs lost to adverse health outcomes is as follows:

DALYs lost = years lived with disability (YLD) + years lost to premature mortality (YLL)

YLD = number of cases (I) * disability weight (DW) * average duration of disability, years (L)

YLL = number of deaths (N) * standard life expectancy at the age at which death occurred (L)

Disability weights for a variety of outcomes have been assessed by the World Health Organization (Table 6).

Table 6. Disability weights for physical health incomes potentially affected by solar energy development

Outcome	Disability weight[a]
Asthma	0.043
Myocardial infarction	0.439
Congestive heart failure	0.201
Lung cancer	0.15 (diagnosis/therapy/waiting stage), 0.75 (metastasis stage), 0.81 (terminal stage)
Non-Hodgkins' lymphoma	0.06 (diagnosis/therapy/waiting stage), 0.75 (metastasis stage), 0.81 (terminal stage)
Hearing loss, adult onset	0–0.333, depending on severity and treatment
Low vision	0.17
Blindness	0.43–0.6

Source: World Health Organization 2004
[a] Disability weights are on a scale from 0 to 1, with 0 corresponding to a healthy person.

Another approach to measuring the economic effect of a change in mortality rates is through a value of statistical life metric, which is the value of avoiding one mortality, often used by government agencies for policy cost-benefit analyses. This value can be estimated with stated preference surveys that capture people's willingness to pay to reduce the risk of mortality or revealed preferences, but ranges in the estimates are large and vary according to methodological factors (Lindhjem et al. 2011). The current value of statistical life used by the U.S. EPA is $7.4 million ($2006) (U.S. EPA).

The EPA also publishes medical costs of illness estimates, which capture only direct medical costs associated with an illness, not all other costs related to an illness (lost work and educational time, support services, opportunity costs, costs to unpaid caregivers, anxiety, and suffering) and therefore represent a lower boundary. The 2007 version of the EPA handbook uses cost data from the 1980s and 1990s in many cases and is therefore out of date, but it includes medical cost estimates for several relevant conditions, including lung cancer, asthma, and symptoms such as eye irritation and sinus congestion (EPA 2007).

Strength of Evidence

Moderate: The social costs of poor public health are widely recognized and measured using a variety of monetary and non-monetary metrics. The DALY is a widely used nonmonetary metric for the environmental burden of disease. Its accuracy in estimating the burden of a particular disease depends on the evidence available for the components needed to calculate DALY (see Description of Relationship and Summary of Evidence sections) for that disease. The value of a statistical life metric is widely used but is subject to high variability, depending on how it is measured, and the EPA's cost of illness estimates are based on outdated information.

Other Factors

Location

Exposure to causes of disease and availability of treatment vary by location and affect the number of cases or deaths and disability weights used to calculate DALYs.

Technology

Different types of solar energy technology can create different amounts of air pollution and noise, which result in varying health effects (see links 3a, 4a, and 5a).

Sources

Lindhjem, H., S. Navrud, N.A. Braathen, and V. Biausque. 2011. "Valuing Mortality Risk Reductions from Environmental, Transport, and Health Policies: A Global Meta-analysis of Stated Preference Studies." *Risk Analysis* 31(9): 1381–1407.

Theakston, F., ed. 2011. *Burden of Disease from Environmental Noise: Quantification of Healthy Life Years Lost in Europe.* World Health Organization Regional Office for Europe. http://www.euro.who.int/__data/assets/pdf_file/0008/136466/e94888.pdf.

U.S. EPA (Environmental Protection Agency). 2007. *Cost of Illness Handbook*. https://nepis.epa.gov/Exe/ZyPDF.cgi/901A0E00.PDF?Dockey=901A0E00.PDF.
———. Mortality Risk Valuation. https://www.epa.gov/environmental-economics/mortality-risk-valuation.
WHO (World Health Organization). 2004. Global Burden of Disease 2004 Update: Disability Weights for Diseases and Conditions. http://www.who.int/healthinfo/global_burden_disease/GBD2004_DisabilityWeights.pdf.

4a: Solar Development → Traffic Volume

Description of Relationship

During construction of a solar facility, nearby roads will experience additional traffic from workers and materials traveling to and from the construction site.

Temporary link: This link is temporary because traffic volumes on existing roads are only affected during the construction of a solar energy facility.

During operation of a solar facility, nearby roads will experience additional traffic from workers traveling to and from the facility.

Summary of Evidence

Traffic volume, measured in average daily trips to and from a site, is estimated on the basis of the number of workers on the site, the number of truck deliveries to the site, and the work schedule (work hours and total length of project). These variables are project specific and are usually provided by the entity planning the solar facility.

Construction

In general, each construction worker at a site is assumed to add two average daily trips (one arriving at the site in the morning and one leaving the site in the evening), and each construction truck entering or leaving the site is counted as three average daily trips (LOS Engineering 2011).

A traffic study for the Centinela Solar Energy Project (2,000 acres, 275 MW) estimated there would be 1,260 average daily trips to and from the facility during construction (LOS Engineering 2011). A traffic study for the Imperial Solar Energy Center West project (1,130 acres, 250 MW) estimated that there would be 750 average daily trips to and from the facility during construction (LOS Engineering 2010).

Operations

Each operations and maintenance worker at a site is assumed to add two average daily trips (one arriving at the site in the morning and one leaving the site in the evening), and each truck entering or leaving the site is counted as three average daily trips (LOS Engineering 2011). Because the number of average daily trips during operation of a solar facility is much less than during construction, the construction-related traffic levels are usually used to assess potential traffic impacts on surrounding roads (LOS Engineering 2011).

A traffic study for the Centinela Solar Energy Project, a 2,000-acre, 275 MW photovoltaic plant in California, estimates that there will be 15–21 average daily trips to and from the facility during operations, with increases to 40–50 average daily trips when the panels are periodically washed (LOS Engineering 2011). A traffic study for the Imperial Solar Energy Center West project, a 1,130-acre, 250 MW photovoltaic plant in California, estimates that there will be 10–15 average daily trips to and from the facility during operations (LOS Engineering 2010).

Strength of Evidence

Moderate: The construction and operation of a solar energy facility are known to add to traffic volumes, and these impacts are considered during the process of planning a new facility. However, no evidence was found that actually measured the change in traffic during construction and operation of a new solar energy facility.

Sources

LOS Engineering, Inc. 2010. Imperial Solar Energy Center West Traffic Impact Analysis. https://eplanning.blm.gov/epl-front-office/projects/nepa/66156/80544/93666/FAppBISECw_Traffic.pdf.
———. 2011. Centinela Solar Energy Draft Traffic Impact Analysis. http://centinelasolar.com/DocsInfo/Generating%20Facility/Imperial%20County%20Documents/Environmental%20Impact%20Report/Draft%20EIR/17%20App%20C-traffic-analysis.pdf.

4b: Traffic → Sound

Description of Relationship

An increase in traffic levels by XX cars/day increases the L_{eq} (equivalent sound level) by XX dBA (A-weighted decibels, a measure of sound that reflects the sensitivity of the human ear to different frequencies).

Temporary link: This link is temporary because it results from a temporary link (see link 4a).

Summary of Evidence

The sound level produced by road traffic depends on traffic volume, vehicle types (sometimes expressed as the percentage of heavy trucks), traffic speed, and pavement type. The traffic sound level heard by receivers also depends on the distance from the roadway to the receiver and noise attenuation by any intervening barriers. The U.S. Department of Transportation's FHWA Traffic Noise Model (originally released 1998; draft version 3.0 released 2017) predicts traffic sound levels from a database of vehicle sound emissions and acoustic algorithms, taking into account pavement type, constant or interrupted traffic flow, and attenuation by sound barriers, buildings, and vegetation (Menge et al. 1998). The model has been validated through field testing and found to perform well, over-predicting sound levels by an average of 0.5 dBA with no correction for site bias and by an average of 0.2 dBA when calibrated with a reference microphone to remove site bias (Rochat and Fleming 2004). It is widely used for traffic noise modeling and is considered to be a high-quality and accurate model (Steele 2001).

Likely negligible link: This link is likely to be negligible for solar energy projects on BLM lands due to their remote nature and low background traffic levels (see link 4a). However, this link has been retained in the simplified model due to possible human health effects (see links 4c, 4d, and 4e).

Strength of Evidence

Moderate: The relationship between vehicular traffic and sound production is clear and straightforward, but it's not evident that traffic always causes significant changes to the background sound level.

Predictability: The effect of changes in traffic volume on traffic sound levels can be predicted by accepted, validated, and well-documented tools that model traffic sound as a function of traffic volume and other factors.

Other Factors

Location

Location has no effect (assumed).

Technology

The type of solar energy technology in use may affect traffic volumes, and therefore sound levels, if it causes differences in construction workforce and construction project length (see link 4a).

Other

Widespread adoption of electric vehicles, which are much quieter than conventional vehicles, would influence the relationship between traffic volumes and sound levels.

Sources

Menge, C.W., C.F. Rossano, G.S. Anderson, and C.J. Bajdek. 1998. FHWA Traffic Noise Model Version 1.0 Technical Manual. U.S. Department of Transportation Federal Highway Administration. https://www.fhwa.dot.gov/environment/noise/traffic_noise_model/old_versions/tnm_version_10/tech_manual/TNM10TechManual.pdf.

Rochat, J.L., and G.G. Fleming. 2004. Addendum to Validation of the FHWA's Traffic Noise Model (TNM): Phase 1. U.S. Department of Transportation Federal Highway Administration. https://www.fhwa.dot.gov/environment/noise/traffic_noise_model/model_validation/addendum/add25_valid.pdf.

Steele, C. 2001. "A Critical Review of Some Traffic Noise Prediction Models." *Applied Acoustics* 62(3): 271–287.

4c: Sound → Public Health: Physical

Description of Relationship

An increase in sound levels of 10 dBA (A-weighted decibels, a measure of sound that reflects the sensitivity of the human ear to different frequencies) causes an increased risk of disease in exposed persons by XX%.

Summary of Evidence

Exposure to environmental sound has been linked to increased risks for a variety of diseases; the evidence is strongest for hypertension and cardiovascular disease. The pathway by which noise (unwanted sound) exposure causes health effects is likely related to stress caused by arousal of the nervous and endocrine systems and sleep disturbance, but few studies examine noise-related health effects through this pathway (Theakston et al. 2011; Fyhri and Klaeboe 2009; Babisch et al. 2001; Selander et al. 2009).

The amount and strength of evidence for the relationship between noise exposure and disease varies by the disease in question; enough studies exist that meta-analyses were possible for myocardial infarction, hypertension, and coronary heart disease (Theakston 2011; Babisch 2014). A meta-analysis of the relationship between road traffic noise and coronary heart disease, based on 12 studies, found that the relative risk of coronary heart disease increased by 8% for each 10-dbA increase in the weighted day-night noise level, within the range of 52–77 dBA (Babisch 2014). Similarly, a meta-analysis of the relationship between road traffic noise and hypertension found an increase in the relative risk of hypertension of 3.4% for each 5-dBA increase in the 16-hour average noise level when noise levels were between 45 and 75 dBA (van Kempen and Babisch 2012). The risk of myocardial infarction increases when the 16-hour average sound level exceeds 60 dBA, with pooled odds ratios of 1.14–1.19 compared to sound levels below 60 dBA, but these results were not statistically significant (Theakston 2011). One large-scale study on traffic noise exposure and risk of non-Hodgkin's lymphoma found that people exposed to traffic noise above 65 dB (as a 5-year time-weighted mean) had an 18% higher risk for non-Hodgkin's lymphoma than people exposed to traffic noise below 55 dB (as a 5-year time-weighted mean) (Sorensen et al. 2015). Individual studies also suggest links between noise exposure and the use of antihypertensive, anxiolytic, and antacid medication use (Floud et al. 2011) and cardiovascular-related hospital admissions (Hansell et al. 2013; Corriea et al. 2013).

Most studies of health effects from environmental noise focus on transportation noise; similarities between effects of transportation noise and other sources of noise in terms of health effects are unclear.

Likely negligible link: This link is likely to be negligible due to the remoteness of solar development on Bureau of Land Management lands. However, this link has been retained in the simplified model due to possible human health effects.

Strength of Evidence

Fair: Many large-scale observational studies of health effects of environmental noise exist, and meta-analyses have been conducted in certain cases, but studies are unevenly distributed across the various noise-influenced health effects, making it difficult to assess the overall impact of environmental noise on health. The body of evidence for noise effects on certain diseases (e.g., hypertension) is solid and consistent, but little exists for other health effects of noise. The applicability of some studies is limited because of noise source (the overwhelming majority assess only vehicular noise).

Other Factors

Location

The location of a solar energy facility will determine the number of people exposed to increased noise levels.

Technology

The type of solar energy technology may affect this relationship through its influence on traffic and construction noise levels (see links 4a and 5a).

Other

Sound frequency: Small studies have found that exposure to low-frequency sounds influences cortisol levels, causes feelings of tiredness and irritation, increases time to fall asleep (Waye et al. 2013), and causes greater cardiovascular responses than exposure to higher-frequency sounds (Walker et al. 2016). A study of people living near high-traffic roads in Taiwan found that exposure to low-frequency (63 and 125 Hz) sounds and high-frequency (1000 Hz) sounds appears to increase the risk of hypertension more than exposure to medium-frequency sounds (Chang et al. 2014). Because A-weighted sound levels predict exposure to low-frequency sound less accurately than exposure to mid- or high-frequency sound, these results suggest that measuring or modeling low-frequency sound may be necessary to fully capture health impacts of sound exposure (Walker et al. 2017).

Individual susceptibility to noise and noise-influenced diseases may differ; one study found that hypertension and chest pain were related to noise sensitivity, not to the actual noise level, suggesting that some individuals may be especially vulnerable to both health issues and noise (Fyhri and Klaeboe 2009).

Sources

Babisch, W., H. Fromme, A. Beyer, and H. Ising. 2001. "Increased Catecholamine Levels in Urine in Subjects Exposed to Road Traffic Noise: The Role of Stress Hormones in Noise Research." *Environment International* 26: 475–481.

Babisch, W. 2014. "Updated Exposure-Response Relationship between Road Traffic Noises and Coronary Heart Diseases: A Meta-analysis." *Noise and Health* 16(68).

Basner, M., W. Babisch, A. Davis, M. Brink, C. Clark, S. Janssen, and S. Stansfeld. 2014. "Auditory and Non-auditory Effects of Noise on Health." *Lancet* 383: 1325–1332.

Chang, T.-Y., R. Beelen, S.-F. Li, T.-I. Chen, Y.-J. Lin, B.-Y. Bao, and C.-S. Liu. 2014. "Road Traffic Noise Frequency and Prevalent Hypertension in Taichung, Taiwan: A Cross-sectional Study." *Environmental Health* 13: 37.

Correia, A.W., J.L. Peters, J.I. Levy, S. Melly, and F. Dominici. 2013. "Residential Exposure to Aircraft Noise and Hospital Admissions for Cardiovascular Diseases: Multi-airport Retrospective Study." *BMJ* 347, f5561. Doi: http://dx.doi.org/10.1136/bmj.f5561.

Floud, S., F. Vigna-Taglianti, A. Hansell, M. Blangiardo, D. Houthuijs, O. Breugelmans, and L. Jarup. 2011. "Medication Use in Relation to Noise from Aircraft and Road Traffic in Six European Countries: Results of the HYENA Study." *Occupational and Environmental Medicine* 68(7): 518–24. http://doi.org/10.1136/oem.2010.058586.

Fyhri, A., and R. Klaeboe. 2009. "Road Traffic Noise, Sensitivity, Annoyance and Self-reported Health – A Structural Equation Model Exercise." *Environment International* 35(1): 91–97.

Hansell, A.L., M. Blangiardo, L. Fortunato, S. Floud, K. de Hoogh, D. Fecht, and L. Beale. 2013. "Aircraft Noise and Cardiovascular Disease Near Heathrow Airport in London: Small Area Study." *BMJ* 347. http://dx.doi.org/10.1136/bmj.f5432.

Selander, J., G. Bluhm, T. Theorell, G. Pershagen, W. Babisch, I. Seiffert, and L. Järup. 2009. "Saliva Cortisol and Exposure to Aircraft Noise in Six European Countries." *Environmental Health Perspectives* 117(11): 1713–1717. http://doi.org/10.1289/ehp.0900933.

Sorensen, M., A.H. Poulsen, M. Ketzel, S.O. Dalton, S. Friis, and O. Raaschou-Nielsen. 2015. "Residential Exposure to Traffic Noise and Risk for Non-Hodgkin Lymphoma among Adults." *Environmental Research* 142: 61–65. https://doi.org/10.1016/j.envres.2015.06.016.

Theakston, F., ed. 2011. "Burden of Disease from Environmental Noise: Quantification of Healthy Life Years Lost in Europe." World Health Organization European Centre for Environment and Health, Bonn, Germany.

van Kempen, E., and W. Babisch. 2012. "The Quantitative Relationship between Road Traffic Noise and Hypertension: A Meta-analysis." *Journal of Hypertension* 30: 1075–1086.

Walker, E.D., A. Brammer, M.G. Cherniack, F. Laden, and J.M. Cavallari. 2016. "Cardiovascular and Stress Responses to Short-term Noise Exposures—A Panel Study in Healthy Males." *Environmental Research* 150: 391–397.

Walker, E.D., J.E. Hart, P. Koutrakis, J.M. Cavallari, T. VoPham, M. Luna, and F. Laden. 2017. "Spatial and Temporal Determinants of A-weighted and Frequency Specific sound Levels—An Elastic Net Approach." *Environmental Research* 159: 491–499.

Waye, K.P., A. Clow, S. Edwards, F. Hucklebridge, and R. Rylander. 2003. "Effects of Nighttime Low Frequency Noise on the Cortisol Response to Awakening and Subjective Sleep Quality." *Life Sciences* 72(8): 863–875.

4d: Sound → Nuisance to People

Description of Relationship

The percent of a population "annoyed" by unwanted sound (noise) can be estimated from the DNL (day-night sound level, dBA, A-weighted decibels, a measure of sound that reflects the sensitivity of the human ear to different frequencies) from the following equation (Miedema and Oudshoorn 2001):

$$\% \text{ annoyed} = 1.732 - 10^{-4}(\text{DNL} - 37)^3 + 2.079 - 10^{-2}(\text{DNL} - 37)^2 + 0.566(\text{DNL} - 37)$$

Temporary link: This link is temporary because it results from temporary links (see links 4b and 5a).

Summary of Evidence

A meta-analysis of studies on annoyance caused by transportation noise found the relationship between the day-night sound level (DNL) and the percent of exposed people who were annoyed described above (Miedema and Oudshoorn 2001). DNL can be calculated from the average daytime (LD) and nighttime (LN) sound levels (both in dBA) as follows:

$$DNL = 10\log((15/24) * 10^{LD/10} + (9/24) * 10^{(LN+10)/10})$$

This study also reported the relationships between the DNL and the percent of exposed people who were "a little annoyed" and "highly annoyed" (Miedema and Oudshoorn 2001).

A later study accepted the relationship between sound levels and annoyance found by Miedema and Oudshoorn, but it suggested the use of EDNL, which takes into account on-site sound absorption to more accurately reflect the sound level that people actually hear, instead of DNL (Kryter 2009). The EDNL can be calculated from the DNL as follows:

$$EDNL = DNL - 2\text{ dBA} - \text{sum of on-site attenuations}$$

The 2-dBA correction factor reflects lower annoyance from sounds occurring during the colder months of the year, when people spend less time outside and windows are more likely to be closed. Average on-site attenuation values for houses are listed in Kryter 2009.

These studies all examined the relationship between transportation-related noise and annoyance; no studies were found that specifically examined the relationship between sound level and annoyance for construction noise, but a study that evaluated the effect of construction noise characteristics on annoyance suggests that people may be generally more annoyed by construction noise, which tends to be rougher, than by transportation noise, which is more consistent (see other factors, below).

Likely negligible link: This link is likely to be negligible for solar energy development on BLM lands due to their remote nature and low surrounding populations. However, this link has been retained in the simplified model due to possible human health effects (see link 4e).

Strength of Evidence

Fair: Many studies have examined the relationship between transportation sound and annoyance levels, especially in Europe, and some meta-analyses of those individual studies exist; these use well-documented and accepted methods, but they may not be fully applicable to a U.S. context (Miedema and Oudshoorn 2001). No meta-analyses of nuisance or annoyance caused by construction noise exist, but individual studies have examined this relationship (Lee et al. 2015).

Other Factors

Location

The effects of noise from solar developments on people will depend on the exact location of the installation relative to areas where people live and work.

Technology

As noted in link 5a, different types of solar technology may require different construction activities that result in varying sound levels; these variations should be reflected in sound modeling results.

Other

Ambient sound level: A meta-analysis of stated preference studies suggests that annoyance (and willingness to pay to remove the noise) associated with a 1-dBA increase in noise increases with the ambient sound level (Bristow et al. 2015)

Sound attributes: Combined construction noise (from multiple machines/sources operating simultaneously) was rated as more annoying than an equivalent level of noise from a single source when sound levels were above 65 dBA. Sound roughness was an important factor for the annoyance level of construction noise (Lee et al. 2015).

Individual differences: Certain people will be more or less annoyed than others by a given level of noise (Kryter 2009).

Sources

Bristow, A.L., M. Wardman, and V.P.K. Chintakayala. 2015. "International Meta-analysis of Stated Preference Studies of Transportation Noise Nuisance." *Transportation* 42: 71–100.

Kryter, K.D. 2009. "Acoustical Modeling and Theory for Predicting Effects of Environmental Noise on People." *The Journal of the Acoustical Society of America* 125(6): 3707–3721.

Lee, S.C., H.Y. Hong, and J.Y. Jeon. 2015. "Effects of Acoustic Characteristics of Combined Construction Noise on Annoyance." *Building and Environment* 92: 657–667.

Miedema, H.M.E., and C.G.M. Oudshoorn. 2001. "Annoyance from Transportation Noise: Relationships with Exposure Metrics DNL and DENL and Their Confidence Intervals." *Environmental Health Perspectives* 109(4): 409–416.

Weinhold, D. 2013. "The Happiness-reducing Costs of Noise Pollution." *Journal of Regional Science* 53(2): 292–303.

4e: Noise Nuisance → Public Health: Mental

Description of Relationship

People reporting moderate noise annoyance are 20% more likely to be depressed and 42% more likely to have anxiety than people reporting no noise annoyance (Beutel et al. 2016).

People reporting extreme noise annoyance are 97% more likely to be depressed and 114% more likely to have anxiety compared to people reporting no noise annoyance (Beutel et al. 2016).

Temporary link: This link is temporary because it results from a temporary link (see link 4d).

Summary of Evidence

A large-scale study (15,000 participants) showed that the prevalence of depression and anxiety was substantially higher in people reporting moderate noise annoyance compared to no noise annoyance, and even higher in people reporting extreme noise annoyance (Beutel et al. 2016). Self-reported quality of life has also been shown to decline with noise annoyance, especially in mental health-related quality of life (Dratva et al. 2010).

The World Health Organization's report on environmental noise considers annoyance itself an adverse health outcome with an associated disability weight that can be used to calculate the burden of disease (see link 4f) (Theakston 2011).

Likely negligible link: This link is likely to be negligible for solar energy development on Bureau of Land Management lands due to their remote nature and low surrounding populations. However, this link has been retained in the simplified model due to possible human health effects.

Strength of Evidence

Low: Very limited evidence exists; the relationships described above are from one large-scale study, which was the only one found that directly examined the relationship between noise-induced annoyance and mental health. Another large-scale study that examined self-reported quality of life found that increased noise annoyance was associated with decreased mental-health-related quality of life, which supports this relationship conceptually, but the results of the two studies can't be directly compared due to differences in their measured outcomes. Because these studies are correlative rather than causative, it is possible that people with depression or anxiety are more likely to report being annoyed by noise than people without these conditions, rather than noise annoyance being a contributing factor to depression or anxiety.

Sources

Beutel, M.E., C. Junger, E.M. Klein, P. Wild, K. Lackner, M. Blettner, H. Binder, M. Michal, J. Wiltink, E. Brahler, and T. Munzel. 2016. "Noise Annoyance Is Associated with Depression and Anxiety in the General Population—The Contribution of Aircraft Noise." *PLoS ONE* 11(5).

Dratva, J., E. Zemp, D.F. Dietrich, P.-O. Bridevaux, T. Rochat, C. Schindler, and M.W. Gerbase. 2010. "Impact of Road Traffic Noise Annoyance on Health-related Quality of Life: Results from a Population-based Study." *Quality of Life Research* 19(1): 37–46.

Theakston, F., ed. 2011. "Burden of Disease from Environmental Noise: Quantification of Healthy Life Years Lost in Europe." World Health Organization European Centre for Environment and Health, Bonn, Germany.

4f: Public Health: Mental → Burden of Disease

Description of Relationship

The societal effect of adverse health outcomes is captured by the burden of disease, which can be quantified using several indicators. The use of one indicator, disability-adjusted life years (DALYs), is described below.

Summary of Evidence

The evidence for this link is the same as that for the section of link 3g that describes the use of DALYs to quantify the societal burden of adverse physical health outcomes. This link captures the burden of the adverse mental health outcomes that are associated with noise-related nuisance and increased traffic levels (see links 4e and 4g). Table 8 presents disability weights for relevant mental health outcomes.

Table 8. Disability weights for mental health outcomes potentially affected by solar energy development

Outcome	Disability weight[a]
Annoyance[b]	0.02
Mild depressive episode	0.14
Moderate depressive episode	0.34
Severe depressive episode	0.76
Dysthymia	0.14

Source: World Health Organization (2004).
[a] Disability weights are on a scale from 0 to 1, with 0 corresponding to a healthy person.
[b] The disability weight for annoyance is from Theakston (2011).

Strength of Evidence

Moderate: The social costs of poor public health are widely recognized and measured using a variety of monetary and non-monetary metrics. The DALY is a widely used nonmonetary metric for the environmental burden of disease. Its accuracy in estimating the burden of a particular disease depends on the evidence available for the components needed to calculate DALY (see Description of Relationship and Summary of Evidence sections) for that disease.

Other Factors

Location

Exposure to causes of disease and availability of treatment vary by location and affect the number of cases or deaths and disability weights used to calculate DALYs.

Technology

Different types of solar energy technology can create different amounts of traffic noise, which result in varying mental health effects (see links 4a and 5a).

Sources

Theakston, F., ed. 2011. Burden of Disease from Environmental Noise: Quantification of Healthy Life Years Lost in Europe. World Health Organization Regional Office for Europe.

WHO (World Health Organization). 2004. Global Burden of Disease 2004 Update: Disability Weights for Diseases and Conditions. http://www.who.int/healthinfo/global_burden_disease/GBD2004_DisabilityWeights.pdf.

4g: Traffic → Public Health: Mental

Description of Relationship

Spending time traveling on roads with increased traffic volume increases the probability of an adverse mental health outcome (e.g., depression, anxiety).

Temporary link: This link is temporary because it results from a temporary link (see link 4a).

Summary of Evidence

Multiple studies have found a positive association between increased commuting times or increased traffic congestion and self-reported stress and annoyance levels (Stokols et al. 1978; Gottholmseder et al. 2009; Hansson et al. 2011; Hennessy and Wiesenthal 1997). A small study of Los Angeles bus drivers found that drivers experiencing higher peak traffic conditions had higher levels of urinary stress hormones (Evans and Carrére 1991). Two larger-scale studies that used established protocols for measuring mental health found positive associations between reported traffic stress and depressive symptoms

(Gee et al. 2004) and between commuting time and psychological distress (in women; no such relationship was found in men) (Feng and Boyle 2014).

Likely negligible link: This link is likely to be negligible for solar energy development on Bureau of Land Management lands due to their remote nature and low surrounding populations. However, this link has been retained in the simplified model due to possible human health effects.

Strength of Evidence

Low: Although research about this relationship does exist, and in general supports the idea that traffic congestion causes stress and decreased mental health, many of the identified studies are either small in scale or narrow in focus, and most use self-reported measures of mental health or stress.

Other Factors

Location

The location of a solar facility and its associated traffic relative to metropolitan areas and major commuting routes influences the number of people affected by increased traffic levels.

Technology

Different types of solar energy technology may have different requirements for construction and operations that influence the amount, type, and duration of increased traffic (see link 4a).

Sources

Evans, G.W., and S. Carrére. 1991. "Traffic Congestion, Perceived Control, and Psychophysiological Stress among Urban Bus Drivers. *Journal of Applied Psychology* 76(5): 658–663.

Feng, Z., and P. Boyle. 2014. "Do Long Journeys to Work Have Adverse Effects on Mental Health? *Environment and Behavior* 46(5): 609–625.

Gee, G.C., and D.T. Takeuchi. 2004. "Traffic Stress, Vehicular Burden and Well-being: A Multilevel Analysis." *Social Science and Medicine* 59: 405–414.

Goodwin, P. 2004. The Economic Costs of Road Traffic Congestion. ESRC Transport Studies Unit, University College London. Rail Freight Group. http://discovery.ucl.ac.uk/1259/1/2004_25.pdf.

Gottholmseder, G., K. Nowotny, G. Pruckner, and E. Theurl. 2009. "Stress Perception and Commuting." *Health Economics* 18: 559–576.

Hansson, E., K. Mattisson, J. Björk, P.-O. Östergren, and K. Jakobsson. 2011. "Relationship between Commuting and Health Outcomes in a Cross-sectional Population Survey in Southern Sweden." *BMC Public Health* 11: 834–847.

Hennessy, D.A., and D.L. Wiesenthal. 1997. "The Relationship between Traffic Congestion, Driver Stress and Direct versus Indirect Coping Behaviours." *Ergonomics* 40(3): 348–361.

Stokols, D., R.W. Novaco, J. Stokols, and J. Campbell. 1978. "Traffic Congestion, Type A Behavior, and Stress." *Journal of Applied Psychology* 63(4): 467–480.

4j: Traffic → Animal Deaths

Description of Relationship

The probability of an individual being killed during a road crossing can be calculated with the following equation:

$$P_{\text{killed}} = 1 - (e^{-\text{Na/v}})$$

where N is traffic volume (vehicles/minute), a is the width of the kill zone (meters), and v is the animal's velocity (meters/minute) (Hels and Buchwals 2001). This probability can be combined with an estimate of the number of road crossings an individual makes per year to calculate an annual road mortality rate:

$$P_{\text{killed/year}} = 1 - (1 - P_{\text{killed}})^n$$

where $P_{\text{killed/year}}$ is the probability that an individual of a given species will be killed in a one-year period when it makes n road crossings/year (Litvaitis and Tash 2008).

Temporary link: This link is temporary because it results from a temporary link (see link 4a).

Summary of Evidence

The general vehicle collision model for the probability of death during a road crossing is useful for identifying species at risk of mortality from a specific road segment or in geographic areas where roads may be particularly harmful to species of concern.

The width of the kill zone (a in the equation above) is a function of vehicle and animal size; for small animals, which can only be killed by the tires,

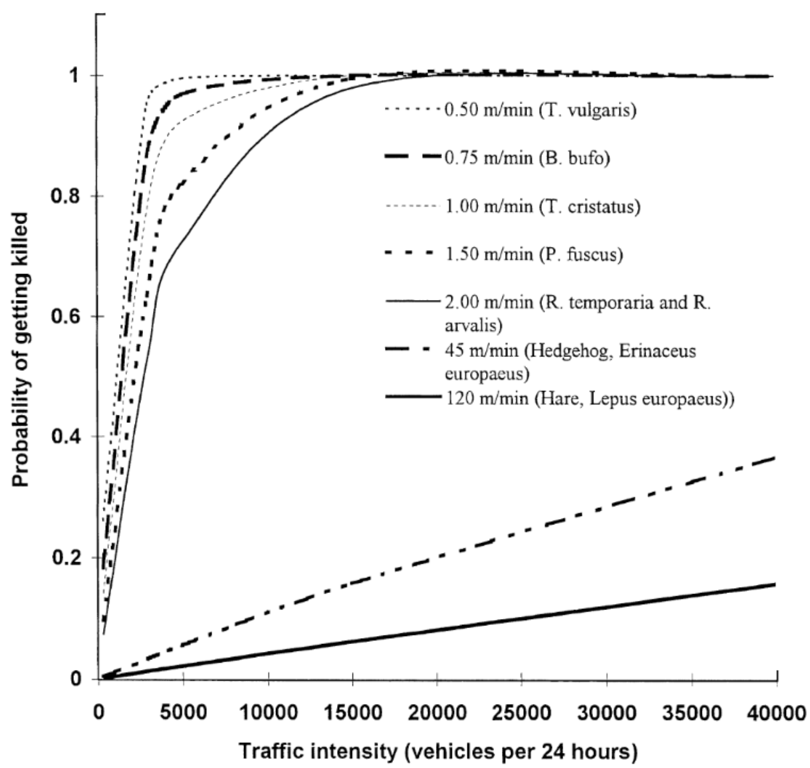
kill zone width per lane = (average tire width * 2) + (average animal body length * 2).

For larger animals, which can be struck and killed by any part of the vehicle,

kill zone width per lane = (average vehicle width * 2) + (average animal body length * 2).

Using this model to predict kill probabilities for a variety of wildlife species shows that the traffic volume and animal velocity have large effects on the outcome of a road crossing (Figure 4, Hels and Buchwald 2001).

Figure 4: Probability of an Individual being killed during a road crossing as a function of traffic volume (vehicles/day) and animal velocity (m/min)



Source: Hels and Buchwald (2001).

The vehicle collision model has been validated by several field studies with varying results. A study that assessed road mortality per crossing for black rat snakes on a low-traffic road and compared the results to the mortality predicted by the collision model described above found that the mortality rate from the field results (0.026) was about half that predicted by the model (0.053) (Row et al. 2007). The discrepancy could be due to inaccuracies in the model parameters (especially animal velocity) or due to driver behavior after seeing a relatively large animal on the road, which the model does not take into account (Row et al. 2007). Another study that validated the vehicle collision model with field measurements found almost identical mortality rates for each method for salamanders (Gibbs and Shriver 2005).

This approach does not give an annual road mortality rate because it does not take into account the number of times an individual of a given species will attempt to cross a road over a one-year period. Some species may live in areas with low road density or have very small home ranges and therefore rarely cross roads, whereas others may live in areas of high road density or have large home ranges and must cross roads frequently. This collision analysis technique could be combined with species range maps, road maps, and an understanding of species movement to identify species at risk from certain roads and to estimate the number of times an individual of a given species might cross a road each year, which can be used to estimate an annual mortality rate, using the equation in the Description of Relationship section. Several studies have used this technique to estimate annual road mortality rates for water snakes, salamanders, and turtles (Roe et al. 2006; Gibbs and Shriver 2005; Gibbs and Shriver 2002).

Strength of Evidence

Moderate: Wildlife-vehicle collisions are common in the United States; a variety of field studies and predictive models demonstrate that roads can be a relatively large cause of mortality for many types of wildlife. Road mortality estimates are location- and species-specific and have limited applicability to other contexts.

Predictability: A predictive model has been validated by several field studies with varying results and has been used by researchers to estimate per-crossing and annual mortality rates for a variety of species (Hels and Buchwals 2001; Litvaitis and Tash 2008).

Other Factors

Location

The location of the solar facility and associated traffic increases will determine which wildlife species are affected by vehicle collisions on a particular road.

Technology

The type of solar technology in use will influence wildlife-vehicle collisions if different technology types result in varying traffic volumes (see link 4a).

Species

As discussed above, species' movement patterns and velocities influence their susceptibility to road mortality. Temporal patterns of activity can also affect road mortality; diurnal species are more likely to cross roads during high-traffic periods than nocturnal species (Hels and Buchwald 2001). This likelihood is reflected in the traffic volume variable in the vehicle collision model.

Sources

Gibbs, J.P., and W.G. Shriver. 2002. "Estimating the Effects of Road Mortality on Turtle Populations." *Conservation Biology* 16(6): 1647–1652.

———. 2005. "Can Road Mortality Limit Populations of Pool-breeding Amphibians"? *Wetlands Ecology and Management* 3: 281–289.

Hels, T., and E. Buchwald. 2001. "The Effect of Road Kills on Amphibian Populations." *Biological Conservation* 99: 331–340.

Litvaitis, J.A., and J.P. Tash. 2008. "An Approach toward Understanding Wildlife-Vehicle Collisions." *Environmental Management* 42: 688–697.

Roe, J.H., J. Gibson, and B.A. Kingsbury. 2006. "Beyond the Wetland Border: Estimating the Impact of Roads for Two Species of Water Snakes." *Biological Conservation* 130(2): 161–168.

Row, J.R., G. Blouin-Demers, and P.J. Weatherhead. 2007. "Demographic Effects of Road Mortality in Black Ratsnakes (*Elaphe obsoleta*)." *Biological Conservation* 137: 117–124.

4k: Animal Deaths → Wildlife Populations

Description of Relationship

The death of 10% of individuals in a given population decreases the population size by 10%.

Summary of Evidence

In general, the death of an individual animal due to an anthropogenic cause lowers the population size by 1. Under certain circumstances, a population may show a compensatory response to anthropogenic mortality—that is, an increase in anthropogenic mortality causes a decrease in other ("natural") sources of mortality, and the population size remains stable. This response is observed in species with shorter life histories and in populations that are at or above the carrying capacity for their habitat and therefore subject to density-dependent sources of mortality, such as disease and competition for resources (Péron 2003). Because most rare and threatened species' populations are not adversely affected by density-dependent factors, they are not likely to have a compensatory response to fatalities caused by solar facilities (McGowan et al. 2011).

Population models have been developed for individual species (e.g., Sleep and Loehle 2010; Rhodes et al. 2011), but these are specific to the species and population for which they were created, and they are not often validated with field data to assess their accuracy. Validation of a model for caribou with field data found that the model had very wide confidence intervals and low predictive power, limiting its usefulness for decision making (Sleep and Loehle 2010). The strength of a particular model depends on how well the population dynamics influencing the modeled species are understood and captured in the model.

Strength of Evidence

Fair: Although the connection between animal deaths and wildlife population size seems straightforward, the dynamics of an individual population influence the strength and existence of this relationship. A meta-analysis confirmed the effects of life-history strategy and population size relative to carrying capacity on a population's ability to compensate for increased anthropogenic mortality.

Predictability: As discussed above, population models attempt to capture the effects of additional mortality on wildlife populations, but these must be developed for the particular species and population of interest, and their accuracy depends on a good understanding of the population's dynamics.

Other Factors

Location

The location of a given solar facility, and the local wildlife community, will determine which species are affected by the facility.

Technology

The effect of the solar energy technology type on wildlife populations is captured by differing effects on ecosystem components that influence wildlife populations (see links 4a, 6a, 7a, 8a, and 9a).

Other

As described above, other sources of mortality in a particular wildlife population determine whether this additional source of mortality will increase total mortality in the population, or if there will be a compensatory response.

Sources

McGowan, C.P., M.R. Ryan, M.C. Runge, J.J. Millspaugh, and J.F. Cochrane. 2011. "The Role of Demographic Compensation Theory in Incidental Take Assessments for Endangered Species." *Biological Conservation* 144: 730–737.

Péron, G. 2013. "Compensation and Additivity of Anthropogenic Mortality: Life-history Effects and Review of Methods." *Journal of Animal Ecology* 82: 408–417.

Rhodes, J.R., C.F. Ng, D.L. de Villiers, H.J. Preece, C.A McAlpine, and H.P. Possingham. 2011. "Using Integrated Population Modelling to Quantify the Implications of Multiple Threatening Processes for a Rapidly Declining Population." *Biological Conservation* 144: 1081–1088.

Sleep, D.J.H., and C. Loehle. 2010. "Validation of a Demographic Model for Woodland Caribou." *Journal of Wildlife Management* 74(7): 1508–1512.

4l: Wildlife Populations → Population Persistence

Description of Relationship

Decreasing the population size reduces the population's long-term viability (probability of persistence).

Summary of Evidence

A reduction in the size of a wildlife population can influence the population's long-term viability in several ways. Population size thresholds represent a minimum viable size for a population of a given species to persist; if a population falls below that threshold, it will go extinct (Traill et al. 2007). There are multiple reasons for the existence of population size thresholds. Demographic stochasticity (the probabilistic nature of reproduction and death) causes population size fluctuations that average out in large populations but can cause extinction in small populations. Allee effects refer to the positive effects of higher population density on processes that lead to individual fitness (e.g., finding mates, social dynamics, predator-prey interactions); at low population densities, these processes can break down (Kramer et al. 2009). A decline in the population size brings the population closer to its minimum viable size and lowers the probability of long-term persistence (Traill et al. 2007).

Smaller populations also have reduced genetic diversity and inbreeding depression, which can decrease their probability of persistence (Frankham 2005). Loss of genetic diversity and inbreeding depression both depend on the effective population size (the number of adults that are actually breeding in the population) (Frankham 2005).

In laboratory studies, inbreeding depression has been shown to affect many aspects of reproduction and survival, decreasing overall fitness rates; subsequent research in captive and wild populations of wildlife species has shown that wildlife in natural habitats experience inbreeding depression (Frankham 2005). Few field studies have examined the effect of inbreeding depression on extinction risk for wild populations, but those that do exist have found a significant effect of inbreeding depression on extinction risk, and computer simulations of inbred populations showed that the median time to extinction was reduced by 25%–31% relative to populations with no inbreeding depression (Brook et al. 2002). A later study that estimated the levels of inbreeding depression in wild populations using a meta-analysis found much higher inbreeding depression levels than was assumed in the Brook study. When population persistence was simulated using these results, it was found that the mean overall inbreeding effect seen in wild populations decreased the median time to extinction by 37% on average (O'Grady et al. 2006).

Lower genetic diversity limits the ability of the population to adapt to environmental change in the future through evolution. This effect takes place over a much longer time period than effects from inbreeding depression, and some studies have shown that inbreeding depression is likely a much stronger determinant of extinction risk than reduced genetic diversity (Frankham 2005).

Population viability analysis models are available to model the potential effects of population size decrease on long-term population viability; a long-term retrospective analysis of the predictive accuracy of these models found that they accurately predicted population sizes and growth rates (Brook et al. 2000). A comparison of six population viability analysis models for the whooping crane found that the projected mean population size and extinction risk (after 50 years) varied among PVA packages, mostly due to differences in package features (Brook et al. 1999). When the models were standardized to remove these differences (essentially, the more complex models were simplified to match features available in the simplest models), results across packages were much more similar. Because researchers generally want to be conservative in modeling rare and threatened species, it is generally better to use the full models that include more potential threats. It is not usually known which of the models will provide the most accurate prediction for the species in question, so there is a moderate degree of uncertainty associated with population viability analysis.

Strength of Evidence

Fair: As discussed above, there is evidence that small population size decreases the long-term persistence of a wildlife population in several ways. A meta-analysis of minimum viable population studies estimated a mean minimum viable population for various taxa, but it found that minimum viable population is very specific to each individual population. Without knowing the minimum viable population size and history of a particular population, it is difficult to determine whether a given decrease in population size represents a minor fluctuation or a significant drop toward the minimum viable population.

Predictability: As discussed above, population viability analysis models can predict the long-term effects of a population size decrease on viability; these models appear to be fairly accurate when adequate data on the focal population are available.

Other Factors

Demographic Factors

A population's demographic structure, including age distribution and background population level, influence its likelihood of persistence in the face of threats. Population viability analysis models take these factors into account.

Other Threats
Populations affected by multiple threats at once are less likely to persist; some population viability analysis models include the effects of multiple threats to the population.

Sources

Brook, B.W., J.R. Cannon, R.C. Lacy, C. Mirande, and R. Frankham. 1999. "Comparison of the Population Viability Analysis Packages GAPPS, INMAT, RAMAS and VORTEX for the Whooping Crane (*Grus americana*)." *Animal Conservation* 2: 23–31.

Brook, B.W., J.J. O'Grady, A.P. Chapman, M.A. Burgman, H.R. Akcakaya, and R. Frankham. 2000. "Predictive Accuracy of Population Viability Analysis in Conservation Biology." *Nature* 404: 385–387.

Brook, B.W., D.W. Tonkyn, J.J. O'Grady, and R. Frankham. 2002. "Contribution of Inbreeding to Extinction Risk in Threatened Species." *Conservation Ecology* 6(1): 16–31.

Frankham, R. 2005. "Genetics and Extinction." *Biological Conservation* 126: 131–140.

Kramer, A.M., B. Dennis, A.M. Liebhold, and J.M. Drake. 2009. "The Evidence for Allee Effects." *Population Ecology* 51: 341–354.

O'Grady, J.J., B.W. Brook, D.H. Reed, J.D. Ballou, D.W. Tonkyn, and R. Frankham. 2006. "Realistic Levels of Inbreeding Depression Strongly Affect Extinction Risk in Wild Populations." *Biological Conservation* 133: 42–51.

Traill, L.W., C.J. A. Bradshaw, and B.W. Brook. 2007. "Minimum Viable Population Size: A Meta-analysis of 30 Years of Published Estimates." *Biological Conservation* 139: 159–166.

4m: Population Persistence → Existence Value (Species)

Description of Relationship
People hold non-use values for particular species and are willing to pay to increase the probability of their persistence.

Summary of Evidence
A variety of studies have examined willingness to pay (WTP) for conservation efforts targeting particular species, with various persistence-related outcomes including changes to population size, listing status, and probability of extinction within a certain timeframe. A meta-analysis of willingness-to-pay studies for endangered and threatened species in the United States found that people were willing to pay $0.101 more for each 1% increase in population size that a particular program created; this figure reflects the total value of those species (not just existence value) and only applies to threatened/endangered species (Richardson and Loomis 2009). Whether a species had only nonuse or both use and nonuse value was included as a factor in this analysis; species with only nonuse values were valued at about $39 lower than species with both use and nonuse values, when all other factors were equal. The other factors found to influence people's valuation of a species may also be relevant to nonuse valuation (see "Other Factors" below).

The USGS Benefit Transfer Toolkit provides estimates of total economic value for a variety of threatened, endangered, and rare species within the United States, based on a database of individual nonmarket valuation estimates. These estimates may include values other than existence value (e.g., recreational value), but they can provide a starting point for valuation of a particular species' persistence.

One stated preference choice survey included in the USGS Benefit Transfer Toolkit estimated the willingness to pay for a dam removal and restoration project in the Klamath River Basin, including changes to the extinction risk for two sucker species and the Coho salmon. It found that the 20-year annual willingness to pay to reduce the extinction risk of the coho salmon was $21.28/household nationally and that the 20-year annual willingness to pay to reduce the extinction risk of both the coho salmon and the suckers was $78.77/household nationally (Mansfield et al. 2012). Another study of willingness to pay to improve endangered wildlife population status found that the mean WTP was $7.64/household/year to improve an endangered species' status to "rare" within a group of respondents that appeared to be primarily driven by existence value (Jacobsen et al. 2012). This survey was conducted in Denmark and is likely not fully applicable to American valuation.

Strength of Evidence
Low: Several studies have examined willingness to pay for conservation programs or for particular species. However, many do not explicitly separate existence values from other types of value that wildlife can provide to people nor do they associate values with changes in population persistence. The relevance of the USGS Benefit Transfer Toolkit for the valuation of a particular species depends on how well studies in the database match the situation.

Other Factors

Location

The distance between people and the population in question may influence the value they place on its continued existence (Loomis 2000). For example, the Klamath River Basin study found differences in responses among people within the Klamath area, outside of that area but within Oregon or California, and in the rest of the United States (Mansfield et al. 2012).

Technology

Technology has no effect (assumed).

Other

The type of species affected people's willingness to pay, with marine mammals, fish, and birds valued higher than land mammals and reptiles (Richardson and Loomis 2009).

Sources

Jacobsen, J.B., T.H. Lundhede, and B.J. Thorsen. 2012. "Valuation of Wildlife Populations above Survival." *Biodiversity and Conservation* 21(2): 543–563.

Loomis, J.B. 2000. "Vertically Summing Public Good Demand Curves: An Empirical Comparison of Economic versus Political Jurisdictions." *Land Economics* 76(2): 312–321.

Mansfield, C., G. Van Houtven, A. Hendershott, P. Chen, J. Porter, V. Nourani, and V. Kilambi. 2012. Klamath River Basin Restoration Nonuse Value Survey. RTI International Project Number 0212485.001.010. Prepared for R. Graham, Klamath River Dams Project Office, U.S. Bureau of Reclamation.

Richardson, L. and J. Loomis. 2009. "The Total Economic Value of Threatened, Endangered and Rare Species: An Updated Meta-analysis." *Ecological Economics* 68: 1535–1548.

USGS (United States Geological Survey). N.d. Benefit Transfer Toolkit. https://my.usgs.gov/benefit-transfer/.

4n: Wildlife Populations → Value of Recreational Activity to Participants

Description of Relationship

People are willing to pay $XX more to visit a recreational area with one additional species.

Summary of Evidence

There are multiple ways to estimate recreational value, including revealed preference methods (based on travel cost or direct spending on a recreational activity related to a certain species) and stated preference studies. Most valuation studies attempt to put a value on recreational use as a whole (sometimes with a few distinctions between habitat types, more often with factors related to the user, such as household income); few have examined the value of individual species to recreation. A revealed-preference study of eBird users in Washington and Oregon found that birders are willing to pay $3.38 per additional bird species at a site in June and that the total willingness to pay for an outing to a particular site increased by about 17% if an endangered species had been seen at the site in the previous year (Kolstoe and Cameron 2017). A positive relationship has also been shown between the rarity of a bird species and the number of people who go see it (Booth et al. 2011).

The USGS Benefit Transfer Toolkit provides regression functions that estimate the value of hunting, fishing, and wildlife watching opportunities on the basis of the type of species involved. The wildlife viewing function gives separate values for birds, charismatic megafauna, and general wildlife; the hunting function gives separate values for deer, elk, moose, mountain goat, pheasant, waterfowl, large game, and small game; and the fishing function gives separate values for tuna, salmon, steelhead, bass, muskellunge, arctic grayling, and perch. These estimates can provide a general idea of the recreational value of a particular species' presence in an area.

Several methods are available for estimating the recreational value of wildlife in a particular context. The Kolstoe and Cameron study provides a good example for the value of particular species for birdwatching, but it depends on a widely used database that is not available for other types of wildlife (2017). A 2009 study of the recreational value of elk viewing in Oregon is an example of the travel cost method of valuation (Donovan and Champ). The contingent valuation method is exemplified in a study of the benefits of roadside bear viewing in Yellowstone National Park (Richardson et al. 2014).

Strength of Evidence

Low: No meta-analyses exist; although some studies have assessed the recreational values associated with certain wildlife species in particular locations, many of these studies were conducted outside of the southwestern United States and are likely not applicable to other locations.

Predictability: The regression functions in the USGS Benefit Transfer Toolkit provide fair estimates for the value of certain species for recreation, but these functions are not available for all species or recreation types and they may not account for other factors that can influence a species' recreational value. The strength of benefit transfer from studies of recreational value associated with particular wildlife species in specific places depends on how well the study matches the relevant context.

Other Factors

Location

The value of a recreational experience varies by its location within the United States; the USGS Benefit Transfer Toolkit functions include region as a variable, but there may be additional variation at more local levels.

Species

Different species provide varying recreational values. The USGS Benefit Transfer Toolkit functions include species as a variable, but not all relevant species are included.

Sources

Booth, J.E., K.J. Gaston, K.L. Evans, and P.R. Armsworth. 2011. "The Value of Species Rarity in Biodiversity Recreation: A Birdwatching Example." *Biological Conservation* 144: 2728–2732.

Donovan, G., and P. Champ. 2009. "The Economic Benefits of Elk Viewing at the Jewell Meadows Wildlife Area in Oregon." *Human Dimensions of Wildlife* 14: 51–60.

Kolstoe, S., and T.A. Cameron. 2017. "The Non-market Value of Birding Sites and the Marginal Value of Additional Species: Biodiversity in a Random Utility Model of Site Choice by eBird Members." *Ecological Economics* 137: 1–12.

Richardson, L., T. Rosen, K. Gunther, and C. Schwartz. 2014. "The Economics of Roadside Bear Viewing." *Journal of Environmental Management* 140: 102–110.

USGS (United States Geological Survey). N.d. Benefit Transfer Toolkit. https://my.usgs.gov/benefit-transfer/.

5a: Solar Development → Sound

Description of Relationship

The equipment used to construct a solar energy facility creates sound. The equivalent sound level (L_{eq}, in dBA, A-weighted decibels, a measure of sound that reflects the sensitivity of the human ear to different frequencies) produced by a single piece of equipment is equal to L_{max} – 20 * log(distance from receptor/50) - shielding + 10 * log((time-averaged equipment usage factor, in %)/100).

The total equivalent sound level (L_{eq}, in dBA) produced by all equipment is equal to 10 + log(sum of individual equipment L_{eq} values) (Reherman et al. 2006).

Temporary link: This link is temporary because sound levels are only expected to increase substantially during the construction of a solar energy facility.

Summary of Evidence

The use of heavy machinery for grading, excavation, and installation of solar equipment creates sound. The level of construction sound heard by a person (receptor) at a given location depends on the total amount of sound being emitted by the construction activity and the distance from the receptor to the sound source.

The sound levels created by construction activities can be predicted using models; for example, the Roadway Construction Noise Model, created by the U.S. Department of Transportation, takes into account the ambient sound at sensitive receptors, the maximum sound level generated by each piece of equipment (can be measured or taken from a standard reference table), the proportion of time that the equipment will be emitting its maximum sound level, the distance from each piece of equipment to each receptor, and shielding (absorption of sound by a barrier between the noise source and receptor, such as a dirt mound, a building, or commercial noise shielding material). This model also lets the user specify local noise limits and will determine if these limits are likely to be exceeded by the construction activity (Reherman et al. 2006). Although actual sound levels may vary from predicted values, the model is useful for determining whether a project will violate local noise ordinances or adversely affect sensitive receptors, in which case appropriate noise-reduction measures can be taken.

Strength of Evidence

Moderate: Construction of a solar energy facility does create sound; noise impacts are considered during the planning process for a particular facility. Although no studies were found that measured the actual cumulative sound levels from solar-related construction activities, the amount of sound expected can be assessed using models.

Predictability: The amount of sound emitted from a certain piece of equipment or construction activity can be easily measured or obtained from technical specifications. Models can compute predicted sound levels given inputs related to noise emission and receptor locations (see Summary of Evidence for details).

Other Factors

Location

The location of the solar facility and conditions at the site determine the specific type of construction activities required, in particular for site preparation. Desert sites may require less site preparation (land clearing and grading) than other landscape types and therefore may generate less sound, generate construction sound for a decreased period of time, or both (Patton et al. 2013).

Technology

The solar technology type determines the specific type of construction activities required; these different activities should be reflected in the sound models described above.

Other Potential Impacts

Although the highest potential for sound generation from solar development occurs during construction, there are some sources of sound from an operating solar power plant, including inverters and transmission lines (Ldn Consulting 2011). Sound from transmission lines (Corona effect noise) generally only occurs for transmission lines >345kV. Transformers, inverters, and array trackers required for commercial PV arrays produce sound (58–65 dBA at 5 feet), but sound reduction due to distance means that these elements are unlikely to cause a noise impact unless they are very close (within 100 feet) to sensitive receptors (Ldn Consulting 2011).

Sources

Ldn Consulting, Inc. 2011. Noise Assessment: Centinela Solar Energy Project, County of Imperial.

Patton, T., L. Almer, H. Hartmann, and K.P. Smith. 2013. An Overview of Potential Environmental, Cultural, and Socioeconomic Impacts and Mitigation Measures for Utility-scale Solar Energy Development. Argonne National Laboratory, Environmental Science Division.

Reherman, C.N., J.L. Rochat, E.S. Thalheimer, M.C. Lau, G.G. Fleming, M. Ferroni, and C. Corbisier. 2006. FHWA Roadway Construction Noise Model, Version 1.0 User's Guide. U.S. Department of Transportation. https://www.fhwa.dot.gov/Environment/noise/construction_noise/rcnm/rcnm.pdf.

6a: Solar Development → Reflective Surfaces

Description of Relationship

A 100-MW solar power plant would require approximately 165 acres of photovoltaic panels (assuming 18 ft^2 panels with 250 W peak capacity).

The number and surface area of heliostat mirrors required for a 100-MW concentrating solar power plant depend on site factors and are determined during project design.

Summary of Evidence

Solar power plants and PV panels are both rated according to their peak capacity under standard test conditions. Currently, PV panels on the market have peak capacities between 200 and 350 W (ENF Solar 2017); a 100-MW power plant would require 400,000 panels with peak capacities of 250 W. A common size for PV panels is about 18 square feet (ENF Solar 2017), so the area of 400,000 panels is about 165 acres.

The number and area of heliostat mirrors required for a concentrating solar power plant depend on many site-specific factors; the Ivanpah Solar Electric Generating System, a 392-MW power plant, contains about 170,000 heliostats, each with a reflective surface of 163 square feet (Cauble 2013). In total, the Ivanpah plant contains 642 acres, or about 163 acres/100MW capacity, of reflective surfaces (Ho et al. 2014).

Strength of Evidence

High: The total area of PV panels required for a particular facility can be calculated on the basis of facility design and technical specifications of the selected panels. The total number and area of reflective heliostats for concentrating solar power systems is also determined during the design phase.

Other Factors

Location

The location of a solar energy facility will influence the number of heliostats or photovoltaic panels required and therefore the total area of reflective surfaces at the facility.

Technology

The type of solar facility (photovoltaic or concentrating solar power) will determine the type and extent of reflective surfaces.

The peak capacity and physical dimensions of the PV panels used at a solar energy facility will determine the number of panels and total panel area required to achieve a total plant rated capacity of 100MW.

Sources

Cauble, A. 2013. "Brightsource's Heliostat Technology." Brightsource Energy Blog – Solar Dispatch. http://www.brightsourceenergy.com/brightsource%E2%80%99s-heliostat-technology. Accessed July 28, 2017.

ENF Solar. 2017. "Solar Panel Directory." https://www.enfsolar.com/pv/panel?page=1. Accessed July 27, 2017.

Ho, C.K., C.A. Sims, and J.M. Christian. 2014. Ivanpah Solar Electric Generating System Heliostat Positioning Plan Report. Sandia National Laboratories, SAND2014-15847. http://docketpublic.energy.ca.gov/PublicDocuments/09-AFC-07C/TN202734_20140718T130035_Ex1191__Ivanpah_SEGS_Heliostat_Positioning_Plan_Report.pdf. Accessed July 28, 2017.

6b: Reflective Surfaces → Glare

Description of Relationship

PV panels reflect less than 5% of received sunlight; heliostat mirrors (used in concentrating solar power systems) reflect more than 90% of received sunlight (Ho 2012).

Summary of Evidence

PV panels and heliostats (used in concentrating solar power systems) are reflective and can cause glare (Chiabrando et al. 2009; Rose and Wollert 2015). PV panels are designed to minimize reflection, because reflected sunlight does not contribute to electricity production, whereas heliostat mirrors in concentrating solar plants are designed to maximize reflection. The intensity of reflection depends on the position of the sun (varies by day of the year and time of day), the geographical location and angle of the panel or mirror, and the surface reflectance properties.

The Federal Aviation Administration (FAA) and Department of Energy (DOE) have created a software tool, SGHAT, to predict the potential glare that would be caused by proposed solar projects near airports (FAA 2013), and other similar software tools are available to simulate the glare created by solar energy facilities (Rose and Wollert 2015). These tools can predict the locations at which glare can be seen, when (during the day and year) glare will exist, and how severe the glare will be. Site-specific field tests can assess the extent and direction of glare from a proposed installation (HMMH 2010).

Strength of Evidence

High: The reflective surfaces at utility-scale solar facilities cause glare; reflectivity of light is a physical property of the materials used for solar development and can easily be determined for specific photovoltaic panels and mirrors.

Predictability: As described above, models and geometric analyses can predict the amount and location of glare created by solar facilities.

Other Factors

The potential for glare depends on the location of the facility, the orientation and angle of the panel or mirror, and the day of the year and time of day (Chiabrando et al. 2009).

Sources

Chiabrando, R., E. Fabrizio, and G. Garnero. 2009. "The Territorial and Landscape Impacts of Photovoltaic Systems: Definition of Impacts and Assessment of the Glare Risk." *Renewable and Sustainable Energy Reviews* 13: 2441–2451.

Harris, Miller, Miller, and Hanson Inc. (HMMH). 2010. Technical Guidance for Evaluating Selected Solar Technologies on Airports. Federal Aviation Administration Office of Airports. https://www.faa.gov/airports/environmental/policy_guidance/media/airport-solar-guide-print.pdf.

Ho, C.K. 2012, February. "Glare Impacts from Solar Power Plants Near Airports." Presented at the AAC/AAAE Airport Planning, Design, and Construction Symposium, Denver, Colorado.

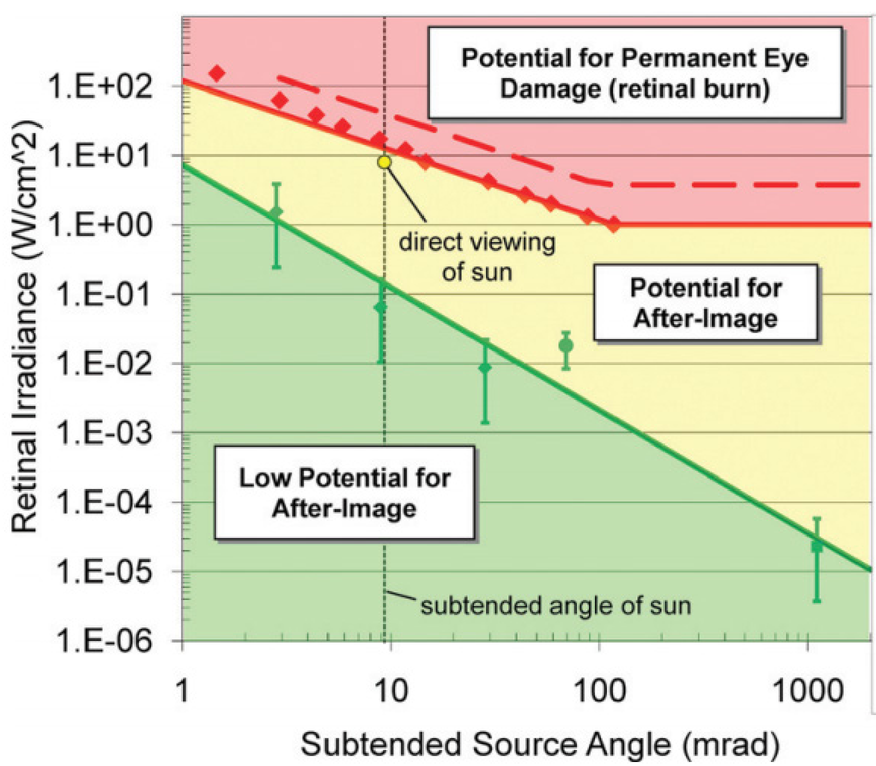
Rose, T. and A. Wollert. 2015. "The Dark Side of photovoltaic – 3D Simulation of Glare Assessing Risk and Discomfort." *Environmental Impact Assessment Review* 52: 24–30.

6c: Glare → Physical Health (Vision, Accident Risk)

Description of Relationship

Glare from solar development can cause eye damage. As shown in Figure 5, the potential for adverse effects on vision from glare is a function of the amount of energy from the glare entering the cornea (measured in W/cm^2) and the angle at which glare enters the eye (subtended source angle) (Ho et al. 2011).

Figure 5: Potential for vision effects as a function of the retinal irradiance and subtended source angle of glare entering the eye



Source: Ho et al. (2011).

Temporary visual impairment and distraction to drivers and pilots caused by glare may also increase the probability of accidents.

Summary of Evidence

Glare is temporary loss/reduction of vision when the luminance of a surface exceeds the luminance that the human eye can detect (Ho 2012). Figure 3, which shows the potential effects of glare depending on irradiance and source angle, is based on multiple experimental studies and represents the outcomes for short exposures to glare corresponding to the typical human blink response time (Ho et al. 2011). Glare can impair the vision of pilots and drivers and make travel by plane and automobile unsafe, but no studies or models were found that assess the increased transportation risks posed by glare. The tools for predicting glare described in link 6b do not predict health or transportation-related outcomes.

In 2013, the U.S. Department of Defense encouraged military installations to assess solar PV arrays within two nautical miles of air control towers, air traffic areas, and helicopter landing zones as well as to assess concentrating solar power systems within 10 nautical miles of U.S. Department of Defense (DoD) flight operations for their potential to create glint/glare and blind pilots (Conger 2013). The Ivanpah Solar Electric Generating System Final Environmental Impact Statement identifies glare as a potential source of distraction for drivers, but it states that the effect cannot be quantified (BLM 2010). An assessment of potential effects on pilots from glare originating from the Ivanpah plant found that glare from heliostats could cause "significant ocular impact" but not permanent damage to pilots' eyes (Ho et al. 2014).

Likely negligible link: This link is likely to be negligible for solar energy development on BLM lands due to their remote nature and low surrounding populations. However, this link has been retained in the simplified model due to possible human health effects.

Strength of Evidence

Fair: The potential for glare to cause impacts to vision is well-understood, and equations to assess these impacts exist (Ho et al. 2011). No studies have assessed the actual effects of glare from solar facilities on transportation safety (e.g., likelihood of accidents), but the Federal Aviation Authority and the Department of Defense both recognize glare from solar energy facilities as a potential threat to air transit safety and have issued guidelines for airports to assess nearby solar facilities' glare-creating potential.

Other Factors

Location

The location of a solar facility relative to air traffic areas/landing zones, and the angle and direction in which the reflective surfaces face, influences the magnitude of the hazard to air travel.

Technology

Different types of solar energy technology have different potentials for glare creation (see links 6a and 6b).

Sources

BLM (Bureau of Land Management). 2010. Final Environmental Impact Statement for Ivanpah Solar Electric Generating System. FEIS-10-31. https://energy.gov/sites/prod/files/nepapub/nepa_documents/RedDont/EIS-0416-FEIS-2010.pdf.

Conger, J. 2013. Glint/Glare Issues On or Near Department of Defense Aviation Operations. Memo, Department of Defense. http://www.acq.osd.mil/dodsc/library/Procedures_Memo_4_Glint%20Glare%20Issues%20on%20or%20near%20DoD%20Aviation%20Operations.pdf.

Ho, C.K., C.M. Ghanbari, and R.B. Diver. 2011. "Methodology to Assess Potential Glint and Glare Hazards from Concentrating Solar Power Plants: Analytical Models and Experimental Validation." *Journal of Solar Energy Engineering* 133:031021-1–031021-9.

Ho, C.K. 2012, February. Glare Impacts from Solar Power Plants Near Airports. Presented at the AAC/AAAE Airport Planning, Design, and Construction Symposium, Denver, Colorado.

Ho, C.K., C.A. Sims, and J.M. Christian. 2014. Ivanpah Solar Electric Generating System Heliostat Positioning Plan Report. Sandia National Laboratories, SAND2014-15847. http://docketpublic.energy.ca.gov/PublicDocuments/09-AFC-07C/TN202734_20140718T130035_Ex1191__Ivanpah_SEGS_Heliostat_Positioning_Plan_Report.pdf. Accessed 28 July 2017.

6d: Glare → Animal Deaths

Description of Relationship

Glare from utility-scale solar facilities cause XX flying animal deaths annually per MWh of electricity produced (or per acre of photovoltaic panels or mirrors).

Summary of Evidence

Glare at large-scale solar facilities can cause fatalities in birds, bats, and flying insects in several ways: reflective panels can appear transparent or water-like to animals, causing collisions, and insect-attracting lights can draw birds into solar farms

(USFWS 2014). An initial U.S. Fish and Wildlife Service (USFWS) study of bird mortality at three solar power plants in California found evidence for deaths due to impact trauma at all three plants and suggested that many of the birds killed by predators may have first sustained impact trauma that increased their vulnerability (Kagan et al. 2014). This study was opportunistic and did not follow a sampling protocol, so it cannot be used to estimate mortality rates. A study at the Ivanpah Solar Electric Generating Station, a concentrating solar power plant that uses heliostat mirrors, estimated annual bird mortalities from collisions in the heliostat areas at 0.3 fatalities/acre (HT Harvey and Associates 2015).

Field sampling can give a fairly accurate estimate of glare-related fatalities at a particular site. The Ivanpah Avian and Bat Monitoring Plan provides an example of a standardized protocol for detecting and categorizing bird and bat deaths in the facility in order to estimate annual fatalities from various causes (HT Harvey and Associates 2015). The accuracy of field studies is limited by imperfect detection—some animals are missed or removed by scavengers before sampling (possibilities that can be accounted for in mortality estimates; see HT Harvey and Associates 2015)—and inability to determine the cause of death for all fatalities.

Strength of Evidence

Low: A few studies at particular facilities give initial indications that glare-related animal deaths are common at solar facilities, but methods are still being developed. Results from a study at one site are likely to have limited applicability to solar facilities in other locations.

Other Factors

Location

The number of animal fatalities caused by a solar facility is likely dependent on its location (e.g., relative to bird migration routes); however, no studies were found that include location or migration routes as factors in determining fatality rates.

Technology

The number of animal fatalities caused by a solar facility is likely influenced by the specific technologies in use; however, no studies exist that compare animal deaths at different types of solar facilities.

Sources

H.T. Harvey and Associates. 2015. Ivanpah Solar Electric Generating System Avian and Bat Monitoring Plan: 2013–2014 Annual Report (revised). Solar Partners, LLC. Project #2802-07.

Kagan, R.A., T.C. Viner, P.W. Trail, and E.O. Espinoza. Avian Mortality at Solar Energy Facilities in Southern California: A Preliminary Analysis. U.S. Fish and Wildlife Service. http://alternativeenergy.procon.org/sourcefiles/avian-mortality-solar-energy-ivanpah-apr-2014.pdf. Accessed July 28, 2017.

USFWS (U.S. Fish and Wildlife Service). 2014. Agency Review of "Preliminary Analysis Report on Avian Mortality at Solar Energy Facilities in Southern California." USFWS, Pacific Southwest Region. http://docketpublic.energy.ca.gov/PublicDocuments/09-AFC-07C/TN202013_20140411T155507_Forensic_Lab_Report_Evaluation.pdf.

6e: Reflective surfaces → Heat

Description of Relationship

The focal point of concentrating solar power systems can reach 550 degrees Celsius (C) (linear Fresnel and parabolic trough systems), 800 degrees C (solar power receivers), or 1600 degrees C (parabolic dish systems) (Serrano and Isabel 2017).

Large areas of PV panels may increase or decrease temperatures slightly; more research is needed to determine the spatial extent and magnitude of this effect.

Summary of Evidence

Some concentrating solar power systems have thermal towers to which solar energy is directed by mirrors, causing high temperatures in specific areas. The temperature reached is a function of the concentration ratio of the collectors that focus the energy; maximum temperatures measured for specific system types are listed above.

Large areas of PV panels change the albedo and energy balance of the landscape, which influences surrounding temperatures; researchers disagree on whether PV panels are likely to increase or decrease temperatures. Some models have shown potential for decreased temperatures from PV systems in urban environments, but a monitoring study of a PV plant in the desert compared to the intact desert landscape found a heat island effect associated with the plant of about

+4 degrees C compared to the desert (Barron-Gafford et al. 2016). The authors suggest that more research is needed to determine the factors that control the formation, magnitude, and extent of PV heat islands.

Strength of Evidence

Fair: High temperatures at certain locations within concentrating solar power systems are an accepted fact, but few studies were found that actually measure the temperatures of such systems. Temperature changes associated with PV systems have been modeled, but the only identified empirical study of PV heat effects in natural environments gave results inconsistent with the models, likely because of differences in underlying factors.

Other Factors

Location

The geographical location and surrounding land use of a PV solar plant likely determine the magnitude of a heat island effect; more research is needed.

Technology

As described above, the specific type of solar technology determines its expected temperature range.

Sources

Barron-Gafford, G.A., R.L. Minor, N.A. Allen, A.D. Cronin, A.E. Brooks, and M.A. Pavao-Zuckerman. 2016. "The Photovoltaic Heat Island Effect: Larger Solar Power Plants Increase Local Temperatures." *Scientific Reports* 6.

Serrano, R., and M. Isabel. 2017. "Concentrating Solar Thermal Technologies." In *Concentrating Solar Thermal Technologies: Analysis and Optimisation by CFD Modelling*. Springer International Publishing, Switzerland.

6f: Heat → Animal Deaths

Description of Relationship

Heat from utility-scale solar facilities causes XX flying animal deaths per MWh of electricity produced.

Summary of Evidence

Concentrated solar energy on solar thermal towers can burn animals (USFWS 2014). The total number of animals killed by solar facilities is unknown; more research is underway. An initial monitoring study at Ivanpah Solar Plant in California, which uses solar thermal towers to generate electricity, estimated that total bird mortality from singeing was 690 birds/year (H.T. Harvey and Associates 2015). The USFWS also conducted an initial analysis of birds killed at three solar facilities in California and recommended strategies for preventing bird fatalities (USFWS 2014).

Field sampling can give a fairly accurate estimate of heat-related fatalities at a particular site; see link 6d for an example of a long-term monitoring study of wildlife fatalities at a solar energy facility.

Strength of Evidence

Low: Initial research studies for particular solar facilities indicate that heat-related animal deaths at concentrated solar power facilities do occur, but methods are still being developed, and results from a study at one site are likely to have limited applicability to solar facilities in other locations.

Other Factors

Location

The number of animal fatalities caused by a solar facility is likely dependent on its location (e.g., relative to habitat areas or bird migration routes); however, no studies exist that include location as a factor in determining fatality rates.

Technology

The type of solar energy technology determines the maximum temperatures produced (see link 6e) and therefore likely influences fatality rates due to heat; however, no studies exist that compare animal deaths at different types of solar facilities.

Sources

USFWS (U.S. Fish and Wildlife Service). 2014. Agency review of "Preliminary Analysis Report on Avian Mortality at Solar Energy Facilities in Southern California." USFWS, Pacific Southwest Region. http://docketpublic.energy.ca.gov/PublicDocuments/09-AFC-07C/TN202013_20140411T155507_Forensic_Lab_Report_Evaluation.pdf.

H.T. Harvey and Associates. 2015. Ivanpah Solar Electric Generating System Avian and Bat Monitoring Plan: 2013–2014 Annual Report. http://docketpublic.energy.ca.gov/PublicDocuments/07-AFC-05C/TN204258_20150420T145549_Ivanpah_Solar_Electric_Generating_System_Avian__Bat_Monitoring.pdf.

6h: Habitat → Wildlife Populations

Description of Relationship

A loss of 1 acre of habitat for a given species decreases that species' population by 1 acre * the original population density for that habitat (individuals/acre).

Degradation of 1 acre of habitat for a given species, such that the habitat can only support XX% of its original capacity, decreases that species' population by 1 acre * (100% - XX%) * the original population density for that habitat (individuals/acre).

Summary of Evidence

Both of the relationships stated above assume that habitat loss/degradation results in the death of individuals formerly living on that habitat; if some of them move to a different area and survive long term, population size decreases would be less than stated here. As has been noted in spotted owls, mobile species displaced by habitat loss or degradation may move into habitat areas already occupied by other individuals, temporarily increasing the population density of that habitat above its long-term capacity (Noon and McKelvey 1992).

Many studies have examined the influence of habitat loss on wildlife populations and found strong negative effects (Fahrig 2003). Although studies often fail to distinguish between habitat loss and habitat fragmentation (the spatial arrangement of habitat within a landscape), the studies that have assessed fragmentation effects directly show that these effects are weaker than the effects of habitat loss and that some species are positively affected by fragmentation; by contrast, habitat loss has consistently negative effects (Fahrig 2003). Specific effects of fragmentation on wildlife populations is strongly influenced by species characteristics such as dispersal and movement patterns (Cushman 2006).

Some studies have shown that habitat loss results in population declines larger than expected based on the amount of habitat lost; this phenomenon is due to patch size effects that cause decreased population density in smaller habitat patches. A meta-analysis of studies that examined this effect found that species that live in habitat interiors show a strong positive relationship between patch size and population density, whereas species that prefer habitat edges show a strong negative relationship (Bender et al. 1998). This finding indicates that population changes predicted from habitat patch size alone will underestimate population declines due to habitat loss in interior species and will overestimate population declines due to habitat loss in edge species.

Researchers have suggested that there may be habitat amount (as proportion of the landscape) thresholds below which population size decreases sharply. Support for this hypothesis varies by species and landscape; some simulations have shown these thresholds, but the few small- and large-scale landscape studies that have been conducted have shown inconsistent effects (Swift and Hannon 2010). Modeling and empirical studies show that habitat loss can cause wildlife populations to decline over a long period of time, creating an "extinction debt" that is difficult to detect in the short term and can affect even the best competitors in the ecosystem (Kuussaari et al. 2009; Tilman et al. 1994).

Habitat quality is difficult to define and measure; many studies use population density as a proxy for habitat quality, but the link between habitat quality and population density has not been substantiated (Mortelliti et al. 2010). Habitat characteristics, such as vegetation, soils, and climate, are easy to measure but may not accurately capture patch quality. Measurements of key resources (food, nest sites, and so on) can provide a better assessment of habitat quality, assuming that the critical limiting resources for a population are known. A review of the research on habitat quality and population effects concluded that more research is needed, including research on a wider range of species taxa and more potential explanatory variables (species' traits, spatial arrangement of habitat, and so on), to assess the importance of habitat quality relative to the amount and fragmentation of habitat (Mortelliti et al. 2010).

A field study can give an estimate of the population effects from habitat loss or degradation on energy installations. The specific field methods will vary on the basis of the species and habitat type; the 2015–2016 annual report for the Mojave population of the desert tortoise provides an example of a systematic protocol for sampling populations and estimating population density (Allison 2016).

Strength of Evidence

Low: Many studies examine the various effects of habitat loss and fragmentation on wildlife populations, and they generally show consistent adverse effects (with the exception of certain species that do well in disturbed edge environments), but the studies measure a range of outcomes and indicators for population effects, making it difficult to derive a general relationship like this one. The relationship between habitat quality and population density is often assumed, but supporting research is lacking.

Other Factors

Location

The location of solar energy development determines which wildlife species may be affected by it.

Technology

The type of solar energy technology influences the specific effects on wildlife habitat (see links 6a, 8a, and 9a).

Other

The effects of habitat destruction and fragmentation on wildlife populations depends on what wildlife species are present in the vicinity of the development and how they respond individually to disruptions. Some studies have shown differences, based on taxon and body size, in the scale at which species are affected (Benítez-López 2010).

Sources

Allison, L. 2016. Range-wide Monitoring of the Mojave Desert Tortoise (*Gopherus agassizii*): 2015 and 2016 Annual Reporting. U.S. Fish and Wildlife Service. https://www.fws.gov/nevada/desert_tortoise/documents/reports/2015/201516_rangewide-mojave-desert-tortoise-monitoring.pdf.

Bender, D.J., T.A. Contreras, and L. Fahrig. 1998. "Habitat Loss and Population Decline: A Meta-analysis of the Patch Size Effect." *Ecology* 79(2): 517–533.

Benítez-López, A., R. Alkemade, and P.A. Verweij. 2010. "The Impacts of Roads and Other Infrastructure on Mammal and Bird Populations: A Meta-analysis." *Biological Conservation* 143: 1307–1316.

Cushman, S.A. 2006. "Effects of Habitat Loss and Fragmentation on Amphibians: A Review and Prospectus." *Biological Conservation* 128(2): 231–240.

Fahrig, L. 2003. "Effects of Habitat Fragmentation on Biodiversity." *Annual Review of Ecology, Evolution, and Systematics* 34: 487–515.

Kuussaari, M., R. Bommarco, R.K. Heikkinen, A Helm, J. Krauss, R. Lindborg, …, and I. Steffan-Dewenter. 2009. "Extinction Debt: A Challenge for Biodiversity Conservation." *Trends in Ecology and Evolution* 24(10): 564–571.

Mortelliti, A., G. Amori, and L. Boitani. 2010. "The Role of Habitat Quality in Fragmented Landscapes: A Conceptual Overview and Prospectus for Future Research." *Oecologia* 163(2): 535–547. https://link.springer.com/article/10.1007/s00442-010-1623-3.

Noon, B.R., and K.S. McKelvey. 1992. "Stability Properties of the Spotted Owl Metapopulation in Southern California." In *The California Spotted Owl: A Technical Assessment of Its Current Status*, edited by J. Verner, K.S. McKelvey, B.R. Noon, R.J. Gutiérrez, G.L. Gould, and T.W. Beck, 187–206.

General Technical Report PSW-GTR-133. Albany, CA: Pacific Southwest Research Station, Forest Service, U.S. Department of Agriculture.

Swift, T.L., and S.J. Hannon. 2010. "Critical Thresholds Associated with Habitat Loss: A Review of the Concepts, Evidence, and Applications." *Biological Reviews* 85(1): 35–53.

Tilman, D., R.M. May, C.L. Lehman, and M.A. Nowak. 1994. "Habitat Destruction and the Extinction Debt." *Nature* 371: 65–66.

6k: Habitat → Species Distribution

Description of Relationship

Habitat changes can shift the distributions of plant and animal species, including invasive species, competitors, and predators, by changing physical habitat characteristics and resource availability.

Summary of Evidence

Changes to species distributions are very specific to location and species, so no generalized relationships can be established. Some examples of habitat effects on species distribution are given below.

Many studies identify habitat disturbance as a factor facilitating the establishment and spread of invasive plant species. A meta-analysis found that 86% of invasive plant species identified in research papers as successfully establishing in new areas were associated with disturbed areas (Lozon and MacIsaac 1997). Specific disturbances associated with plant introductions include soil disturbance and development activities (Lozon and MacIsaac 1997).

Ravens are attracted to human development due to the availability of food (trash and roadkill), water, and perching and nesting sites (transmission lines and poles) (Kristan and Boarman 2003; Howe et al. 2014; CH2MHILL 2008). During the planning process for Ivanpah, trash, roadkill, standing water from dust suppression and equipment cleaning, and transmission lines were identified as aspects of solar development that could attract large populations of ravens (CH2MHILL 2008). Monitoring at Ivanpah after the facility was completed found that ravens made up of more than half of all large birds seen at the facility and that more ravens were seen at the facility than in the surrounding desert, indicating that the solar energy facility does attract ravens (Western EcoSystems Technology, Inc. 2016).

It is hypothesized that new development, including solar energy facilities, increases the available water supply and allows certain animal species such as the coyote to expand into new areas. However, an experiment in the Mojave and Great Basin deserts did not find evidence to support this hypothesis (Hall et al. 2013).

Site-specific field research can be conducted to understand the effects of habitat changes from a particular solar energy project on species distribution. The Ivanpah avian monitoring survey provides an example of a standardized method for assessing bird species' presence and abundance on a solar energy facility (Western EcoSystems Technology, Inc. 2016).

Strength of Evidence

Low: Because the effects of habitat changes on species distributions vary with species, location, and habitat variables, there is no evidence to support a generalized relationship. Some land use effects on animal species distribution are well-understood, whereas others have been hypothesized but lack empirical research.

Other Factors

Location

The location of a solar facility will determine what wildlife and plant species will be influenced by land use impacts (e.g., are close enough to the facility to be affected by resource availability changes).

Technology

The type of solar energy technology can determine water availability (wet cooling systems use evaporation ponds), which is a resource that may influence animal distributions (Lovich and Ennen 2011).

Sources

CH2MHILL. 2008. Draft Raven Management Plan, Ivanpah Solar Electric Generating System. https://eplanning.blm.gov/epl-front-office/projects/nepa/65894/79908/92793/BA_attachment_E_Raven_Management_Plan.pdf. Accessed 26 July 2017.

Hall, L.K., R.T. Larsen, R.M. Knight, K.D. Bunnell, and B.R. McMillan. 2013. Water Developments and Canids in Two North American Deserts: A Test of the Indirect Effect of Water Hypothesis. *PLOS ONE* 8(7).

Howe, K.B., P.S. Coates, and D.J. Delehanty. 2014. "Selection of Anthropogenic Features and Vegetation Characteristics by Nesting Common Ravens in the Sagebrush Ecosystem." *The Condor* 116(10): 35–49.

Kristan, W.B. III, and W.I. Boarman. 2003. "Spatial Pattern of Risk of Common Raven Predation on Desert Tortoises." *Ecology* 84(9): 2432–2443.

Lovich, J.E., and J.R. Ennen. 2011. "Wildlife Conservation and Solar Energy Development in the Desert Southwest, United States." *BioScience* 61(12): 982–992.

Lozon, J.D., and H. MacIsaac. 1997. "Biological Invasions: Are They Dependent on Disturbance?" *Environ. Rev.* 5: 131–144.

Western EcoSystems Technology, Inc. 2016. Ivanpah Solar Electric Generating System Avian and Bat Monitoring Plan: 2015 Summer Report. https://www.scribd.com/doc/304853667/Ivanpah-Solar-Avian-and-Bat-Monitoring-Report-Summer-2015. Accessed July 26, 2017.

6l: Reflective Surfaces → Visual Aesthetics

Description of Relationship

Reflective surfaces from solar energy development are visible from certain surrounding observation points, thus changing the aesthetics of the view from those points.

Summary of Evidence

Solar energy infrastructure is visible from a distance because it contrasts with the surrounding landscape in color, reflectivity, and shape (Hartmann et al. 2016). The distance at which infrastructure is visible and the number of surrounding receptors (residential areas, roads, recreational areas) from which the infrastructure is visible depend on several factors, including the infrastructure height, surrounding terrain and land cover, air quality, and receptor location (Hartmann et al. 2016; Nutsford et al. 2015). A visibility study of various types of solar facilities found that they were “easily visible” from more than 10 miles away, and in some cases, they were visible at more than 20 miles away. With increasing distance, the facilities become more difficult to distinguish from the surrounding landscape and to recognize as solar facilities (Sullivan et al. 2012).

The extent of viewshed changes caused by a particular land use impact can be assessed through geographical information system (GIS) viewshed analysis, which uses an elevation model to evaluate which areas can be seen from a given vantage point; a cutoff distance (e.g., the visual range in the study area) is used to limit the viewshed extent from an observation point (Nutsford et al. 2015; Baranzini and Schaerer 2011). This technique has been used in a variety of fields, including urban planning and economic research; some studies have used viewshed analysis to assess the visual impacts of energy infrastructure (Nutsford et al. 2015; Baranzini and Schaerer 2011; Sander and Polasky 2008). Improvements, such as including a distance-decay function to emphasize visible objects closer to the observer, have been suggested to make viewshed analysis more reflective of human perception (Nutsford et al. 2015).

The visibility of a particular solar energy project can be assessed with on-site testing during the design phase by placing individual reflective surfaces (PV panels or mirrors) in appropriate locations at the facility site and by observing these surfaces, photographing them, or both from surrounding viewpoints (see Sullivan et al. 2012 for methods for assessing the visibility of solar energy facilities). However, this process is time-consuming and may not convey the full visual impacts of the completed facility, which will have a greater extent of reflective surfaces than is tested. Results will also be inaccurate if testing is not conducted with the reflective surfaces at their planned final heights.

Strength of Evidence

Moderate: Large-scale solar energy infrastructure does change visual aesthetics; the remaining question is at what distance the infrastructure is visible. There has been limited research into the visibility of solar energy infrastructure; the best evidence is from a field study that assessed the visibility of eight solar facilities (of different technology types) at various distances (Sullivan et al. 2012). Although this study documented many infrastructure and environmental variables that can influence visibility, its small sample size does not provide an adequate basis for developing a general relationship.

Predictability: Information from solar energy visibility studies (Sullivan et al. 2012) can be combined with a site-specific viewshed analysis to assess the likely visual impacts from the reflective surfaces of a solar energy facility. Existing viewshed analysis methods are generally accepted and have been used for research in a variety of fields, but they do not capture all aspects of visibility as perceived by humans, and their applicability to the visibility of solar energy infrastructure is unknown (Nutsford et al. 2015).

Other Factors

Location

The location of a solar energy facility with respect to surrounding terrain features and vegetation can influence its visibility and contrast with its surroundings.

Technology

The type of solar technology determines the height, color, and reflectivity of surfaces, and therefore it influences how visible it is at a distance (Sullivan et al. 2012).

Other

Sun angle: The angle of the sun, which changes with the day of the year and time of day, was found to influence the visibility of reflective surfaces through effects on contrast and reflection (Sullivan et al. 2012).

Observation point position: Many solar facilities are built in valleys, and when viewed from another point within the valley, low-profile infrastructure such as solar panels can blend in with surrounding features or the horizon. However, when viewed from an elevated observation point, the contrast of the facility against the valley floor increases, and visibility is enhanced (Sullivan et al. 2012). The direction from which the infrastructure is observed also influences its appearance; because PV panels are oriented toward the south, they appear black when viewed from the north, but they can appear to be other colors (blue, white) when viewed from other directions (Sullivan et al. 2012).

Sources

Hartmann, H.M., M.A. Grippo, G.A. Heath, J. Macknick, K.P. Smith, R.G. Sullivan, L.J. Walston, and K.L. Wescott. 2016. Understanding Emerging Impacts and Requirements Related to Utility-scale Solar Development. Argonne National Laboratory Environmental Science Division, ANL/EVS-16/9.

Nutsford, D., F. Reitsma, A.L. Pearson, and S. Kingham. 2015. "Personalising the Viewshed: Visibility Analysis from the Human Perspective." *Applied Geography* 62: 1–7.

Sullivan, R.G., L.B. Kirchler, C. McCoy, J. McCarty, K. Beckman, and P. Richmond. 2012. Visual Impacts of Utility-scale Solar Energy Facilities on Southwestern Desert Landscapes. Argonne National Laboratory.

6m: Visual Aesthetics → Recreation

Description of Relationship

People may be less likely to visit recreational areas with views of solar energy infrastructure than recreational areas with natural views.

Summary of Evidence

No studies were found that examine the effect of viewshed changes on visits to recreational sites. However, the importance of scenic views to recreationists has been established in a variety of contexts. A stated preference study based on photographs of views in Spain found that the "naturalness" of ecosystems was the most important characteristic in determining whether a landscape was preferred for recreation (Peña et al. 2015), and visitors to an urban forest in Sweden preferred natural areas to anthropogenic objects in a visitor-employed photography study in which participants took photos of places they most and least liked on a walk along a trail (Heyman 2012). Scenic beauty, as assessed by a focus group, was also used as an attribute to estimate areas' recreation and ecotourism potential in southern Chile (Nahuelhual et al. 2013). A series of 67 National Park Service (NPS) surveys from 1988 to 2011 asked visitor groups which park attributes were the most important to protect; scenic views were ranked as the most important attribute by 67% of those surveyed and were ranked in the top five attributes in 90% of surveys (Kulesza et al. 2013). This information suggests that changes to the viewsheds of recreational areas that result in less natural views could result in a degraded visitor experience and potentially lower visitation; however, no specific research was found to confirm this relationship.

The National Park Service is concerned about impacts to NPS resources that may occur as a result of viewshed changes from renewable energy development, including solar energy facilities. The agency has developed a Renewable Energy Visual Impact Assessment Evaluation Guide to help NPS staff review visual impact assessments (VIAs) that are prepared as part of utility-scale energy project environmental impact statements (Sullivan and Meyer 2014).

Strength of Evidence

Low: There is no direct evidence for the effect of viewshed changes on visits to recreational areas. Potential effects are extrapolated from stated preference studies that establish tourists' preference for natural-appearing landscapes and the importance of scenic views to visitors of U.S. national parks (Peña et al. 2015; Kulesza et al. 2013).

Other Factors

Location

The location of a solar energy facility relative to areas used for recreation will determine the visual impact it has on these areas (see links 6l and 9w).

Technology

The type of solar technology is expected to influence the visual impacts on recreation through its effect on visibility (see link 6l).

Sources

Heyman, E. 2012. "Analyzing Recreational Values and Management Effects in an Urban Forest with the Visitor-employed Photography Method." *Urban Forestry and Urban Greening* 11(3): 267–277.

Kulesza, C., Y. Le, M. Littlejohn, and S.J. Hollenhorst. 2013. National Park Service Visitor Values and Perceptions of Clean Air, Scenic Views, and Dark Night Skies, 1988–2011. Natural Resource Report NPS/NRSS/ARD/NRR-2013/632.

Nahuelhual, L., A. Carmona, P. Lozada, A. Jaramillo, and M. Aguayo. 2013. "Mapping Recreation and Ecotourism as a Cultural Ecosystem Service: An Application at the Local Level in Southern Chile." *Applied Geography* 40: 71-82.

Peña, L., I. Casado-Arzuaga, and M. Onaindia. 2015. "Mapping Recreation Supply and Demand Using an Ecological and a Social Evaluation Approach." *Ecosystem Services* 13: 108–118.

Sullivan, R., and M. Meyer. 2014. Guide to Evaluating Visual Impact Assessments for Renewable Energy Projects. Argonne National Laboratory Environmental Science Division. Natural Resource Report NPS/ARD/NRR—2014/836.

6n: Visual Aesthetics → Residential Property Values

Description of Relationship

For every additional XX% of a property's view occupied by solar energy infrastructure, the property's value decreases by XX%.

Summary of Evidence

No studies have examined the influence of solar energy infrastructure in the viewshed on property values, but a variety of studies have used hedonic pricing models to assess the effects of views on those values. These studies have generally found that property values are positively correlated with total view extent and the amount of a view made up of natural land cover types (Sander and Polasky 2008; Barazini and Schaerer 2011; Bourassa et al. 2004). One study in Geneva, Switzerland, found that a 1-hectare increase in industrial area in a view decreased rent values by 5.2% (Baranzini and Schaerer 2011). Given these findings, the construction of solar energy infrastructure in a previously natural area would be expected to decrease values for those properties with a view of the infrastructure.

Studies of the effects of views of wind turbines on property values provide the closest analogue to the effects of solar energy infrastructure. Several studies using hedonic pricing models to evaluate the influence of wind turbine views on property values found no evidence of an effect (Sunak and Madlener 2013; Hoen et al. 2009), even when local residents thought that their property values had been affected (Vyn and McCullough 2014). It is unknown whether these findings are applicable to the effect of solar energy infrastructure on property values, or if differences in appearance between the two infrastructure types result in different viewshed impacts on property values.

Strength of Evidence

Low: There is no direct evidence for the effect of solar energy infrastructure in the viewshed on property values. Potential effects are extrapolated from general studies of view effects on property values and from studies of the effects of views of wind turbines on property values. Both of these types of studies have limited applicability to viewshed effects from solar energy infrastructure, and their results are not consistent with each other.

Other Factors

Location

The location of a solar energy facility determines the number of properties it may affect through visual impacts (this number can be assessed with a viewshed analysis; see link 6l). View may be more highly valued in certain places (e.g., places with particularly scenic natural views).

Technology

Different types of solar technologies have different appearances, which could result in varying visual impacts if people are more or less accepting of certain infrastructure types. No research was found that assessed differences among technology types.

Property Value

More expensive luxury properties have been found to be more sensitive to viewshed impacts than less expensive properties (Bourassa et al. 2004).

Sources

Barazini, A., and C. Schaerer. 2011. "A Sight for Sore Eyes: Assessing the Value of View and Land Use in the Housing Market." *Journal of Housing Economics* 20: 191–199.

Bourassa, S.C., M. Hoesli, and J. Sun. 2004. "What's in a View?" *Environment and Planning A* 36: 1427–1450.

Hoen, B., R. Wiser, P. Cappers, M. Thayer, and G. Sethi. 2009. The Impact of Wind Power Projects on Residential Property Values in the United States: A Multi-site Hedonic Analysis. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy.

Sander, H.A., and S. Polasky. 2009. "The Value of Views and Open Space: Estimates from a Hedonic Pricing Model for Ramsey County, Minnesota, USA." *Land Use Policy* 26(3): 837–845.

Sunak, Y., and R. Madlener. 2013. "The Impact of Wind Farms on Property Values: A Geographically Weighted Hedonic Pricing Model." Institute for Future Energy Consumer Needs and Behavior Working Paper No. 3/2012.

Vyn, R.J., and R.M. McCullough. 2014. "The Effects of Wind Turbines on Property Values in Ontario: Does Public Perception Match Empirical Evidence?" *Canadian Journal of Agricultural Economics* 62: 365–392.

6o: Visual Aesthetics → Cultural Resources

Description of Relationship

Changes to visual aesthetics may affect people's ability to use and appreciate cultural resources.

Summary of Evidence

A risk assessment for visual impacts on cultural resources in lands managed by the Bureau of Land Management (BLM) describes various ways in which changes to visual aesthetics could affect the use of cultural resources, including the ability to experience an area as it was in the past, to conduct landscape-level research in intact settings, and to continue cultural traditions in traditional settings (Wescott et al. 2016). This study combined viewshed assessments from a variety of culturally significant "observation points" surrounding an SEZ to identify locations in which visible land use changes would have the greatest impact on cultural resources (in terms of the number of cultural resources affected). In ethnographic analyses conducted by the BLM with Native American tribes with cultural heritage in and around the SEZs, interviewees often cited changes to visual aesthetics as a significant impact to their continued use of cultural resources (e.g., Stoffle et al. 2011). Visual impacts to cultural resources are recognized as a potential issue in BLM solar energy impact assessments and mitigation plans (Wescott 2013; BLM, n.d.)

Strength of Evidence

Moderate: The existence of cultural resource impacts from visual aesthetic changes is recognized and accepted; interviews of affected stakeholders around BLM SEZs provide highly relevant evidence for this relationship. Specific impacts are difficult to measure and may not be possible or appropriate to quantify.

Other Factors

Location

The location of solar energy facilities relative to cultural resources will determine the extent of the visual impact (see link 6l).

Technology

Different types of solar technologies have different appearances, which could result in varying visual impacts if people are more or less accepting of certain infrastructure types. No research was found that assessed differences among technology types.

Sources

BLM (Bureau of Land Management). N.d. "Cultural Resources Mitigation Measures." Tribal Energy and Environmental Information Clearinghouse. https://teeic.indianaffairs.gov/er/oilgas/mitigation/culture/index.htm. Accessed July 26, 2017.

Stoffle, R.W., K.A. Van Vlack, H.Z. Johnson, P.T. Dukes, S.C. De Sola, and K.L. Simmons. 2011. Tribally Approved American Indian Ethnographic Analysis of the Proposed Amargosa Valley Solar Energy Zone. Solar Programmatic Environmental Impact Statement and Solar Energy Study Areas in Portions of Arizona, California, Nevada, and Utah. http://solareis.anl.gov/documents/ethnographic/EthnographicAnalysis_AmargosaValley.pdf. Accessed July 26, 2017.

Wescott, K. 2013. Impacts of Utility-scale Solar Development on Cultural Resources. Presentation at Solar Workshop, February 20–22, 2013. Argonne National Laboratory.

Wescott, K., J.M. Abplanalp, J. Brown, B. Cantwell, M. Dicks, B. Fredericks, …, and E.A. Zvolanek. 2016. San Luis Valley–Taos Plateau Landscape-level Cultural Heritage Values and Risk Assessment Final Report. Argonne National Laboratory.

6p: Species Distribution (Competitive, Predator) → Wildlife Populations

Description of Relationship

When species distribution shifts influence competition or predator-prey dynamics between species, a shift in the distribution of one species can affect the populations of other wildlife species.

Summary of Evidence

A shift in the distribution of one species can have an effect on the population of another species when the two species influence each other through inter-species competition or predation. These changes are very specific to location and the species involved, so no generalized relationships can be established. Some examples of species distribution impacts on another species' population are given below.

Ravens and Desert Tortoises

Raven predation on juvenile desert tortoises is a significant source of mortality in desert tortoise populations (Berry et al. 2013; Kristan and Boarman 2003). The availability of resources in developed areas, including solar energy facilities, allows ravens to expand into more remote desert areas (see link 6k). Therefore, a solar energy facility may expose the local desert tortoise population to higher raven predation levels, decreasing the tortoise population. Studies have shown that desert tortoise densities are negatively correlated with raven densities (Berry et al. 2013) and that desert tortoise predation risk is associated with large flocks of ravens at human developments (Kristan and Boarman 2003). Because ravens are generalist predators and not dependent on desert tortoises as a food source, raven populations do not decline with tortoise populations, and ravens can continue to prey on very small populations of desert tortoises, potentially driving them to extinction (Kristan and Boarman 2003).

A population assessment of a species of interest at a particular location is necessary to determine the specific effects of wildlife distribution shifts on that species. The study of raven predation on desert tortoises provides a good example of assessing how the distribution of a predator species can influence the population of a prey species, but the extent of raven predation on a particular tortoise population is likely influenced by local factors (Kristan and Boarman 2003). Field research at a particular solar energy facility would help to determine the effect of ravens on local desert tortoise populations.

Coyotes and Desert Kit Foxes

Desert kit foxes are thought to compete with coyotes for food but are able to utilize resources in areas that coyotes cannot survive due to a lack of water (kit foxes can more effectively meet their water demands by food intake than coyotes can) (Hall et al. 2013). As stated in link 6k, it is hypothesized increased water supply at solar energy facilities could allow coyote populations to expand into new areas. This relationship has not been fully assessed; population surveys show a negative correlation between coyote density and desert kit fox density (Kadaba 2014), but an experiment in the Mojave and Great Basin deserts did not find evidence for the hypothesis that increased water availability benefits coyote populations at the expense of desert kit foxes (Hall et al. 2013).

Strength of Evidence

Low: This relationship is highly dependent on the species involved, location, and species-specific resource availability, so no research was found that assesses the generalized relationship. Evidence for specific effects varies, as discussed above for the coyote-kit fox and raven-desert tortoise relationships.

Sources

Berry, K.H., J.L. Yee, A.A. Coble, W.M. Perry, and T.A. Shields. 2013. "Multiple Factors Affect a Population of Agassiz's Desert Tortoise (*Gopherus agassizii*) in the Northwest Mojave Desert." *Herpetological Monographs* 27(1): 87–109.

Hall, L.K., R.T. Larsen, R.M. Knight, K.D. Bunnell, and B.R. McMillan. 2013. "Water Developments and Canids in Two North American Deserts: A Test of the Indirect Effect of Water Hypothesis." *PLOS ONE* 8(7).

Kadaba, D. 2014. Ecology of the Desert Kit Fox (*Vulpes macrotis arsipus*) in Chuckwalla Valley, California. Unpublished master's thesis. Duke University, Durham, North Carolina.

Kristan, W.B. III, and W.I. Boarman. 2003. "Spatial Pattern of Risk of Common Raven Predation on Desert Tortoises." *Ecology* 84(9): 2432–2443.

6q: Species Distribution (Invasive) → Natural Ecosystems/Flora

Description of Relationship

The spread of invasive plant populations can cause declines in native plant richness and change the fire regime.

Summary of Evidence

Invasive plants can have widespread effects on natural ecosystem function and individual native species. On the ecosystem level, invasive plants have been shown to increase total plant production, microbial activity, and nitrogen/phosphorus/carbon pools, while decreasing pH (Vilá et al. 2011). Invasive plants also decrease overall diversity and abundance of native plant species (Vilá et al. 2011; Schirmel et al. 2016). In desert ecosystems, several invasive plants (red brome, Mediterranean grass, and red-stemmed filaree) can use soil water and nitrogen more effectively than native plants, decreasing native plant biomass and diversity (Brooks and Pyke 2001).

In the western United States, a major impact of invasive plants occurs through changes to the fire regime. The U.S. desert ecosystems rarely experienced fire in the past, and native plants are not fire-tolerant (Brooks and Esque 2002). A 2013 study of invasive cheatgrass in the Great Basin found that land dominated by the cheatgrass was at least twice as likely to burn as land with native vegetation, and cheatgrass-dominated land was overrepresented in the largest fire events during the study period (Balch et al. 2013). The specific effects of invasive plant on fire regimes depends on fire-related factors of the invading plant and the native plants it's replacing. Brooks et al. (2004) describe several ways in which an invasive plant could reduce the risk of fire (e.g., if a succulent with high moisture levels replaces drier woody vegetation), but no studies have examined whether this risk reduction has actually occurred.

More frequent fires can benefit invasive plants over native species, creating a positive feedback loop. Annual plants are the most common invasive plant species in the Mojave and Colorado deserts, and fire facilitates their spread; in the Sonoran Desert, even low-intensity fires caused native shrubs to be replaced by annual plants and nonnative fire-tolerant species (Brooks and Esque 2002; Brown and Minnich 1986).

Field monitoring of plant communities can provide strong evidence for the effects of invasive plants on native plants. A field study conducted in the Mojave Desert shows that two widespread invasive grasses, *Bromus* and *Schismus*, cause declines in native annual plant biomass and density through competition (Brooks 2000).

Strength of Evidence

Fair: This link includes individual relationships among invasive plant distributions, native plant diversity, and fire regimes. The amount and strength of available evidence differs for each. In general, the ability of invasive plants to displace native plants and to alter the fire regime is well-established, but the degree to which invasive plants cause specific effects depends on the species in question and other contextual factors.

Other Factors

Location

The location of a nonnative plant invasion will determine the native species with which it is competing, and therefore the extent to which it can displace the native species.

Technology

Technology has no effect (assumed).

Other

The effects of invasive plants on ecosystem function and native species vary by ecosystem type (Schirmel et al. 2016; McCary et al. 2016), study area size (Powell et al. 2011), basal food type (living plant or detritus), and ecosystem plant diversity (McCary et al. 2016).

Other Potential Impacts

Introduction of Invasive Species Increases the Likelihood of Fire

Invasive plants alter natural fire regimes by increasing the fuel load, altering the fuel type (moisture levels, size), increasing fuel continuity, and changing the timing of fuel availability. These changes can extend the fire season, increase the size and number of fires, and allow fires to spread more rapidly in invaded ecosystems (Brooks et al. 2004).

Increased Likelihood of Fire Increases the Likelihood of Smoke

Wildfires create smoke consisting of carbon dioxide, water vapor, carbon monoxide, nitrogen oxide, particulates, and organic chemicals. Smoke from fires can travel long distances, but the direction and length of smoke plumes depend on many factors (see below) (Lipsett et al. 2008). Fuel type, moisture content, and fire temperature affect smoke composition. Smoke plume travel depends on weather, regional prevailing winds, fire temperature, and terrain (Lipsett et al. 2008).

Smoke Causes Particulate Air Pollution

Smoke from wildfires has caused exceedances of National Ambient Air Quality Standards for ozone and particulate matter (both sub-10 and sub-2.5 microns) (Last et al. 2009; Viswanathan et al. 2006). Particulate air pollution has well-established effects on human respiratory health (see link 3f).

Sources

Balch, J.K., B.A. Bradley, C.M. D'Antonio, and J. Gómez-Dans. 2013. "Introduced Annual Grass Increases Regional Fire Activity across the Arid Western USA (1980–2009). *Global Change Biology* 19: 173–183.

Brooks, M.L. 2000. "Competition between Alien Annual Grasses and Native Annual Plants in the Mojave Desert." *American Midland Naturalist* 144: 92–108.

Brooks, M.L., and D.A. Pyke. 2001. "Invasive Plants and Fire in the Deserts of North America." In *Proceedings of the Invasive Species Workshop: The Role of Fire in the Control and Spread of Invasive Species*, edited by K.E.M. Galley and T.P. Wilson, 1–14. Miscellaneous Publication No. 11. Tall Timbers Research Station, Tallahassee, FL.

Brooks, M.L., and T.C. Esque. 2002. "Alien Plants and Fire in Desert Tortoise (*Gopherus agassizii*) Habitat of the Mojave and Colorado Deserts." *International Journal of Turtle and Tortoise Research* 4(2): 330–340.

Brooks, M.L., C.M. D'Antonio, D.M. Richardson, J.B. Grace, J.E. Keeley, J.M. DiTomaso, R.J. Hobbs, M. Pellant, and D. Pyke. 2004. "Effects of Alien Invasive Plants on Fire Regimes." *BioScience* 54(7): 677–688.

Brown, D.E., and R.A. Minnich. 1986. "Fire and Changes in Creosote Bush Scrub of the Western Sonoran Desert, California." *The American Midland Naturalist* 116(2): 411–422.

Last, J.A., K.E. Pinkerton, and T.C. Wegesser. 2009. "California Wildfires of 2008: Coarse and Fine Particulate Matter Toxicity." *Environmental Health Perspectives* 117(6): 893.

Lipsett, M., B. Materna, S. Lyon Stone, S. Therriault, R. Blaisdell, and J. Cook. 2008. Wildfire Smoke: A Guide for Public Health Officials. California Department of Health, US Environmental Protection Agency, California Office of Environmental Health Hazard Assessment, Missoula County Health Department, California Air Resources Board. https://www3.epa.gov/airnow/wildfire_may2016.pdf.

McCary, M.A., R. Mores, M.A. Farfan, and D.H. Wise. 2016. "Invasive Plants Have Different Effects on Trophic Structure of Green and Brown Food Webs in Terrestrial Ecosystems: A Meta-analysis." *Ecology Letters* 19: 328–335. doi: 10.1111/ele.12562.

Powell, K.I., J.M. Chase, and T.M. Knight. 2011. "A Synthesis of Plant Invasion Effects on Biodiversity across Spatial Scales." *American Journal of Botany* 98(3): 539–548. http://www.jstor.org/stable/41149203.

Schirmel, J., M. Bundschuh, M.H. Entling, I. Kowarik, and S. Buchholz. 2016. "Impacts of Invasive Plants on Resident Animals across Ecosystems, Taxa, and Feeding Types: A Global Assessment." *Global Change Biology* 22: 594–603. doi: 10.1111/gcb.13093.

Vilá, M., J.L. Espinar, M. Hejda, P.E. Hulme, V. Jarosik, J.L. Maron, J. Pergl, U. Schaffner, Y. Sun, and P. Pysek. 2011. "Ecological Impacts of Alien Invasive Plants: A Meta-analysis of Their Effects on Species, Communities, and Ecosystems." *Ecology Letters* 14: 702–708. http://dx.doi.org/10.1111/j.1461-0248.2011.01628.x.

Viswanathan, S., L. Eria, N. Diunugala, J. Johnson, and C. McClean. 2006. "An Analysis of Effects of San Diego Wildfire on Ambient Air Quality." *Journal of the Air and Waste Management Association* 56(1): 56–67.

6r: Natural Ecosystems/Flora → Habitat Persistence

Description of Relationship

If ecosystem function and vegetation communities change to a large extent, they can cause habitat conversion to a different habitat type. Therefore, changes to natural ecosystems and flora can influence habitat persistence (the probability that an area of a certain habitat type will remain intact long term).

Summary of Evidence

The best-studied process of habitat type conversion due to ecosystem function and vegetation changes is the fire-grass cycle, in which nonnative grass invasion increases fire frequency, and nonnative grasses recover faster after a fire than native vegetation, perpetuating the cycle and resulting in habitat conversion to a nonnative grassland ecosystem (Brooks and Esque 2002; Olsson et al. 2012). This type of conversion has been observed throughout the western United States (Brooks and Pyke 2001); satellite data showed that the largest cause of land cover conversion in the Northern and Central Basin and Range ecoregions from 1973 to 2000 was due to fires likely driven by the spread of invasive annual grasses such as cheatgrass (Soulard and Sleeter 2012). Under some conditions, intensive invasions by nonnative grasses can cause habitat type shifts in deserts driven by competition with native plants, even without changes to the fire regime (Olsson et al. 2012).

Strength of Evidence

Fair (fire-grass cycle): Although the widespread process of habitat conversion in the southwestern United States through the grass-fire cycle has been extensively studied, no meta-analyses or models were found that predict the likelihood of habitat conversion as a function of changes to vegetation communities and ecosystem functions.

Low (other systems): Drivers of habitat conversion other than changes to the fire regime have not been as extensively studied, and effects are likely inconsistent across habitat types.

Other Factors

Location

The location of a solar energy facility and related changes to vegetation and ecosystem functions determine the climate and affected habitat types, and therefore the habitat types to which they are likely to be converted and the likelihood of conversion.

Technology

No effect is assumed.

Sources

Brooks, M.L., and D.A. Pyke. 2001. "Invasive Plants and Fire in the Deserts of North America." In *Proceedings of the Invasive Species Workshop: The Role of Fire in the Control and Spread of Invasive Species,* edited by K.E.M. Galley and T.P. Wilson, 1–14. Miscellaneous Publication No. 11. Tall Timbers Research Station, Tallahassee, FL.

Brooks, M.L., and T.C. Esque. 2002. "Alien Plants and Fire in Desert Tortoise (*Gopherus agassizii*) Habitat of the Mojave and Colorado Deserts." *International Journal of Turtle and Tortoise Research* 4(2): 330–340.

Olsson, A.D., J. Betancourt, M.P. McClaran, and S.E. Marsh. 2012. "Sonoran Desert Ecosystem Transformation by a C4 Grass without the Grass/Fire Cycle." *Diversity and Distributions* 18: 10–21.

Soulard, C.E., and B.M. Sleeter. 2012. "Late Twentieth Century Land-cover Change in the Basin and Range Ecoregions of the United States." *Regional Environmental Change* 12: 813–823.

6s: Habitat Persistence → Existence Value (Habitat)

Description of Relationship

The continued persistence of one acre of a certain habitat type has an existence value of $XX.

Summary of Evidence

Few studies have attempted to estimate the non-use values (including existence value, option value, and bequest value) of intact habitats. A 2016 review of economic values of wilderness found six studies of wilderness values that included non-use values; annual household WTP was estimated at $0.01–$0.61/1000 acres (Holmes et al. 2016). These studies were carried out for individual locations, and with such little research available, no comparison of non-use values for different types of habitat is possible. The authors of the review article suggest that new studies are needed to update these estimates.

It may also be difficult to separate non-use values for habitat existence from non-use values for the species dependent on that habitat; if these non-use values are not separated, double-counting may occur (e.g., the non-use value for a certain species may be counted towards the species non-use value and the habitat non-use value).

Contingent valuation methods can be used to estimate the existence value that a population holds for a particular habitat area. An example of this method can be found in a study that assessed the existence value of a wilderness area in Vermont (Gilbert et al. 1992).

Strength of Evidence

Low: Very few studies have estimated the existence value of intact habitat, and the most recent of these was published in 1994, so no general relationship can be assessed.

Other Factors

Location

The distance of a particular habitat area from people may influence the value they place on its continued existence (Loomis 2000).

Technology

Technology has no effect (assumed).

Other

The specific type of habitat may influence its existence value (no evidence was found to assess this hypothesis).

Sources

Gilbert, A., R. Glass, and R. More. 1992. "Valuation of Eastern Wilderness: Extra-market Measures of Public Support." In *Economic Value of Wilderness*, edited by C. Payne, J.M. Bowker, and P. Reed, 57–70. Asheville, NC: United States Department of Agriculture, Forest Service. https://www.srs.fs.usda.gov/pubs/gtr/gtr_se078.pdf.

Holmes, T.P., J.M. Bowker, J. Englin, E. Hjerpe, J.B. Loomis, S. Phillips, and R. Richardson. 2016. "A Synthesis of the Economic Values of Wilderness." *Journal of Forestry* 114(3): 320–328.

Loomis, J. B. 2000. "Vertically Summing Public Good Demand Curves: An Empirical Comparison of Economic versus Political Jurisdictions." *Land Economics* 76(2): 312–321.

6t: Natural Ecosystems/Flora → Habitat

Description of Relationship

Changes to plant communities and ecosystem function, including fire regimes, can affect the quality and amount of habitat for wildlife species that use affected ecosystem components for food, shelter, and other resources.

Summary of Evidence

Habitat is species specific, so changes in plant communities and ecosystem function will affect each species differently. Therefore, no general relationship can be stated. An example of one particular relationship, among vegetation, fire regime, and desert tortoise habitat, is given below.

Desert tortoises in intact habitats depend on native plants for food and cover; tortoises selectively forage for plants with high water and protein content and low potassium (Oftedal et al. 2002). Grasses are generally of lower dietary quality than forbs, and several invasive grass species are becoming widespread in western deserts. When invasive plants cause declines in native plant abundance and diversity, tortoises are less able to access their preferred foods, which can lead to weight loss and other physiological challenges (Brooks and Esque 2002; Hazard et al. 2009). Therefore, changes in plant communities can result in lower-quality habitat for desert tortoises.

Invasive plants' effects on desert fire regimes also have negative implications for desert tortoises. In addition to killing tortoises directly, fires alter habitat structure by killing the native woody shrubs that tortoises use for cover (Brooks and Esque 2002). After a fire, woody shrub cover can take up to 50 years and the native plant community several hundred years to recover (Drake et al. 2015). Fires also facilitate invasive plant dominance, further reducing the availability of high-quality food as described above. Although a study of desert tortoises following a large fire in the Mojave Desert found that the tortoises will continue to use burned areas for foraging, especially if certain plant species are present, repeated fires in the same area (facilitated by large populations of invasive plants) can result in conversion of the desert to a nonnative grassland, which does not provide habitat for desert tortoises (Brooks and Esque 2002; Drake et al. 2015).

The effects of plant community and fire regime shifts on habitat quantity and quality for desert tortoises have been well-studied, as described above. Similar studies may need to be conducted for other species of interest in order to fully assess the impacts of plant and ecosystem changes on habitat for those species.

Strength of Evidence

Low: The strength of evidence available for effects of plant communities and ecosystem functioning on habitat will depend on the species in question; no general evidence for this relationship was found, but individual studies show that the relationship does exist in certain contexts.

Other Factors

Species

The wildlife species found near a solar facility, and the habitat requirements of that species, determines the habitat effects caused by changes to the ecosystem and plant communities.

Technology

Technology has no effect (assumed).

Sources

Brooks, M.L., and T.C. Esque. 2002. "Alien Plants and Fire in Desert Tortoise (*Gopherus agassizii*) Habitat of the Mojave and Colorado Deserts. *International Journal of Turtle and Tortoise Research* 4(2): 330–340.

Drake, K.K., T.C. Esque, K.E. Nussear, L.A. Defalco, S.J. Scoles-Sciulla, A.T. Modlin, and P.A. Medica. 2015. "Desert Tortoise Use of Burned Habitat in the Eastern Mojave Desert." *The Journal of Wildlife Management* 79(4): 618–629.

Hazard, L.C., D.R. Shemanski, and K.A. Nagy. 2009. "Nutritional Quality of Natural Foods of Juvenile Desert Tortoises (*Gopherus agassizii*): Energy, Nitrogen, and Fiber Digestibility." *Journal of Herpetology* 43(1): 38–48.

Oftedal, O.T., S. Hillard, and D.J. Morafka. 2002. "Selective Spring Foraging by Juvenile Desert Tortoises (*Gopherus agassizii*) in the Mojave Desert: Evidence of an Adaptive Nutritional Strategy." *Chelonian Conservation and Biology* 4(2): 341–352.

6u: Reflective Surfaces → Habitat

Description of Relationship

The installation of 1 acre of reflective surfaces decreases habitat area by 1 acre for the wildlife species that previously used that land and can no longer survive there.

Summary of Evidence

Reflective surfaces at a solar facility are "built environment" elements that are unsuitable habitat for wildlife species. The habitat loss directly caused by the installation of manmade infrastructure, such as reflective surfaces, is more permanent than other types of habitat loss, such as land clearing, that do not entirely replace the natural area with manmade infrastructure (McKinney 2002).

The loss of wildlife habitat under raised reflective surfaces, such as PV panels and mirrors, can be partially mitigated in some contexts by planting native vegetation beneath and between the structures. Minnesota's standards for pollinator-friendly solar energy development, based on the installation of native plants around and underneath PV panels, have been adopted by five other states as of May 2017 (Benage 2017). However, this kind of restoration only benefits species that can make use of small habitat patches, and it is difficult to carry out in arid ecosystems in the southwestern United States, where water scarcity and soil disturbance slow plant establishment (Cameron et al. 2012). No examples of habitat restoration beneath reflective surfaces on large-scale solar energy installations in the southwestern United States were found.

Strength of Evidence

Moderate: Although few studies specifically examine this relationship, the unsuitability of built-up areas, including reflective surfaces, for habitat for most wildlife species is indisputable, and many studies document urban areas' low native species richness and wildlife abundance.

Other Factors

Location

The location of the solar energy development will determine which wildlife species are affected by habitat conversion to reflective surface infrastructure.

Technology

The type of solar technology will influence the spatial extent of reflective surfaces (see link 6a).

Sources

Benage, M. 2017. "Solar Sites Double as Pollinator Habitat." *Minnesota Conservation Volunteer*, May-June 2017. http://www.dnr.state.mn.us/mcvmagazine/issues/2017/may-jun/solar-site-pollinators.html.

Cameron, D.R., B.S. Cohen, and S.A. Morrison. 2012. "An Approach to Enhance the Conservation Compatibility of Solar Energy Development." *PLoS ONE* 7(6): e38437.

McKinney, M.L. 2002. "Urbanization, Biodiversity, and Conservation." *BioScience* 52(10): 883–890.

8a: Solar Development → Roads

Description of Relationship

Solar energy facilities require the construction of new roads; road density in solar energy facility sites is XX km/km.[2]

Summary of Evidence

The impacts of access road construction for solar energy facilities is discussed in the summary of environmental impacts for solar energy development, but no studies have been found that estimate road density associated with solar energy facilities (Patton et al. 2013). The road density at a particular solar energy facility can be calculated during the planning process.

Strength of Evidence

High: The fact that access roads are a necessary part of solar energy facilities is not in dispute; although there are no studies of road density at solar energy facilities in general, the road density at a particular solar energy facility can be easily calculated during the process of planning the facility.

Sources

Patton, T., L. Almer, H. Hartmann, and K.P. Smith, eds. 2013. An Overview of Potential Environmental, Cultural, and Socioeconomic Impacts and Mitigation Measures for Utility-scale Solar Energy Development. Environmental Science Division, Argonne National Laboratory.

8c: Roads → Habitat

Description of Relationship

An increase in road density by 1 km/km^2 causes a decline in wildlife population density of XX%.

Or

Wildlife population density declines by XX% within XX km of roads.

Summary of Evidence

Many studies have examined the effects of roads on wildlife populations, but differences in species responses, road characteristics, habitat type, and measured variables make it very difficult to determine a general relationship between roads and wildlife habitat suitability. Roads alter the physical and chemical environment (including through changes to temperature, soil density, soil water content, runoff flow, pollutant levels, and noise) and can cause further changes in leaf litter and vegetation composition and soil macroinvertebrate communities (Trombulak and Frissell 2000; Coffin 2007). Together, all of these changes can make surrounding habitat less suitable for certain wildlife species (Trombulak and Frissell 2000). Many animals avoid roads, and especially sensitive species may avoid the areas near roads as well (Forman and Deblinger 2000). Avoiding these areas and being unable to cross roads to reach additional habitat effectively decreases the amount of habitat available to certain wildlife species (Rytwinski and Fahrig 2012).

Several studies have measured the effects of roads on wildlife populations. A meta-analysis of infrastructure effects on birds and mammals found that bird abundances declined by 28%–36% within 2.6 km of infrastructure, and mammal abundances declined by 25%–38% within 17 km of infrastructure (Benitez-López et al. 2010). Studies from Europe have found that forest-interior bird species abundances are about 33% lower within 650 meters of roads, and that grassland bird species abundances were reduced within 950 meters of roads (Forman and Deblinger 2000). Amphibians have been shown to be more sensitive to roads than mammals or birds are (Rytwinski and Fahrig 2012).

Roads act as barriers to many animals that avoid crossing them; some mammals have been shown to shift their home ranges away from roads (Trombulak and Frissell 2000). Therefore, roads can also fragment wildlife populations when they are built through an existing population's habitat.

Strength of Evidence

Fair: The function of roads as barriers to animal movement and the physical habitat effects of roads are well documented. No studies were found that estimated changes in habitat quality (using wildlife population density as a proxy) associated with increases in road density. Several studies have measured wildlife population abundance changes associated with roads (within a certain distance), but the effects are influenced by many variables, making it difficult to assess a general relationship.

Other Factors

Species

Species' life history traits and behavioral responses to roads influence their sensitivity to road effects (Rytwinski and Fahrig 2012). A meta-analysis of wildlife population responses to roads that examined these factors found that amphibians and reptiles are the most negatively affected of all taxa, and that amphibians with low reproductive rates are particularly susceptible. Of mammals, species with large home range, greater body mass, and low reproductive rates are the most negatively affected by roads. Mammal species that avoid roads and the surrounding habitats (including elk and caribou) are more negatively affected than species that avoid roads but not nearby habitat (such as cougars and black bears) (Rytwinski and Fahrig 2012).

Road Traffic Characteristics

The maximum distance at which roads affect bird populations has been found to increase with traffic volume in individual studies (Forman and Alexander 1998), but a meta-analysis found no evidence of a traffic volume effect on bird populations (Benitez-López et al. 2010).

Sources

Benitez-López, A., R. Alkemade, and P.A. Verweij. 2010. "The Impacts of Roads and Other Infrastructure on Mammal and Bird Populations: A Meta-analysis." *Biological Conservation* 143: 1307–1316.

Coffin, A.W. 2007. "From Roadkill to Road Ecology: A Review of the Ecological Effects of Roads." *Journal of Transport Geography* 15: 396–406.

Forman, R.T.T., and L.E. Alexander. 1998. "Roads and Their Major Ecological Effects." *The Annual Review of Ecology, Evolution, and Systematics* 29:207–231.

Forman, R.T.T., and R.D. Deblinger. 2000. "The Ecological Road-effect Zone of a Massachusetts (USA) Suburban Highway." *Conservation Biology* 14(1): 36–46.

Rytwinski, T., and L. Fahrig. 2012. "Do Species Life History Traits Explain Population Responses to Roads? A Meta-analysis." *Biological Conservation* 147: 87–98.

Trombulak, S.C., and C.A. Frissell. 2000. "Review of Ecological Effects of Roads on Terrestrial and Aquatic Communities." *Conservation Biology* 14(1): 18–30.

8d: Roads → Species Distribution

Description of Relationship

Newly constructed roads can enable the spread of invasive plant species by facilitating the movement of seeds and propagules and by creating conditions favorable to establishment.

Summary of Evidence

Although no instances of PV development causing the introduction of invasive species have been reported, the construction and road-building activities associated with PV development have the potential to directly introduce and facilitate the establishment of invasive species. Roads provide ideal corridors for invasive species to spread to new areas; one study in Canada found that common ragweed, an invasive plant and agricultural pest, spreads more readily along paved roadways than gravel or other unpaved roads (Joly et al. 2011). Cogon grass has spread throughout Florida as a result of rhizome transport by construction equipment and in fill dirt (Coffin 2007).

Research in the desert ecosystems in which many large-scale solar energy facilities in the United States are located shows that roads and off-highway vehicle tracks in the Mojave Desert provide dispersal pathways for invasive plants to access rural areas; higher nutrient levels and soil moisture in these areas facilitate plant establishment, and vehicles are a source of plant seeds or propagules (Brooks 2009). Periodic vehicle travel to livestock watering sites in the desert has been shown to provide colonization opportunities for nonnative plants (Brooks 2009); routine vehicle traffic to solar energy facilities could have a similar effect.

Vegetation surveys in habitat along roads and in similar areas far from roads can be conducted to assess the effect that new roads have had on vegetation communities in a particular area. A study of plants in roadside habitat and road-adjacent interior communities in southern Utah provides a good example of methods that can be used to assess the impact of roads on the spread and establishment of invasive plant species (Gelbard and Belnap 2003).

Strength of Evidence

Low: Because the effects of land use impacts on species distributions vary with species, location, and habitat variables, it is not possible to describe a generalized relationship. The effects of disturbance on invasive plant dispersal and establishment are well-studied with generally consistent results, but the specific impact depends on the species and location. Some land use effects on animal species distribution are well-understood, whereas others have been hypothesized but lack empirical research. Site-specific research will likely be needed to understand the effects of a particular solar energy project.

Other Factors

Location

The location of a solar facility will determine which invasive plant species might take advantage of the road conduits and which native plant species could be adversely affected.

Other

The type of road (width and surface type) has been shown to influence the total cover and species richness of exotic plant species along the roadside and in nearby communities, with larger and more-improved roads facilitating exotic plant invasion to a greater degree than less-improved tracks (Gelbard and Belnap 2003).

Sources

Brooks, M.L. 2009. "Spatial and Temporal Distribution of Nonnative Plants in Upland Areas of the Mojave Desert." In *The Mojave Desert: Ecosystem Processes and Sustainability*, edited by R.H. Webb, L.F. Fenstermaker, J.S. Heaton, D.L. Hughson, E.V. McDonald, and D.M. Miller, 101–124. University of Nevada Press.

CH2MHILL. 2008. Draft Raven Management Plan, Ivanpah Solar Electric Generating System. https://eplanning.blm.gov/epl-front-office/projects/nepa/65894/79908/92793/BA_attachment_E_Raven_Management_Plan.pdf. Accessed July 26, 2017.

Coffin, A.W. 2007. "From Roadkill to Road Ecology: A Review of the Ecological Effects of Roads." *Journal of Transport Geography* 15: 396–406.

Gelbard, J.L., and J. Belnap. 2003. "Roads as Conduits for Exotic Plant Invasions in a Semiarid Landscape." *Conservation Biology* 17(2): 420–432.

Hall, L.K., R.T. Larsen, R.M. Knight, K.D. Bunnell, and B.R. McMillan. 2013. "Water Developments and Canids in Two North American Deserts: A Test of the Indirect Effect of Water Hypothesis." *PLOS ONE* 8(7).

Howe, K.B., P.S. Coates, and D.J. Delehanty. 2014. "Selection of Anthropogenic Features and Vegetation Characteristics by Nesting Common Ravens in the Sagebrush Ecosystem." *The Condor* 116(10): 35–49.

Joly, M., P. Bertrand, R.Y. Gbangou, M. White, J. Dubé, and C. Lavoie. 2011. "Paving the Way for Invasive Species: Road Type and the Spread of Common Ragweed (*Ambrosia artemisiifolia*)." *Environmental Management* 48:514–522. http://dx.doi.org/10.1007/s00267-011-9711-7.

Kadaba, D. 2014. Ecology of the Desert Kit Fox (*Vulpes macrotis arsipus*) in Chuckwalla Valley, California. Unpublished master's thesis. Duke University, Durham, North Carolina.

Kristan, W.B. III, and W.I. Boarman. 2003. "Spatial Pattern of Risk of Common Raven Predation on Desert Tortoises." *Ecology* 84(9): 2432–2443.

Lovich, J.E., and J.R. Ennen. 2011. "Wildlife Conservation and Solar Energy Development in the Desert Southwest, United States." *BioScience* 61(12): 982–992.

Western EcoSystems Technology, Inc. 2016. Ivanpah Solar Electric Generating System Avian and Bat Monitoring Plan: 2015 Summer Report. https://www.scribd.com/doc/304853667/Ivanpah-Solar-Avian-and-Bat-Monitoring-Report-Summer-2015. Accessed July 26, 2017.

9a: Solar Development → Cleared Land

Description of Relationship

A large-scale PV solar energy facility has a total footprint of about 7.9 acres/MW, approximately 0.7 acres/MW of which is permanently cleared of vegetation but not occupied by infrastructure.

A concentrating solar power facility has a total footprint of about 9.5 acres/MW (trough) or 10.0 acres/MW (power tower), approximately 3.3 acres/MW (trough) or 1.1 acres/MW (power tower) of which is permanently cleared of vegetation but not occupied by infrastructure (Ong et al. 2013).

Summary of Evidence

Solar development requires land clearing and the construction/installation of a variety of structures, including structural elements directly related to electricity generation (for example, PV arrays, concentrating mirrors, or power towers, depending on the technology in use), electricity transmission infrastructure (inverters, transformers, and transmission lines) and supporting structures (auxiliary buildings and access roads). The impact of built infrastructure from solar development is captured in links 6a, 7a, and 8a; this link focuses on land within the facility footprint that is cleared during the construction process but does not have built infrastructure.

The specific amount and layout of cleared land is determined during the design phase of a specific project and depends on many site-specific factors (IFC 2015). However, a retrospective analysis of land use by utility-scale solar installations in the United States gives a general idea of the amount of land taken up by infrastructure ("direct land use") and the total facility footprint ("total land use"), both totaled by facility and as a function of plant capacity (Ong et al. 2013). Subtracting direct land use from total land use gives a rough estimate of the scale of land clearing associated with different types of solar energy facilities. The per-MW land use estimates, based on this calculation, are given above.

Strength of Evidence

High: Solar energy development requires land clearing; the best available general evidence is a study of large-scale solar energy facilities in the United States that examined land use by plant capacity (Ong et al. 2013). This study used well-documented and appropriate methods (primary data from facility owners supplemented with satellite land cover data) and is highly applicable to solar development in the United States. It found fairly consistent results within a given solar technology type. The total area of cleared land associated with a particular project can be easily determined during the design stage.

Other Factors

Location

The average size of large PV installations (by total land use) is highest in the Southeast (FL), Southwest, and West; utility-scale PV installations tend to be smaller in the Midwest and Northeast. Because the average capacity of large PV installations in the Southeast, Southwest, and West is much greater than that in the Midwest and Northeast, the average size of installations in the former regions is likely due to developers building large PV plants to take advantage of those regions' abundant solar energy resources (Ong et al. 2013).

Solar insolation in the continental United States ranges from 320 (Pacific Northwest) to 620 (Southern California, Arizona) watt hours/square foot/day (Energy.gov). Larger solar installations are needed in lower-insolation areas to generate the same amount of electricity as a smaller solar installation in high-insolation areas.

Technology

Large PV system (>20 MWac) land use is also affected by the panel tracking type. One- and two-axis tracking systems require more land than fixed systems due to increased spacing between panels (Ong et al. 2013).

Sources

Energy.gov. Solar Energy Potential. https://energy.gov/maps/solar-energy-potential.

IFC (International Finance Corporation). 2015. Utility-scale Solar Photovoltaic Power Plants: A Project Developer's Guide. World Bank Group. https://www.ifc.org/wps/wcm/connect/f05d3e00498e0841bb6fbbe54d141794/IFC+Solar+Report_Web+_08+05.pdf?MOD=AJPERES.

Ong, S., C. Campbell, P. Denholm, R. Margolis, and G. Heath. 2013. Land-use Requirements for Solar-powered Plants in the United States. National Renewable Energy Laboratory NREL/TP-6A20-56290. http://www.nrel.gov/docs/fy13osti/56290.pdf.

9b Cleared Land → Habitat

Description of Relationship

Clearing of 1 acre of land decreases habitat area by 1 acre for the wildlife species that previously used that land and can no longer survive there. Land clearing may not prevent all species from using the land, but it will decrease habitat suitability and the number of individuals of a given species that the area can support.

Summary of Evidence

Land clearing changes many environmental variables that influence habitat suitability, including important resources for wildlife species such as vegetation cover, food, and temperature. Some wildlife species may be able to survive in cleared areas (potentially in lower numbers than previously existed). For other species, cleared areas are not suitable habitat and represent habitat loss. The persistence of this impact depends on whether the vegetation is allowed to regrow after initial clearing or the land is repeatedly cleared or mowed to prevent vegetation growth. The effect of land clearing on habitat quality is species specific. One study of desert tortoise habitat use in California found that the distance from devegetated areas was an important predictor of tortoise sign density; cleared areas do not provide suitable habitat for tortoises due to lack of canopy cover and forage and increased predation risk (Berry et al. 2013).

In some cases, cleared areas around solar energy facilities become lost habitat not because they are inherently unsuitable for a given species, but because individuals of that species are physically removed from the area and prevented from returning by barriers such as perimeter fences. For example, desert tortoises were removed from the Ivanpah Solar Electric Generating Station facility during construction to avoid mortality of the protected species, essentially decreasing their habitat area by the total footprint of the facility (CH2MHILL 2009).

Field surveys of wildlife populations in cleared and natural areas (or the same area before and after clearing) can give an idea of the effect that land clearing has on habitat suitability for that species. The desert tortoise study mentioned above is a good example of an assessment of changes in population density associated with cleared areas (Berry et al. 2013).

Strength of Evidence

Fair: The unsuitability of cleared areas as habitat for many wildlife species is widely accepted despite the lack of studies examining the generalized relationship; individual studies for particular species show the negative effect of land clearing on habitat suitability. There may be some species that benefit from land clearing due to their particular habitat needs or the removal of competitors.

Other Factors

Location

The location of the solar energy development will determine what wildlife species are affected by habitat changes associated with land clearing.

Technology

The type of solar technology will influence the spatial extent of cleared land (see link 9a).

Other

Certain species will respond differently to habitat alterations; some may still use cleared areas as habitat, while others will be entirely displaced by land clearing.

Sources

Berry, K.H., J.L. Yee, A.A. Coble, W.M. Perry, and T.A. Shields. 2013. "Multiple Factors Affect a Population of Agassiz's Desert Tortoise (*Gopherus agassizii*) in the Northwestern Mojave Desert. *Herpetological Monographs* 27(1): 87–109.

CH2MHILL. 2009. Desert Tortoise Translocation/Relocation Plan for the Ivanpah Solar Electric Generating System. https://eplanning.blm.gov/epl-front-office/projects/nepa/65894/79908/92792/BA_attachment_D_Desert_tortoise_translocation_plan.pdf.

McKinney, M.L. 2002. "Urbanization, Biodiversity, and Conservation." *BioScience* 52(10): 883–890.

9c: Cleared Land → Soil Disturbance

Description of Relationship

Construction of a 100-MW solar power facility will disturb XX acres of soil.

Summary of Evidence

Site preparation and construction of a solar power plant requires grading, excavation, and the use of heavy machinery (DRECP 2014). These activities physically disturb the soil surface (Patton et al. 2013). The total area of disturbed soil must be determined from plans for a specific project, but the estimates for cleared land in link 9a can provide a general idea of the scale of soil disturbance. The area of soil disturbed could extend beyond the facility footprint if access roads and transmission lines are constructed to connect the facility to existing infrastructure.

Strength of Evidence

High: The area of soil disturbed can be estimated from construction plans for a particular facility.

Other Factors

The type of solar technology will determine the specific construction activities required, which in turn influence the extent and magnitude of soil effects.

Sources

California Energy Commission, California Department of Fish and Wildlife, U.S. Bureau of Land Management, and U.S. Fish and Wildlife Service. 2014. Draft Desert Renewable Energy Conservation Plan (DRECP) and Environmental Impact Report/Environmental Impact Statement. California Energy Commission, California Department of Fish and Wildlife, U.S. Bureau of Land Management, U.S. Fish and Wildlife Service.

Patton, T., L. Almer, L., H. Hartmann, and K.P. Smith. 2013. An Overview of Potential Environmental, Cultural, and Socioeconomic Impacts and Mitigation Measures for Utility-scale Solar Energy Development. Argonne National Laboratory, Environmental Science Division.

9d: Soil Disturbance → Erosion

Description of Relationship

Mechanical disturbance of soil causes increased erosion rates relative to undisturbed soil.

Summary of Evidence

Erosion can occur by both wind and water in dryland ecosystems; both types of erosion occur by detaching soil particles and transporting them elsewhere, but they differ in frequency of occurrence (erosion by water occurs during rain events, whereas wind erosion is a more regular occurrence) and location of transport (those eroded by water move downhill, whereas those eroded by wind move with the wind, which can be in any direction) (Breshears et al. 2003). Wind erosion occurs when the wind surface shear velocity exceeds the soil's threshold shear velocity (the velocity required to detach soil particles) (Okin 2008). Disruption of the soil surface facilitates erosion of the soil by wind and water by making soil particles easier to detach (Patton et al. 2013). In many arid and semi-arid environments, a biological crust on the soil surface also protects against erosion and can be damaged by disturbance; erosion effects related to biological soil crusts are captured in link 9j.

Most studies of erosion rates and soil disturbance have focused on agriculture and forest ecosystems, but a few studies have demonstrated the impact of disturbance on erosion rates in arid and semi-arid ecosystems. A field study of sediment flux rates in a part of the Black Rock Desert in western Utah that burned in a severe fire in 2007 found that burned areas that underwent rehabilitation treatments, which involved seeding and mechanical disturbance to bury the seeds, had higher sediment flux rates three years after the fire than did burned, non-rehabilitated areas and included some of the highest sediment flux rates ever recorded in North America (Miller et al. 2012). An experimental study of the effects of military vehicle movement in grasslands in Idaho found a significant negative relationship between the number of passes with a tank and the threshold wind speed required for wind erosion to occur (Grantham et al. 2001). The disturbances in these studies may not be identical to the soil disturbances associated with land clearing and construction of a solar facility, but they show the potential for short-term mechanical disturbance of soil to influence soil erosion rates.

A meta-analysis of soil erosion rates emphasized the extreme variability in erosion rates, the multitude of environmental variables that influence erosion, and the large proportion of variance in erosion rates that is not explained by the environmental and experimental variables captured by the studies included in the meta-analysis (García-Ruiz et al. 2015). Erosion models are data-intensive, and erosion rates are difficult to predict with any accuracy. Several models are available to predict erosion rates, but none are perfectly suited for this relationship. The Rangeland Hydrology and Erosion model (RHEM) is an erosion model specifically developed for rangelands that computes soil loss on the basis of 13 parameters related to slope, soils, and climate (Hernandez et al. 2013). Some of the soil parameters are estimated from ground cover variables, but this model does not specifically take soil disturbance into account in estimating erosion rates. The Universal Soil Loss Equation (USLE) is an erosion model that uses rainfall erosivity, soil erodibility, topography, and management practices to predict soil erosion. Although it was developed for agricultural land, the USLE has been adapted to model erosion in other land cover types, including deserts, and to include effects of some disturbance-related impacts (Villarreal et al. 2016). WEMO, a wind erosion model, takes into account the ability of vegetation to decrease surface shear stresses that cause wind erosion; erosion takes place when surface shear velocity exceeds the soil's threshold shear velocity (Okin 2008) and has been used to model wind erosion in semiarid systems (Miller et al. 2011).

Strength of Evidence

Fair: The positive relationship between soil disturbance and soil erosion rates is well-understood and accepted, but evidence for arid and semi-arid systems is limited. In addition, the large number of factors that influence soil erosion rates precludes stating a general relationship; depending on local conditions, soil disturbance could have a very small or very large effect on erosion rates.

Predictability: Several water and wind erosion models can predict soil loss on the basis of site-specific input variables. Although erosion models are widely used and accepted, they are imprecise and were not developed specifically to model erosion from physical soil disturbances in arid and semi-arid ecosystems.

Other Factors

The location of a project determines the slope, soil type, and climate, all of which influence erosion rates and are included in the models described above. In general, water erosion rates are positively correlated with slope and annual precipitation (García-Ruiz et al. 2015), and wind erosion rates are positively correlated with wind speed and the size of vegetation-free patches (Breshears et al. 2003).

Sources

Breshears, D.D., J.J Whicker, M.P. Johansen, and J.E. Pinder III. 2003. "Wind and Water Erosion and Transport in Semi-arid Shrubland, Grassland and Forest Ecosystems: Quantifying Dominance of Horizontal Wind-driven Transport." *Earth Surface Processes and Landforms* 28: 1189–1209.

García-Ruiz, J., S. Beguería, E. Nadal-Romero, J. González-Hidalgo, N. Lana-Renault, and Y. Sanjuán. 2015. "A Meta-analysis of Soil Erosion Rates across the World." *Geomorphology* 239: 160–173.

Grantham, W.P., E.F. Redente, C.F. Bagley, and M. Paschke. 2001. "Tracked Vehicle Impacts to Vegetation Structure and Soil Erodibility." *Journal of Rangeland Management* 54(6): 711–716.

Hernandez, M., M.A. Nearing, J.J. Stone, F.B. Pierson, H. Wei, K.E. Spaeth, …, and D.C. Goodrich. 2013. "Application of a Rangeland Soil Erosion Model Using National Resources Inventory Data in Southeastern Arizona." *Journal of Soil and Water Conservation* 68(6): 512–525.

Miller, M.E., R.T. Belote, M.A. Bowker, and S.L. Garman. 2011. "Alternative Stable States of a Semiarid Grassland Ecosystem: Implications for Ecosystem Services." *Ecosphere* 2(5), article 55.

Miller, M.E., M.A. Bowker, R.L. Reynolds, and H.L. Goldstein. 2012. "Post-fire Land Treatments and Wind Erosion—Lessons from the Milford Flat Fire, UT, USA." *Aeolian Research* 7: 29–44.

Okin, G.S. 2008. "A New Model of Wind Erosion in the Presence of Vegetation." *Journal of Geophysical Research* 113.

Patton, T., L. Almer, H. Hartmann, and K.P. Smith, eds. 2013. An Overview of Potential Environmental, Cultural, and Socioeconomic Impacts and Mitigation Measures for Utility-scale Solar Energy Development. Environmental Science Division, Argonne National Laboratory.

Villarreal, M.L., R.H. Webb, L.M. Norman, J.L. Psillas, A.S. Rosenberg, S. Carmichael, …, and P.E. Sparks. 2016. "Modeling Landscape-scale Erosion Potential Related to Vehicle Disturbances along the USA-Mexico Border." *Land Degradation and Development* 27: 1106–1121.

9e: Erosion → Nitrogen Availability

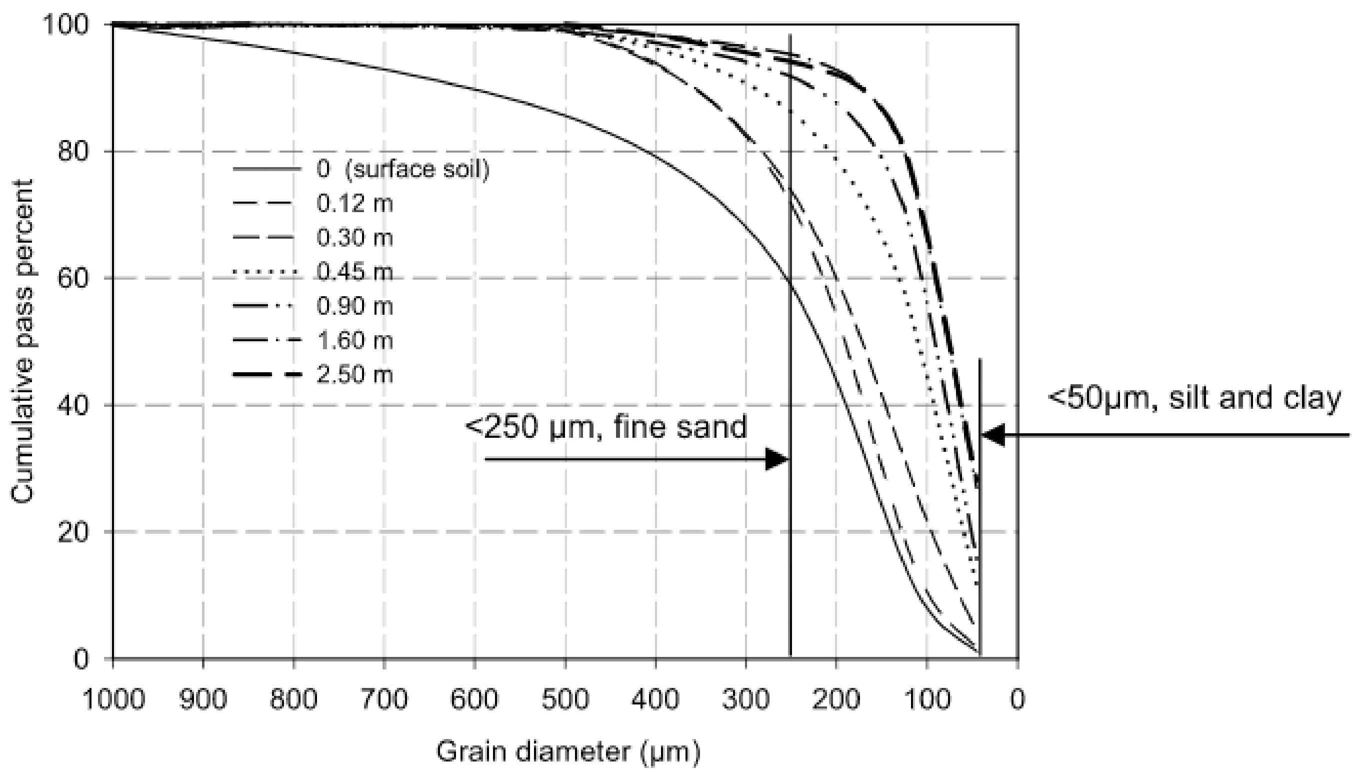
Description of Relationship

Soil erosion causes a loss of soil nitrogen.

Summary of Evidence

Wind and water erosion preferentially move fine soil particles (Li et al. 2008; Ravi et al. 2010). An experimental study of wind erosion found that the soil particles on the surface tend to be larger than those eroded by wind, and that particle sizes of windblown sediments decreased with the sampling height, suggesting that the smaller particles were being carried farther away than the larger ones (Figure 6) (Li et al. 2009).

Figure 6: Particle size distributions for surface soil and windblown sediments



Source: Li et al. (2009).

These fine soil particles are higher in nitrogen than larger soil particles (Ravi et al. 2010). In the study mentioned above, very small particles (< 50 µm) made up 2% of the total mass of eroded sediment, but 9% of the total nitrogen in windblown sediments (Li et al. 2009). This means that nitrogen losses due to soil erosion are larger than would be expected based on the amount of sediment loss. A wind erosion experiment in New Mexico found that up to 25% of total nitrogen in the top 5 cm of soils was lost in three windy seasons following vegetation removal (Li et al. 2007).

In addition, the nitrogen added to arid ecosystem soils by biological soil crusts (see link 9k) is concentrated near the soil surface (less than 10 mm deep), so even small amounts of erosion following crust disturbance (see link 9j) can result in significant nitrogen losses (Barger et al. 2016).

Strength of Evidence

Moderate: Individual research studies and reviews confirm that a large proportion of soil nitrogen is bound to very small soil particles near the soil surface, which are highly susceptible to erosive forces. However, no syntheses or meta-analyses of nitrogen losses due to erosion in arid ecosystems were found.

Sources

Barger, N.N., B. Weber, F. Garcia-Pichel, E. Zaady, and J. Belnap. 2016. "Patterns and Controls on Nitrogen Cycling of Biological Soil Crusts." In *Biological Soil Crusts: An Organizing Principle in Drylands*, edited by B. Weber, B. Budel, J. and Belnap, 257–285. Switzerland: Springer International Publishing.

Li, J., G.S. Okin, L. Alvarez, and H. Epstein. 2007. "Quantitative Effects of Vegetation Cover on Wind Erosion and Soil Nutrient Loss in a Desert Grassland of Southern New Mexico, USA." *Biogeochemistry* 85: 317–332.

Li, J., G.S. Okin, L. Alvarez, and H. Epstein. 2008. "Effects of Wind Erosion on the Spatial Heterogeneity of Soil Nutrients in Two Desert Grassland Communities." *Biogeochemistry* 88: 73–88.

Li, J., G.S. Okin, and H.E. Epstein. 2009. *Journal of Geophysical Research* 114, G02003.

Ravi, S., D.D. Breshears, T.E. Huxman, and P. D'Odorico. 2010. "Land Degradation in Drylands: Interactions among Hydrologic-aeolian Erosion and Vegetation Dynamics." *Geomorphology* 116: 236–245.

9f: Nitrogen Availability → Natural Ecosystems/Flora

Description of Relationship

A reduction in soil nitrogen concentrations by XX% results in a XX% reduction in primary productivity.

Summary of Evidence

Because nitrogen is often a limiting nutrient in desert ecosystems, its decreased availability can result in reduced plant growth (Belnap 1995). A meta-analysis of 68 nitrogen fertilization experiments in arid-subhumid systems found that aboveground net primary productivity increased by 50% with nitrogen fertilization (Yahdjian et al. 2011). Most of these experiments were conducted in North America, including many in the southwestern United States, but some were from other continents. These experiments also focused on the addition of nitrogen to an ecosystem, not the removal of available nitrogen, so the assumption that plants responding positively to nitrogen addition would also respond negatively to nitrogen removal is required.

Likely negligible link: This link is likely to be negligible because of the small scale of the impact relative to the scale of the system. However, this link has been retained in the simplified model due to the potential for cumulative effects if several solar energy facilities are installed in the same area.

Strength of Evidence

Low: The role of nitrogen as a limiting resource for plants in arid systems is generally accepted and supported by a meta-analysis of nitrogen fertilization experiments, which followed accepted methods and included a majority of studies from western North America. However, this meta-analysis did not include soil nitrogen concentration as a factor, so it cannot be used to determine a specific relationship between nitrogen availability and plant growth.

Other Factors

Climate influences plants' response to changes in nitrogen availability. The meta-analysis of nitrogen fertilization experiments found that the response of aboveground net primary productivity to nitrogen addition increased with annual precipitation, suggesting that primary productivity in arid ecosystems can be limited by either water or nitrogen availability, but that nitrogen limitation becomes more important as water availability increases (Yahdjian et al. 2011).

Sources

Belnap, J. 1995. "Surface Disturbances: Their Role in Accelerating Desertification." *Environmental Monitoring and Assessment* 37: 39–57.

Yahdjian, L., L. Gherardi, and O.E. Sala. 2011. "Nitrogen Limitation in Arid-subhumid Ecosystems: A Meta-analysis of Fertilization Studies." *Journal of Arid Environments* 2011: 675–680.

9g: Erosion → Sedimentation

Description of Relationship

Eroded sediment is deposited in terrestrial and aquatic ecosystems.

Summary of Evidence

Soil eroded by wind or water is deposited in a new location, which can be elsewhere on land or in a waterway or water body. The soil erosion models described in link 9d include sediment transport modeling with varying degrees of complexity (see Merritt et al. 2003 for a discussion of various models). The accuracy of these models is limited by the complexity of the natural systems, lack of understanding of some of the processes involved, and data requirements (Merrit et al. 2003), and there is a lack of model validation in non-agricultural systems.

Strength of Evidence

Fair: The logical connection between erosion and sedimentation is sound. However, understanding the amount of sediment eroded and where it is deposited is essential to determining if sedimentation is a significant outcome or if the amount of sediment deposited in any given area is non-consequential.

Predictability: Several models are available that predict the transport and deposition of eroded sediment, but they are data-intensive, have limited accuracy, and were not specifically developed for arid and semi-arid ecosystems.

Other Factors

Location

The location of a project determines the topography, soil type, and prevailing winds, all of which influence the direction and distance that sediment is transported before deposition.

Sources

Merrit, W.S., R.A. Letcher, and A.J. Jakeman. 2003. "A Review of Erosion and Sediment Transport Models." *Environmental Modeling and Software* 18(8-9): 761–799.

9i: Sedimentation → Biological Soil Crust

Description of Relationship

Sedimentation that covers biological soil crust may kill some or all of the crust's photosynthetic components, reverse crust succession, and diminish function.

Summary of Evidence

Because biological crusts need light to photosynthesize, burial of the crust by eroded sediment can kill the photosynthetic components, including mosses, lichens, cyanobacteria, and algae (Belnap et al. 2001; Belnap 2003; Belnap and Lange 2003). Various components of biological crusts can tolerate burial to different degrees; filamentous cyanobacteria and some mosses are more tolerant than other types of cyanobacteria and lichens (Zaady et al. 2016). A study of biological soil crusts in the Kalahari Desert found that cyanobacteria can recover after a dormant period due to sand burial, but the recovery can take a long period of time (more than a year) and resets crust development (Thomas and Dougill 2007). Successional resetting of crust development was also observed following crust burial in a desert in China (Jia et al. 2008).

The immediate effect of burial by sediment on biological soil crusts is likely less severe than the effect of soil disturbance (see link 9l), because burial does not necessarily kill all of the photosynthetic components and does not directly affect the structure of the crust, which is key to its function; however, if crustal components are killed, the organic structure of the crust will decompose (Belnap et al. 2001).

Strength of Evidence

Fair: Burial by sediment's capacity to kill some components of biological soil crusts is generally accepted, but the outcome of sediment burial is influenced by the specific crust species present, the depth of burial, and the length of burial, and some of the research studies examining these factors were conducted in China and southern Africa, which may limit their applicability in the southwestern United States.

Sources

Belnap, J., J.H. Kaltenecker, R. Rosentreter, J. Williams, S. Leonard, and D. Eldridge. 2001. Biological Soil Crusts: Ecology and Management. U.S. Department of the Interior, Technical Reference 1730-2.

Belnap, J. 2003. "The World at Your Feet: Desert Biological Soil Crusts." *Frontiers in Ecology and the Environment* 1(5): 181–189.

Jia, R.L., X.R. Li, L.C. Liu, Y.H. Gao, and X.J. Li. 2008. "Responses of Biological Soil Crusts to Sand Burial in a Revegetated Area of the Tengger Desert, Northern China." *Soil Biology and Biochemistry* 40: 2827–2834.

Thomas, A.D., and A.J. Dougill. 2007. "Spatial and Temporal Distribution of Cyanobacterial Soil Crusts in the Kalahari: Implications for Soil Surface Properties." *Geomorphology* 85: 17–29.

Zaady, E., D.J. Eldridge, and M.A. Bowker. 2016. "Effects of Local-scale Disturbance on Biocrusts." In *Biological Soil Crusts: An Organizing Principle in Drylands*, edited by B. Weber, B. Budel, and J. Belnap, 429–449. Switzerland: Springer International Publishing.

9j: Biological Soil Crust → Erosion

Description of Relationship

Loss of biological soil crusts can increase erosion rates.

Summary of Evidence

Biological soil crusts reduce water and wind erosion; this effect is especially important in arid areas with low vegetation cover (Belnap and Lange 2003). Crusts physically bind soil particles together, which increases the force needed to move soil particles, and rough microtopography slows wind and water movement over the soil (Belnap et al. 2001). Multiple studies by Belnap and others in the southwestern United States have shown that the wind velocity needed to detach soil particles is much higher in areas with well-developed soil crusts than in areas without crusts and that even moderate levels of disturbance (e.g., two passes with a vehicle) greatly reduce biological soil crusts' resistance to wind erosion (Belnap and Gillette 1997; Belnap and Gillette 1998; Belnap et al. 2007). Several researchers have established threshold chlorophyll *a* concentrations (associated with the level of biological crust development) required to confer resistance to wind erosion; soils with at least 0.014 mg chlorophyll *a* per gram of soil are approximately twice as stable as soils with lower chlorophyll *a* concentrations. Rainfall simulation experiments have shown that biological crust cover and cyanobacterial biomass are positively correlated with soil stability and negatively correlated with sediment loss (Belnap and Büdel 2016).

There are models of water erosion that incorporate the effects of biological soil crusts, but erosion is difficult to predict accurately because it depends on modeled water runoff, which is itself inaccurate (Rodriguez-Caballero et al. 2015). No wind erosion models that include biological soil crusts were found.

Strength of Evidence

Moderate: Many field experiments carried out in the southwestern United States show the protective effects of biological soil crusts against wind and water erosion, and researchers are in agreement about this effect. However, no meta-analyses were found that captured the factors that influence soil erosion rates (see link 9d) and the effect of biological crusts on erosion.

Predictability: One widely used water erosion model has been adapted to include biological soil crusts, but validation with field data has shown its results to lack accuracy. No wind erosion models that incorporate biological soil crusts were identified.

Other Factors

Biological crust successional stage is another factor. More well-developed and older biological crusts better cover the soil surface and are more securely attached to the soil, increasing resistance to wind and water erosion (Belnap and Büdel 2016).

Sources

Belnap, J., and O.L. Lange, eds. 2003. *Biological Soil Crusts: Structure, Function, and Management*. Springer Berlin Heidelberg.

Belnap, J., J.H. Kaltenecker, R. Rosentreter, J. Williams, S. Leonard, and D. Eldridge. 2001. Biological Soil Crusts: Ecology and Management. U.S. Department of the Interior, Technical Reference 1730-2.

Belnap, J., and D.A. Gillette. 1997. "Disturbance of Biological Soil Crusts: Impacts on Potential Wind Erodibility of Sandy Desert Soils in Southeastern Utah." *Land Degradation and Development* 8: 355–362.

———. 1998. "Vulnerability of Desert Biological Soil Crusts to Wind Erosion: The Influences of Crust Development, Soil Texture, and Disturbance." *Journal of Arid Environments* 39(2): 133–142.

Belnap, J., S.L. Phillips, J.E. Herrick, and J.R. Johansen. 2007. "Wind Erodibility of Soils at Fort Irwin, California (Mojave Desert), USA, Before and After Trampling Disturbance: Implications for Land Management." *Earth Surface Processes and Landforms* 32: 75–84.

Belnap, J., and B. Büdel. 2016. “Biological Soil Crusts as Soil Stabilizers.” In *Biological Soil Crusts: An Organizing Principle in Drylands*, edited by B. Weber, B. Budel, and J. Belnap, 305–320. Switzerland: Springer International Publishing.

Rodríguez-Caballero, E., Y. Cantón, and V. Jetten. 2015. “Biological Soil Crust Effects Must Be Included to Accurately Model Infiltration and Erosion in Drylands: An Example from Tabernas Badlands.” *Geomorphology* 241: 331–342.

9k: Biological Soil Crust → Nitrogen Availability

Description of Relationship

Loss or disturbance of biological soil crust reduces nitrogen fixation rates and the concentration of soil nitrogen that is available to plants.

Summary of Evidence

Various components of biological soil crusts fix atmospheric nitrogen, and studies have shown that nitrogenase activity in disturbed soil crusts is reduced by 40%–80% immediately and 80%–100% six to nine months after disturbance (Belnap 1995). Estimates of nitrogen fixation rates from biological soil crusts range from 0.7 kg to 100 kg N/hectare/year; 6 kg N/hectare/year has been reported as a global average rate of nitrogen fixation by desert biocrusts (Barger et al. 2016). Nitrogen fixation by plant-bacterial symbioses and atmospheric deposition of nitrogen is generally low in desert ecosystems, so fixation by soil crusts may make up a substantial amount of nitrogen in the system (Belnap et al. 2001). Biological crusts have also been shown to lose nitrogen to the atmosphere through denitrification; there are few studies on the rate of nitrogen loss relative to nitrogen fixation, but in general nitrogen fixation rates exceed denitrification rates, suggesting that biological soil crusts result in a net addition to soil nitrogen pools (Barger et al. 2016).

Biological crusts release nitrogen-containing compounds to the soil; when crustal components die and decompose, they may release a large amount of mineral nitrogen, thus providing a short-term supply of nitrogen available for uptake by plants and other organisms (Barger et al. 2016).

Strength of Evidence

Fair: Several studies have measured the nitrogen inputs from biological soil crusts in desert ecosystems and found consistent evidence that biological soil crusts are a significant source of soil nitrogen in those systems, but no meta-analyses were found, and the specific inputs are determined by local factors.

Other Factors

Species

The dominant species in biological soil crusts influences the potential nitrogen fixation rates. Cyanobaceria, some lichens (with cyanobacterial symbionts), and heterotrophic bacteria all contribute to nitrogen fixation. Cyano-lichen-dominated crusts have the highest nitrogen fixation rates, followed by “dark cyanobacterial crusts” (which contain N-fixing cyanobacterial genera, including *Nostoc* spp or *Scytonema* spp). “Light” crusts, usually dominated by cyanobacteria of the genus *Microcoleus*, have the lowest nitrogen fixation rates (Belnap 2002). “Light” crusts are often early-successional crusts and can occur after disturbance of other crust types.

Climate

Moisture is a key controlling factor for nitrogen fixation by biological soil crusts, as crust organisms are only physiologically active when wet. Air temperature is a secondary factor; when crusts are sufficiently wet, nitrogen fixation rates increase with temperature between the limits of 1 degree C and 26 degrees C (Belnap 2002).

Sources

Barger, N.N., B. Weber, F. Garcia-Pichel, E. Zaady, and J. Belnap. 2016. “Patterns and Controls on Nitrogen Cycling of Biological Soil Crusts.” In *Biological Soil Crusts: An Organizing Principle in Drylands*, edited by B. Weber, B. Budel, and J. Belnap, 257–285. Switzerland: Springer International Publishing.

Belnap, J. 1995. “Surface Disturbances: Their Role in Accelerating Desertification.” *Environmental Monitoring and Assessment* 37: 39–57.

———. 2002. “Nitrogen Fixation in Biological Soil Crusts from Southeast Utah, USA.” *Biology and Fertility of Soils* 35(2): 128–135.

———. 2003. “The World at Your Feet: Desert Biological Soil Crusts.” *Frontiers in Ecology and the Environment* 1(5): 181–189.

Belnap, J., J.H. Kaltenecker, R. Rosentreter, J. Williams, S. Leonard, and D. Eldridge. 2001. Biological Soil Crusts: Ecology and Management. U.S. Department of the Interior, Technical Reference 1730-2.

9m: Soil Disturbance → Biological Soil Crust

Description of Relationship

Mechanical soil disturbance destroys biological soil crusts.

Summary of Evidence

Mechanical disturbance breaks biological soil crusts into pieces that can be carried away by wind or water, and compression crushes the crust, destroying the connections between soil particles (Belnap 2003; Belnap and Lange 2003). Following disturbance, biological soil crusts take a long time to recover; a field study showed reductions in crust species richness and lichen-moss cover after soil was mechanically disturbed (Belnap and Lange 2003).

Strength of Evidence

Moderate: The vulnerability of biological soil crusts to mechanical disturbance is clear, supported by field studies, and accepted by researchers. The specific effects of less severe disturbances (e.g., footsteps) may be less certain, but soil disturbance by heavy machinery or vehicles will destroy biological soil crusts.

Other Factors

Crusts on sandy soils are more susceptible to being crushed when they are dry; crusts on clay soils are more susceptible when wet (Belnap and Lange 2003).

Sources

Belnap, J. 2003. “The World at Your Feet: Desert Biological Soil Crusts.” *Frontiers in Ecology and the Environment* 1(5): 181–189.

Belnap, J., and O.L. Lange, eds. 2003. *Biological Soil Crusts: Structure, Function, and Management*. Springer Berlin Heidelberg.

9n: Cleared Land → Soil Compaction

Description of Relationship

The use of XX piece of machinery on XX acres is predicted to cause soil compaction on that land.

Summary of Evidence

Site preparation and construction of a solar power plant requires the use of heavy machinery, which physically compacts the soil (DRECP 2014; Patton et al. 2013). Most soil compaction research has focused on agricultural systems, but compaction also occurs in other landscapes where construction or industrial activity has taken place (Batey 2009).

Soil compaction models exist and often predict whether compaction will occur by comparing the compressive forces applied to soil by a certain load to soil strengths measured in a laboratory (e.g., van den Akker 2004); if compressive forces exceed soil strengths, compaction would be predicted to occur. Generally, the compaction models were developed for agricultural soils and have been validated in agricultural and (to a lesser degree) forest soils, so they may not be accurate in other land cover types (Goutal et al. 2013; Keller and Lamandé 2010). In addition, the existence and degree of soil compaction is difficult to assess without visual observation of the soil profile, making model validation difficult (Batey 2009).

Strength of Evidence

Fair: Soil compaction from heavy machinery is a straightforward physical process and is considered during environmental impact statements for solar energy facilities; the possibility of soil compaction is widely acknowledged and accepted. However, actual measurements of soil compaction in arid and semi-arid systems are lacking; most related research has been done in agricultural systems.

Predictability: Models to predict soil compaction exist, but they were developed specifically for agricultural systems and have not been validated in arid ecosystems, so they are likely to be less accurate for those systems.

Other Factors

Soil Characteristics

The degree of soil compaction is affected by soil texture structure, organic matter, and water content (Nawaz et al. 2013). Wet soils are more susceptible to compaction than dry soils (Batey 2009).

Machinery Characteristics

Multiple axles, wide tires, and low tire pressure can help to lessen the effects of compaction from heavy machinery (Batey 2009).

Sources

Batey, T. 2009. "Soil Compaction and Soil Management—A Review." *Soil Use and Management* 25: 335–345.

California Energy Commission, California Department of Fish and Wildlife, U.S. Bureau of Land Management, and U.S. Fish and Wildlife Service. 2014. Draft Desert Renewable Energy Conservation Plan (DRECP) and Environmental Impact Report/Environmental Impact Statement. California Energy Commission, California Department of Fish and Wildlife, U.S. Bureau of Land Management, U.S. Fish and Wildlife Service.

Goutal, N., T. Keller, P. Défossez, and J. Ranger. 2013. "Soil Compaction Due to Heavy Forest Traffic: Measurements and Simulations Using an Analytical Soil Compaction Model." *Annals of Forest Science* 70: 545–556.

Keller, T., and M. Lamandé. 2010. "Challenges in the Development of Analytical Soil Compaction Models." *Soil and Tillage Research* 111:54–64.

Patton, T., L. Almer, H. Hartmann, and K.P. Smith, eds. 2013. An Overview of Potential Environmental, Cultural, and Socioeconomic Impacts and Mitigation Measures for Utility-scale Solar Energy Development. Environmental Science Division, Argonne National Laboratory.

Van den Akker, J.J.H. 2004. "SOCOMO: A Soil Compaction Model to Calculate Soil Stresses and the Subsoil Carrying Capacity." *Soil and Tillage Research* 79: 113–127.

9o: Soil Compaction → Natural Ecosystems/Flora

Description of Relationship

Soil compaction causes decreased plant growth.

Summary of Evidence

Compaction decreases soil penetrability to roots and is thought to inhibit the growth of deep roots, slowing overall plant growth (Batey 2009). In agricultural soils, compaction decreases the proportion of deep root biomass, reduces yield, and slows the processes that develop soil structure (Whalley et al. 1995). However, few studies have examined compaction effects on desert plants. A field study of plant cover in compacted soils in the California desert found that the cover of native annual plants was reduced in compacted areas but that the cover of *Schismus* spp., a nonnative grass, increased in those areas (Adams et al. 1962). Soil compaction can also alter the soil microbial community, which may slow the decomposition cycle and cause desertification (Belnap 1995).

Likely negligible link: This link is likely to be negligible because of the small scale of the impact relative to the scale of the system. However, this link has been retained in the simplified model due to the potential for cumulative effects if several solar energy facilities are installed in the same area.

Strength of Evidence

Fair: Although a large body of evidence for agricultural systems is available and the physical processes that connect soil compaction to plant growth are well understood, only a few individual field studies provide support for this relationship in arid ecosystems.

Other Factors

Soil texture can influence the degree of compaction (see link 9m).

Sources

Adams, J.A., L.H. Stolzy, A.S. Endo, P.G. Rowlands, and H.B. Johnson. 1962. "Desert Soil Compaction Reduces Annual Plant Cover." *California Agriculture* September-October 1962: 6–7.

Batey, T. 2009. "Soil Compaction and Soil Management--A Review." *Soil Use and Management* 25: 335–345.

Belnap, J. 1995. "Surface Disturbances: Their Role in Accelerating Desertification." *Environmental Monitoring and Assessment* 37: 39–57.

California Energy Commission, California Department of Fish and Wildlife, U.S. Bureau of Land Management, and U.S. Fish and Wildlife Service. 2014. Draft Desert Renewable Energy Conservation Plan (DRECP) and Environmental Impact Report/Environmental Impact Statement. California Energy Commission, California Department of Fish and Wildlife, U.S. Bureau of Land Management, U.S. Fish and Wildlife Service.

Whalley, W.R., E. Dumitru, and A.R. Dexter. 1995. "Biological Effects of Soil Compaction." *Soil and Tillage Research* 35: 53–68.

9p: Soil Compaction → Infiltration

Description of Relationship

Soil compaction decreases infiltration rates.

Summary of Evidence

Soil compaction makes soil less permeable to water, lowering the maximum rate at which water can infiltrate the soil. If the precipitation rate exceeds the compacted soil's maximum infiltration rate, a smaller proportion of the rainfall can infiltrate the soil, lowering the total infiltration rate, and excess water runs off (Batey 2009). Total infiltration rates are generally low in arid regions due to a lack of precipitation, but appreciable infiltration can occur under certain conditions (Gee and Hillel 1988). Most related research has been conducted in agricultural systems, but a few studies have examined compaction effects in arid ecosystems. A study of trampling effects on rangeland in Utah found that compaction of trampled soils had a strong negative effect on infiltration rates (Dadkhah and Gifford 1980). Because cattle trampling of soils occurs continuously for a period of time, whereas construction-related soil compaction takes place over a shorter time period, studies of infiltration effects from trampling may not be fully applicable to infiltration effects from construction-related compaction. Soils may recover from compaction, but studies have shown that increased penetrometer resistance due to soil compaction can persist for decades (Caldwell et al. 2006). Disturbance from military vehicle traffic has also been shown to reduce saturated conductivity (a measure of how easily water can move through saturated soil) in desert soils by 54% relative to undisturbed soils due to the loss of larger soil pores; this change in saturated conductivity is substantially less than has been recorded in other systems (Caldwell et al. 2006).

Soil erosion models that incorporate infiltration include the Limburg Soil Erosion Model (LISEM), a widely used spatial model, which has previously been used in arid systems (Rodríguez-Cabellero et al. 2015). Although the model requires a substantial amount of data and GIS knowledge to run, it can be used to assess infiltration effects from soil compaction. Equations known as pedotransfer functions have also been developed to predict soil hydraulic conductivity from other soil characteristics, such as bulk density, but these functions are not perfect predictors; one analysis found that pedotransfer functions only explained 12%–29% of variation in near-saturated hydraulic conductivity (Jarvis et al. 2002).

Strength of Evidence

Moderate: The relationship between soil compaction and decreased maximum infiltration rates is logical, based on physical principles, and supported by evidence for certain systems. However, the actual effect of soil compaction on infiltration in a specific context depends on many location-specific variables, including precipitation rate and soil surface characteristics (see link 9l), making it difficult to predict if compaction will have a substantial effect on total infiltration rates.

Predictability: There are erosion models that can be used to predict effects on infiltration from soil compaction, but they were not created for use in arid and semi-arid systems and lack validation in those systems.

Other Factors

Soils that are dry when compacted have smaller changes in infiltration rates than soils that are wet when compacted (Caldwell et al. 2006).

Soil texture influences the magnitude of the effect that compaction has on porosity; small pores between individual soil particles are not affected by compaction (Caldwell et al. 2006).

Sources

Batey, T. 2009. "Soil Compaction and Soil Management—A Review." *Soil Use and Management* 25: 335–345.

Caldwell, T.G., E.V. McDonald, and M.H. Young. 2006. "Soil Disturbance and Hydrologic Response at the National Training Center, Ft. Irwin, California." *Journal of Arid Environments* 67: 456–472.

Dadkhah, M., and G.F. Gifford. 1980. "Influence of Vegetation, Rock Cover, and Trampling on Infiltration Rates and Sediment Production." *Water Resources Bulletin* 16(6): 979–986.

Gee, G.W., and D. Hillel. 1988. "Groundwater Recharge in Arid Regions: Review and Critique of Estimation Methods." *Hydrological Processes* 2: 255–266.

Jarvis, N.J., L. Zavattaro, K. Rajkai, W.D. Reynolds, P.-A. Olsen, M. McGechan, M., … and D. Jacques. 2002. "Indirect Estimation of Near-saturated Hydraulic Conductivity from Readily Available Soil Information." *Geoderma* 108: 1–17.

Rodríguez-Caballero, E., Y. Cantón, and V. Jetten. 2015. "Biological Soil Crust Effects Must Be Included to Accurately Model Infiltration and Erosion in Drylands: An example from Tabernas Badlands. *Geomorphology* 241: 331–342.

9q: Infiltration → Natural Ecosystems/Flora

Description of Relationship

Lower infiltration rates cause decreased plant growth.

Summary of Evidence

Lower infiltration rates lead to decreased soil moisture levels, which create water stress in plants and can decrease plant growth (Daly and Porporato 2005). In desert plants, soil moisture plays a key role in determining vegetative growth and reproduction (Beatley 1974). A physiological ecosystem model of water, carbon, nitrogen, and plant growth in the Chihuahuan, Sonoran, and Mojave deserts found that aboveground productivity responds to soil moisture at rooting depths, not to precipitation (Reynolds et al. 2004).

Likely negligible link: This link is likely to be negligible because of the small scale of the impact relative to the scale of the system. However, this link has been retained in the simplified model due to the potential for cumulative effects if several solar energy facilities are installed in the same area.

Strength of Evidence

Fair: This relationship is logical and based on physical principles; if rainfall does not infiltrate the soil, there is no soil moisture available for plants. Few studies exist that link the growth of desert plants to infiltration-controlled soil variables, but an ecosystem model developed for arid systems found that plant productivity is more responsive to soil moisture than to precipitation. However, many other factors, including the timing of precipitation and background soil moisture conditions, influence the specific response of plants to changes in infiltration (Reynolds et al. 2004).

Other Factors

Different types of plants respond differently to soil moisture, with annual plants most responsive to high soil moisture levels and grasses most responsive when soil moisture increases after a relatively dry period (Reynolds et al. 2004).

Sources

Beatley, J.C. 1974. "Phenological Events and Their Environmental Triggers in Mojave Desert Ecosystems." *Ecology* 55(4): 856–863.

Daly, E., and A. Porporato. 2005. "A Review of Soil Moisture Dynamics: From Rainfall Infiltration to Ecosystem Response." *Environmental Engineering Science* 22(1): 9–24.

Reynolds, J.F., P.R. Kemp, K. Ogle, and R.J. Fernández. 2004. "Modifying the 'Pulse-response' Paradigm for Deserts of North America: Precipitation Pulses, Soil Water, and Plant Responses." *Oecologia* 141: 194–210.

9x: Cleared Land → Visual Aesthetics

Description of Relationship

Land clearing from solar energy development is visible from certain surrounding observation points, thus changing the aesthetics of the view from those points.

Summary of Evidence

Cleared areas are visible from a distance because they contrast with the surrounding landscape in color and shape (Hartmann et al. 2016). The distance at which cleared land is visible and the number of surrounding receptors (residential areas, roads, recreational areas) from which the cleared land is visible depends on several factors, including the surrounding terrain and land cover, air quality, and receptor location (Hartmann et al. 2016, Nutsford et al. 2015).

The extent of viewshed changes caused by a particular land use impact can be assessed through GIS viewshed analysis, which uses an elevation model to evaluate which areas can be seen from a given vantage point; a cutoff distance (e.g., the visual range in the study area) is used to limit the viewshed extent from an observation point (Nutsford et al. 2015; Baranzini and Schaerer 2011). This technique has been used in a variety of fields, including urban planning and economic research; some studies have used viewshed analysis to assess the visual impacts of energy infrastructure (Nutsford et al. 2015; Baranzini and Schaerer 2011; Sander and Polasky 2008). Improvements, such as including a distance-decay function to emphasize visible objects closer to the observer, have been suggested to make viewshed analysis more reflective of human perception (Nutsford et al. 2015).

Strength of Evidence

Fair: There has been limited research into the visibility of solar energy facilities; the best evidence is from a field study that assessed the visibility of eight solar facilities (of different technology types) at various distances (Sullivan et al. 2012). Although this study documented many environmental variables that can influence visibility, its small sample size does not provide an adequate basis for developing a general relationship. Existing viewshed analysis methods are generally accepted and have been used for research in a variety of fields, but they do not capture all aspects of visibility as perceived by humans, and their applicability to the visibility of solar energy infrastructure is unknown (Nutsford et al. 2015). The visibility of a particular solar energy project can be assessed with on-site testing during the design phase, but it may be difficult to accurately assess visibility of the entire facility on the basis of small test areas.

Other Factors

Location

The location of a solar energy facility with respect to surrounding terrain features and vegetation can influence its visibility and contrast with its surroundings.

Technology

The type of solar technology influences the extent of land clearing (see link 9a) and therefore affects how visible the technology is at a distance (Sullivan et al. 2012).

Soil Type

When soil colors contrast with native vegetation or the solar energy infrastructure, cleared areas (where soil is exposed) are much more visible than when exposed soil is a similar color to the surrounding area (Sullivan et al. 2012).

Sources

Hartmann, H.M., M.A. Grippo, G.A. Heath, J. Macknick, K.P. Smith, R.G. Sullivan, L.J. Walston, K.L. and Wescott. 2016. Understanding Emerging Impacts and Requirements Related to Utility-scale Solar Development. Argonne National Laboratory Environmental Science Division, ANL/EVS-16/9.

Nutsford, D., F. Reitsma, A.L. Pearson, and S. Kingham. 2015. "Personalising the Viewshed: Visibility Analysis from the Human Perspective." *Applied Geography* 62: 1–7.

Sullivan, R.G., L.B. Kirchler, C. McCoy, J. McCarty, K. Beckman, and P. Richmond. 2012. Visual Impacts of Utility-scale Solar Energy Facilities on Southwestern Desert Landscapes. Argonne National Laboratory.

9y: Cleared Land → Cultural Resources

Description of Relationship

Construction of a solar energy facility eliminates cultural resources within the project boundary. Increased accessibility of remote cultural resources due to road construction can facilitate human disturbance of those resources.

Summary of Evidence

As stated in the environmental impact summary, construction of solar energy developments would eliminate cultural resources within the project boundary. Road construction resulting in increased vehicular access to previously inaccessible areas could lead to increased human disturbance of cultural sites in the future (Patton et al. 2013). The actual cultural resource impacts of a specific project will depend on the location of the project relative to sites of cultural importance. Archeological surveys and consultation with stakeholders can identify cultural resources during the planning process so that potential impacts can be avoided or mitigated, if necessary.

Effects on cultural resources due to visual aesthetic degradation are captured in links 6l and 6o.

Strength of Evidence

High: The relationship between solar energy development and the destruction of cultural resources within the project boundary is direct and undisputable.

None: No evidence was found for the effect of increased accessibility on adverse impacts to cultural resources.

Sources

Patton, T., L. Almer, H. Hartmann, and K.P. Smith, eds. 2013. An Overview of Potential Environmental, Cultural, and Socioeconomic Impacts and Mitigation Measures for Utility-scale Solar Energy Development. Environmental Science Division, Argonne National Laboratory.

9z: Cultural Resources → Existence Value

Description of Relationship

Cultural resources, including archeological sites and places with significance to certain cultural heritages, are highly valued by stakeholders.

Summary of Evidence

The existence value of cultural resources includes cultural heritage, sense of place, and identity; these things are incredibly difficult to put a value on, and attempts at monetary valuation may be considered inappropriate by some stakeholders (Daniel et al. 2012; Noonan 2003). Non-monetary valuations can provide an alternative, but they may still be considered unsuitable for these types of resources. Contingent valuation methods have been used to estimate the value of some types of cultural resources (museums, artistic performances), but no studies were found that attempted to place a value on the existence of cultural heritage and archaeological resources. Ethnographies conducted by the BLM with Native American tribes located near SEZs make clear that many natural and manmade features within the SEZs hold extremely high cultural significance for the tribes (e.g., Stoffle et al. 2011). Q-methodology is another way to assess the relative importance of various resources to specific groups without placing quantitative values on those resources; this method has been applied to Native American cultural resources (Armatas et al. 2017).

Strength of Evidence

Moderate: Interviews with Native American tribes around BLM lands show that cultural resources in the SEZs and surrounding areas are highly valued. No studies have been found that placed a value (either monetary or nonmonetary) on these resources, but it may not be considered appropriate to do so by many stakeholders.

Other Factors

Location

The location of cultural resources influences the extent to which they are likely to be affected by solar development (see links 6o and 9x) and which stakeholder groups are involved.

Technology

The type of solar energy technology influences the extent of land use impacts that can affect cultural resources (see link 9a).

Sources

Armatas, C., T. Venn, and A. Watson. 2017. "Understanding Social-Ecological Vulnerability with Q-methodology: A Case Study of Water-based Ecosystem Services in Wyoming, USA." *Sustainability Science* 12: 105–121.

Daniel, T.C., A. Muhar, A. Arnberger, O. Aznar, J.W. Boyd, K.M.A. Chan, …, and A. von der Dunk. 2012. "Contributions of Cultural Services to the Ecosystem Services Agenda." *Proceedings of the National Academy of Sciences of the United States of America* 109(3): 8812–8819.

Noonan, D.S. 2003. "Contingent Valuation and Cultural Resources: A Meta-analytic Review of the Literature." *Journal of Cultural Economics* 27: 159–176.

Stoffle, R.W., K.A. Van Vlack, H.Z. Johnson, P.T. Dukes, S. De Sola, and K.L. Simmons. 2011. Tribally Approved American Indian Ethnographic Analysis of the Proposed Escalante Valley Solar Energy Zone. Solar Programmatic Environmental Impact Statement and Solar Energy Study Areas in Portions of Arizona, California, Nevada, and Utah. http://solareis.anl.gov/documents/ethnographic/EthnographicAnalysis_EscalanteValley.pdf. Accessed July 26, 2017.

11a: Solar Development → Cost

Description of Relationship

The installation cost of a utility-scale solar energy system is approximately $1.03/watt DC for a PV system and $3.49–$6.91/watt DC for a concentrating solar power system (Fu et al. 2017; Bolinger and Seel 2016; Bolinger et al. 2017).

Operation and maintenance costs for a utility-scale solar energy system are approximately $8/MWh for a PV system (Bolinger et al. 2017). Operation and maintenance costs for a utility-scale concentrating solar power system are about $0.0495–$0.115/watt capacity for fixed costs, plus $4/MWh generated in variable costs (NREL 2017; Transparent Cost Database 2017).

Summary of Evidence

Installation Costs

Installation costs for solar energy systems are estimated using two main techniques: top-down estimation, which uses regulatory and financial documents for completed projects, and bottom-up estimation, which models installation costs on the basis of individual component and labor costs (Bolinger and Seel 2016). The 2015 installation costs estimated by several organizations were generally consistent across these techniques, ranging from $1.78–$2.01/watt DC for fixed-tilt PV systems (Bolinger and Seel 2016). An update to this report using 2016 data found a median installed cost of $1.7/watt DC (Bolinger et al. 2017). These values are similar to an estimate of the mean installed cost of 1–10 MW photovoltaic systems by NREL ($2.025/watt DC) based on 2012–2015 data (NREL 2016). A recent bottom-up PV installation cost estimate of $1.03/watt DC, updated for the first quarter of 2017, is a based on a 100-MW utility-scale PV system with 17.5% efficient modules; the estimate is an average across states, weighted by solar energy capacity in each state (Fu et al. 2017). Installation costs for PV systems have been dropping steadily over the past decade due to lower prices for system components and higher PV module efficiency (Fu et al. 2017). The NREL's annual technology baseline for utility-scale PV power plants estimates a median capital expenditure (including all hardware, installation, and financial costs to begin commercial operations) at just over $2/watt DC for 2015 and projects that this cost will continue to decrease in coming years (NREL 2017).

The installation cost of utility-scale concentrating solar power ranges from $3.49–$6.91/watt DC, according to a top-down study; due to the small number of concentrating solar power projects that have been completed in the past decade and the variety of technology types in use, no average installation cost was calculated (Bolinger and Seel 2016; Bolinger et al. 2017). The Transparent Cost Database, an open repository of energy data maintained by NREL, includes 42 values for the capital cost of concentrating solar power systems from 2009 to 2015; they range from $1.830/watt to $11.00/watt installed capacity (2017). The annual technology baseline estimates that the capital expenditure for a concentrating solar power plant is about $8.13/watt in 2015 and is projected to decline to $7.04/watt in 2018 (NREL 2017).

The Business Energy Investment Tax Credit (ITC) can offset some of the installation costs of solar energy systems. This federal program currently provides a tax credit of 30% of the project's value for businesses that develop or finance utility solar projects; this credit is scheduled to decrease to 26% of the project's value in 2020; 22% in 2021, and 10% thereafter (U.S. DOE 2016).

Operating and Maintenance Costs

Operating and maintenance costs for utility-scale PV solar facilities were estimated at $7.3/MWh for 2015, but this estimate is from a small sample of facilities and reflects only direct costs for operation and maintenance, not indirect overhead costs such as taxes and insurance (Bolinger and Seel 2016). Operating and maintenance costs increased slightly in 2016, to $8/MWh (Bolinger et al. 2017). NREL estimates operation and maintenance costs for 1–10 MW PV systems at $0.016/watt-year, or about $0.528/watt capacity over the mean lifetime of PV systems (33 years) (NREL 2016). The annual technology baseline projects that operation and maintenance costs will decline to $.01/watt-year by 2020 (low-cost scenario) or 2025 (mid-cost scenario), or could remain constant (high-cost scenario) (NREL 2017).

The Transparent Cost Database includes 40 values for fixed and 25 values for variable operating costs of concentrating solar power systems from 2009 to 2015; fixed costs have a range of $0.0495–$0.115/watt capacity and variable costs $0.71–$25.50/MWh generated (2017). The annual technology baseline estimates fixed operating and maintenance costs for concentrating solar power systems at $0.07/watt-year and variable operating and maintenance costs at $4/MWh through 2018 (NREL 2017).

Levelized Cost of Electricity

The levelized cost of electricity (LCOE) is a metric used to summarize the cost of electricity generation across different technologies; it includes installation, operation, and maintenance costs over a facility's lifetime as well as relevant policy incentives such as tax credits (EIA 2017). The U.S. Energy Information Administration (EIA) has calculated LCOE for a variety of electricity generation methods for 2019, 2022, and 2040. The capacity-weighted mean LCOE for solar photovoltaics, with and without incentives, are shown in Table 7:

Table 7: Estimated LCOE for Solar Photovoltaics, with and without expected tax credits

Year	Without tax credits (2016 $/MWh)	With tax credits (2016 $/MWh)
2019	70.1	53.1
2022	73.7	58.1
2040	59.5	54.9

Source: U.S. Energy Information Administration (2017).

Another analysis estimated the unsubsidized LCOE for utility-scale solar photovoltaics at $46–$61/MWh and solar thermal tower at $119–$182/MWh. With federal tax subsidies, these LCOE estimates drop to $36–$49/MWh for utility-scale solar photovoltaics and $93–$139 for solar thermal tower (Lazard 2016). The annual technology baseline predicts that LCOE for both utility-scale photovoltaics and solar concentrating solar power will decline over the next few years (NREL 2017).

Strength of Evidence

High: Construction and operations costs are direct effects of solar development and are estimated up-front for each planned facility. The evidence described above provides estimates of costs for existing utility-scale PV and concentrating solar power systems. Two widely accepted and well-documented methods for estimating installation costs of utility-scale PV systems, based on different types of evidence, have yielded generally consistent results.

Predictability: The estimated construction, operations, and maintenance costs presented above can be used to get rough estimates of the cost of building and running a new facility based on its capacity, but these estimates do not take into account many other factors that influence final costs. There is a limited amount of data available on operating and maintenance costs for all types of solar power plants and on construction costs for concentrating solar power plants, so estimates of these costs will be less certain than those for the construction costs of PV systems.

Other Factors

Location

The location of a solar energy facility influences installation costs due to different rates for labor, permits, and fees related to construction (Fu et al. 2017). A location-mediated influence on labor costs would also be expected to affect operation and maintenance costs. The location of the facility relative to existing transmission lines will influence the cost of additional infrastructure required to integrate the new facility into the power grid; solar energy zones were delineated in part by their proximity to existing transmission lines (BLM and DOE 2012).

Although the LCOE estimates presented are not differentiated by region, LCOE is sensitive to location-related factors and also varies by location. The Lazard study estimated that LCOE for a fixed-tilt solar PV system is the lowest in the Southwest ($48/MWh) and Texas ($52/MWh) and highest in the Northeast ($75/MWh) (Lazard 2016). Fu et al. (2017) modeled LCOE for a variety of locations across the United States using the System Advisory Model and assuming no investment tax credit. The estimated LCOE for fixed-tilt and one-axis systems in several locations across the southwestern United States is shown in Table 9.

Table 9. Estimated LCOE for solar photovoltaics with a 30% investment tax credit

Location	LCOE, fixed-tilt ($/MWh)	LCOE, one-axis tracker ($/MWh)
Imperial, CA	51.9	45.0
Tucson, AZ	47.0	41.4
Alamosa, CO	47.3	41.6
Albuquerque, NM	47.3	42.1
San Antonio, TX	55.6	51.2

Source: Fu et al. (2017).

Technology

The type of solar technology in use influences the cost. The installation cost of $1.03/watt reported above is for fixed-axis systems; installation costs for one-axis tracking PV systems are estimated at $1.11/watt DC (Fu et al. 2017). The top-down retrospective price study also found that tracking systems cost $0.115/watt DC more than fixed-tilt systems (Bolinger et al. 2017). As shown in Table 8, LCOE also varies by technology type.

Concentrating solar power plants are more expensive than PV systems, and installation costs of concentrating solar power systems do not appear to be decreasing, although there are many fewer of these systems than PV systems. Power purchase agreement (PPA) prices for CSP systems have not seen a drop similar to that of PV PPA prices, and there have been no new CSP contracts in the United States since 2011 (Bolinger and Seel 2016).

Sources

OpenEI. 2017. Transparent Cost Database. *OpenEI*. https://openei.org/apps/TCDB/.

Bolinger, M., and J. Seel. 2016. Utility-scale Solar 2015: An Empirical Analysis of Project Cost, Performance, and Pricing Trends in the United States. Lawrence Berkeley National Laboratory. https://emp.lbl.gov/sites/default/files/lbnl-1006037_report.pdf.

Bolinger, M., J. Seel, and K.H. LaCommare. 2017. Utility-scale Solar 2016: An Empirical Analysis of Project Cost, Performance, and Pricing Trends in the United States. Lawrence Berkeley National Laboratory. https://emp.lbl.gov/sites/default/files/utility-scale_solar_2016_report.pdf.

BLM (Bureau of Land Management) and DOE (U.S. Department of Energy). 2012. Final Programmatic Environmental Impact Statement (PEIS) for Solar Energy Development in Six Southwestern States. Volume 1, Chapters 1-7, 14-16. http://solareis.anl.gov/documents/fpeis/Solar_FPEIS_Volume_1.pdf.

Fu, R., D. Feldman, R. Margolis, M. Woodhouse, and K. Ardani. 2017. U.S. Solar Photovoltaic System Cost Benchmark: Q1 2017. National Renewable Energy Laboratory NREL/TP-6A20-68925. https://www.nrel.gov/docs/fy17osti/68925.pdf.

Lazard. 2016. Lazard's Levelized Cost of Energy Analysis—Version 10.0. https://www.lazard.com/media/438038/levelized-cost-of-energy-v100.pdf.

NREL (National Renewable Energy Laboratory). 2016. Distributed Generation Renewable Energy Estimate of Costs. https://www.nrel.gov/analysis/tech-lcoe-re-cost-est.html.

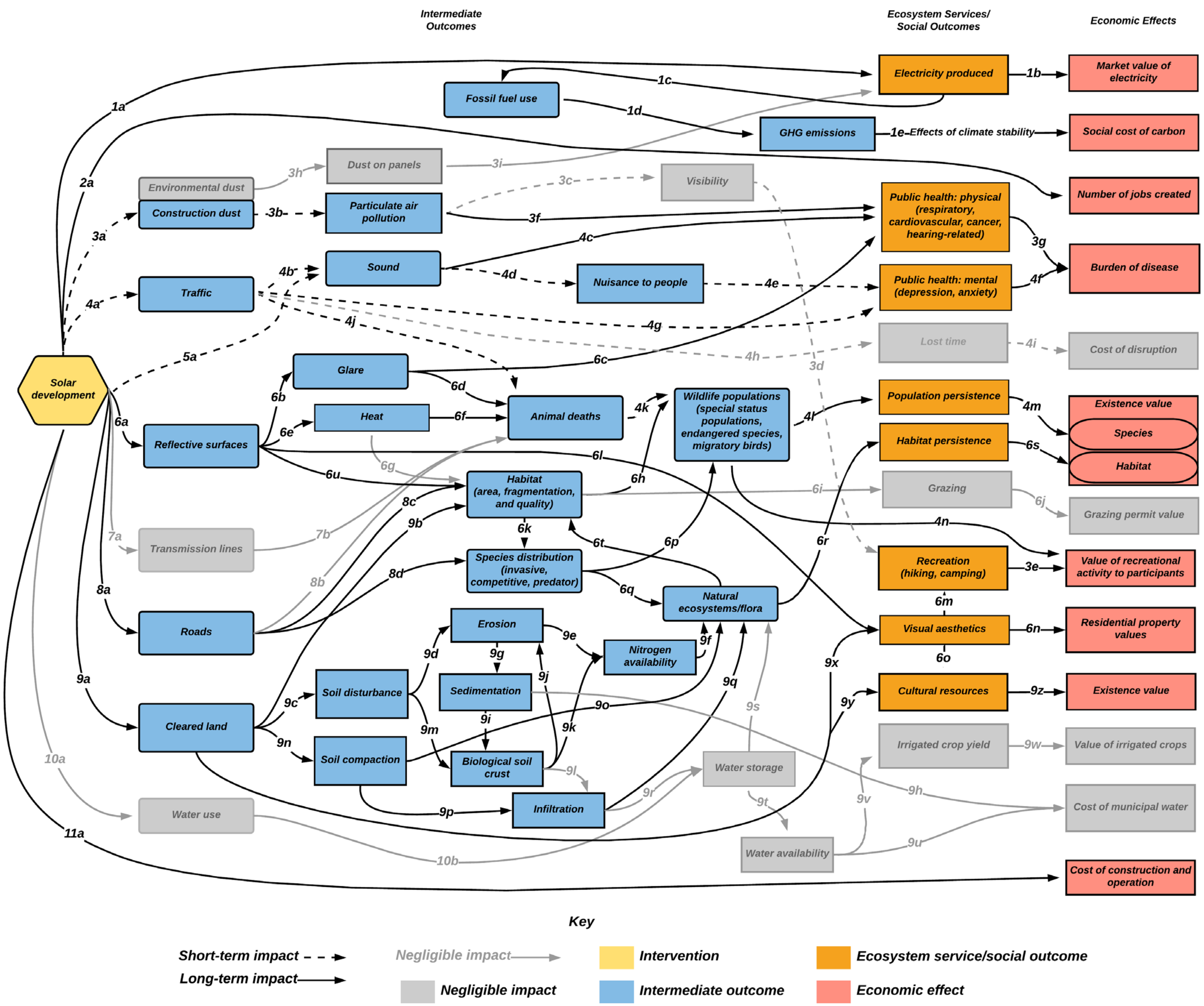
———. 2017. Utility-scale PV Power Plants. *Annual Technology Baseline*. https://atb.nrel.gov/electricity/2017/index.html?t=su.

U.S. DOE (U.S. Department of Energy). 2016. Leveraging Federal Renewable Energy Tax Credits. Resources for State and Local Governments, Publication No. DOE/EE-1509. https://energy.gov/sites/prod/files/2016/12/f34/Leveraging_Federal_Renewable_Energy_Tax_Credits_Final.pdf.

U.S. EIA (U.S. Energy Information Administration). 2017. Levelized Cost and Levelized Avoided Cost of New Generation Resources in the *Annual Energy Outlook 2017*. https://www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf.

APPENDIX A: COMPLETE GENERAL CONCEPTUAL MODEL AND NEGLIGIBLE LINK EVIDENCE

Figure A.1. Complete general conceptual model, including negligible links, for solar energy development on BLM-administered lands



Evidence Summaries: Negligible Links

The following sections contain the summaries of evidence collected for each of the negligible links in the complete general conceptual model (Figure 7).

3c: Particulate Air Pollution → Visibility

Description of Relationship

A 1-μg/m3 increase in PM2.5 fine soil particulates increases the light extinction by 1 Mm^{-1} (Pitchford et al. 2007).

A 1-μg/m3 increase in PM10–PM2.5 coarse particulates increases the light extinction by 1 Mm^{-1} (Pitchford et al. 2007).

Temporary link: This link is temporary because it results from a temporary link (see link 3b).

Summary of Evidence

Particles in the atmosphere decrease visibility by scattering and absorbing light. Light extinction is the loss of intensity of light per unit distance due to scattering and absorption, and it can be calculated by multiplying the concentration of each particulate component by its light extinction efficiency (a measure of the effectiveness of a particular type of particulate in scattering and absorbing light, in m^2/g). The light extinction efficiency values used for the EPA's IMPROVE algorithm are 1 m^2/g for fine soil particulates (PM2.5) and 0.6 m^2/g for coarse particulates (PM10–PM2.5) (Pitchford et al. 2007). A study of the visual properties of desert dust PM2.5 in China also found a mass scattering efficiency (which makes up more than 95% of light extinction efficiency in that context) of 1.0 m^2/g (Xu et al. 2004). Other particulate types that fall into PM2.5 have higher light extinction efficiencies, but coarse and fine soil particulates are the majority of particulate air pollution created by construction dust. The Koschmieder equation can be used to calculate visual range (a common measure of visibility) from the total light extinction efficiency and the maximum observable contrast (usually 0.02–0.05, depending on the observer) (Hyslop 2009):

Visual range = ln(minimum observable contrast)/total light extinction efficiency.

Likely negligible link: This link is likely to be negligible for solar energy development on BLM land because the only outcome of this link is negligible (see link 3d).

Strength of Evidence

High: Light extinction efficiency is a physical property of particulate matter that has been measured in laboratory experiments and that is used in visibility modeling.

Predictability: As described above, the Koschmieder equation can be used to calculate visual range from the light extinction efficiency and the maximum observable contrast.

Other Factors

Location: The location of the particulate matter created by solar development relative to human populations or places used by people for recreation determines the importance of this link (see link 3d).

Technology: There is no effect (other than differences in construction that create varying dust levels; see link 3a).

Other: Increased relative humidity decreases visibility (Boylan and Russell 2006).

Sources

Boylan, J.W., and A.G. Russell. 2006. "PM and Light Extinction Model Performance Metrics, Goals, and Criteria for Three-dimensional Air Quality Models." *Atmospheric Environment* 40: 4946-459.

Hyslop, N.P. 2009. "Impaired Visibility: The Air Pollution People See." *Atmospheric Environment* 43: 182–195.

Pitchford, M., W. Malm, B. Schichtel, N. Kumar, D. Lowenthal, and J. Hand. 2007. "Revised Algorithm for Estimating Light Extinction from IMPROVE Particle Speciation Data." *Journal of the Air and Waste Management Association* 57: 1326–1336.

Xu, J., M.H. Bergin, R. Greenwald, J.J. Schauer, M.M. Shafer, J.L. Jaffrezo, and G. Aymoz. 2004. "Aerosol Chemical, Physical, and Radiative Characteristics Near a Desert Source Region of Northwest China during ACE-Asia." *Journal of Geophysical Research* 109: D19S03.

3d: Visibility →Recreation

Description of Relationship

Decreased visual range decreases recreational visits to natural areas.

Temporary link: This link is temporary because it results from a temporary link (see link 3c).

Summary of Evidence

Although few studies have examined the impact of reduced visibility on recreation, it appears that clean air is generally important to visitors of recreational areas. A survey of visitor preferences at five U.S. national parks found that "clean, clear air" ranked among the top four attributes for each of the parks (Mace et al. 2004). In Great Smoky Mountains National Park, a study estimated that improving the average visibility by 10% would result in an increase in annual visits of about 1 million (Poudyal et al. 2013). According to a study in Mesa Verde National Park, the only one found that quantified visitation rates on the basis of visibility, approximately 8.6 more people visited the park each day for every 1-km increase in visual range, corresponding to a threefold increase in daily visitation from days with the lowest visibility to those with the highest visibility (Winger and McKean 1991).

Likely negligible link: This link is likely to be negligible for solar energy development on BLM lands due to its short-term nature (see link 3a) and the availability of substitute areas for recreation when visibility is low in certain areas.

Strength of Evidence

Low: Few studies have evaluated the relationship between visibility and recreation; those studies that do exist take different approaches and measure different response variables, making it difficult to compare their results. Overall, the results suggest that visibility is an important aspect of recreation to some people, but it is difficult to tell whether visibility influences recreational activities generally or in particular places.

Other Factors

Location: Low visibility in one recreational area may not cause a significant drop in recreational visitors overall if visitors are able to access substitute recreational areas that are not also affected by low visibility. Areas with fewer options for outdoor recreation may be more strongly affected if one of them is affected by low visibility.

Sources

Mace, B.L., P.A. Bell, and R.J. Loomis. 2004. "Visibility and Natural Quiet in National Parks and Wilderness Areas: Psychological Considerations." *Environment and Behavior* 36(1): 5–31.

Poudyal, N.C., B. Paudel, and G.T. Green. 2013. "Estimating the Impact of Impaired Visibility on the Demand for Visits to National Parks." *Tourism Economics* 19(2) 433–452.

Winger, W.D., and J.R. McKean. 1991. "Visibility: A Determinant of Park Visitor Behavior." *Geoforum* 22(4): 391–399.

3h: Environmental Dust → Dust on Panels

Description of Relationship

Solar panels accumulate dust at a rate of 1–50 mg/m^2/day, but rainfall negates this effect in most locations in the United States.[4]

Summary of Evidence

Persistent, naturally occurring dust from the dry surrounding environments can accumulate on solar panels, but this buildup is not generally a concern for solar installations in the United States, where low rates of dust deposition and periodic rainfall prevent significant accumulation (Sarver et al. 2013). A study in Colorado found dry deposition rates of 1–50 mg/m^2/day, but the study did not take into account the effects of rainfall in removing dust (Boyle et al. 2015). Studies have shown that rainfall washes away dust, so the actual rate of dust accumulation is less than is measured by experiments that do not allow precipitation to reach the panels (Sarver et al. 2013).

[4] This link (environmental dust →dust on panels) can be used with link 3i (dust on panels → energy produced) to estimate the energy losses due to dust accumulation on panels. Another approach that captures the same effect is outlined in alternate link 3hi (environmental dust → energy produced), which directly connects environmental dust to energy losses as a function of exposure time. Both approaches were included because a significant amount of evidence was found for all three links, and the two approaches yield consistent results.

Likely negligible link: This link is likely to be negligible for solar energy development in the southwestern United States due to climate and soil factors.

Strength of Evidence

Fair: Several observational studies quantify the dust deposition rates in different locations and under various conditions, but most of these studies are in locations with major differences in environmental conditions from the United States or do not take into account the effect of rainfall in periodically removing accumulated dust. There have also been experimental studies assessing dust accumulation under controlled conditions; these studies are useful for examining the effect of specific variables (e.g., wind speed) on dust accumulation, but they lack applicability to real-world scenarios because of the many other influential variables (e.g., dust characteristics).

Other Factors

Location: Much higher dust accumulation rates have been found in other parts of the world (100–330 mg/m^2/day in Egypt, 125–440 mg/m^2/day in Thailand), likely due to other environmental factors, such as dust concentrations in the air, high humidity (dew formation and subsequent evaporation helps dust adhere to surfaces), and higher wind speeds (Sarver et al. 2013). Research has shown that higher airborne dust concentration leads to higher rates of dust accumulation on panels (Goossens and Van Kerschaever 1999).

Land Use: The Colorado study found higher accumulation rates at an urban site (34–47 mg/m^2/day) than at a rural site (12–19 mg/m^2/day).

Panel Position: Panels at an angle from the horizontal accumulate less dust than horizontal panels do (Boyle et al. 2015).

Wind Velocity: Higher background wind velocities lead to higher dust accumulation on solar panels (Goossens and Van Kerschaever 1999).

Sources

Boyle, L., H. Flinchpaugh, and M.P. Hannigan. 2015. "Natural Soiling of Photovoltaic Cover Plates and the Impact on Transmission." *Renewable Energy* 77: 166–173.

Goossens, D., and E. Van Kerschaever. 1999. "Aeolian Dust Deposition on Photovoltaic Solar Cells: The Effects of Wind Velocity and Airborne Dust Concentration on Cell Performance." *Solar Energy* 66(4): 277–289.

Sarver, T., A. Al-Qaraghuli, and L.L. Kazmerski. 2013. "A Comprehensive Review of the Impact of Dust on the Use of Solar Energy: History, Investigations, Results, Literature, and Mitigation Approaches." *Renewable and Sustainable Energy Reviews* 22: 698–733. http://dx.doi.org/10.1016/j.rser.2012.12.065.

3i: Dust on Panels → Electricity Produced

Description of Relationship

Energy production decreases by 4%–5% for every g/m^2 of dust accumulation on the surface of solar panels.[5]

Summary of Evidence

A variety of studies evaluate the percent transmittance reduction (assumed to correlate with percent energy production reduction) per g/m^2 of dust accumulation on solar panels in various locations. A study in Colorado found a 4.1% transmission reduction per g/m^2 of dust accumulation; one in Egypt found a relatively linear relationship of about 5% transmittance reduction per g/m^2 dust deposition, up to about 3 g/m^2 accumulation, after which the relationship begins to level off (Hegazy 2001). Another found a quadratic relationship that is relatively linear between 3 g/m^2 and 5 g/m^2 of dust, with transmittance reductions at about 5%/g/m^2 over this range (Elminir et al. 2006).

Likely negligible link: This link is likely to be negligible for solar energy development in the southwestern United States due to a lack of dust accumulation on panels (see link 3h).

[5] This link (dust on panels → energy produced) can be used with link 3h (environmental dust → dust on panels) to estimate the energy losses due to dust accumulation on panels. Another approach that captures the same effect is outlined in alternate link 3hi (environmental dust → energy produced), which directly connects environmental dust to energy losses as a function of exposure time. Both approaches were included because a significant amount of evidence was found for all three links, and the two approaches yield consistent results.

Strength of Evidence

Fair: No meta-analyses or synthesis papers exist, but quite a few research studies quantify the relationship between dust accumulation and transmittance reduction or energy production, with accepted methods and consistent results. Some of the studies were conducted in locations other than the United States, so potential differences in dust characteristics (usually not examined) could make them less applicable to U.S. solar projects.

Other Factors

Location: Currently, dust accumulation on solar panels is mostly an issue in extreme desert environments such as those found in the Middle East region of the world, and not in the western United States. However, climate change and increasing development could increase the amount of dust produced over time, therefore increasing the likelihood of negative effects from dust.

Technology: Most studies quantifying the effect of dust on energy production show similar low rates of soiling on photovoltaics and other types of solar energy technology in the United States (Sarver et al. 2013).

Other Potential Impacts

Treatment/Cleaning of Panels with Water and Chemical Products: In areas where persistent dust buildup causes issues with PV power generation, significant dust reduction and remediation activities are required to maintain productivity of the panels. These activities include rinsing the panels with clean water and chemical detergents as well as post-cleaning treatments with chemicals that prevent the buildup of dust. These activities are not necessary in most of the United States due to a combination of low amounts of dust and periodic rainfall (Sarver et al. 2013).

Testing of a wide variety of commercial detergents found that cleaning with mild detergents or high-pressure water restored panel specularity to 98% for glass and 92%–95% for acrylic; 100% specularity can be restored by scrubbing or spraying with detergent (Sarver et al. 2013). "Dry cleaning" methods, including wiping with a cloth and air flow, are less water-intensive but can damage panels and are less effective than washing.

Introduction of Treatment/Cleaning Chemicals into the Water Supply: No studies link the use of solar panel treatment and cleaning chemicals to negative water and soil quality effects, but it is thought that these chemicals could someday pose a threat to the environment and should be closely monitored (Stoms et al. 2013).

Sources

Boyle, L., H. Flinchpaugh, and M.P. Hannigan. 2015. "Natural Soiling of Photovoltaic Cover Plates and the Impact on Transmission." *Renewable Energy* 77: 166–173.

Elminir, H.K., A.E. Ghitas, R.H. Hamid, F. El-Hussainy, M.M. Beheary, and K.M. Abdel-Moneim. 2006. "Effect of Dust on the Transparent Cover of Solar Collectors." *Energy Conversion and Management* 47(18): 3192–3203.

Hegazy, A.A. 2001. "Effect of Dust Accumulation on Solar Transmittance through Glass Covers of Plate-type Collectors." *Renewable Energy* 22: 525–540.

Sarver, T., A. Al-Qaraghuli, and L.L. Kazmerski. 2013. "A Comprehensive Review of the Impact of Dust on the Use of Solar Energy: History, Investigations, Results, Literature, and Mitigation Approaches." *Renewable and Sustainable Energy Reviews* 22: 698–733. http://dx.doi.org/10.1016/j.rser.2012.12.065.

Stoms, D.M., S.L. Dashiell, and F.W. Davis. 2013. "Siting Solar Energy Development to Minimize Biological Impacts." *Renewable Energy* 57: 289–298. http://dx.doi.org/10.1016/j.renene.2013.01.055.

Sulaiman, S.A., A.K. Singh, M.M.M. Mokhtar, and M.A. Bou-Rabee. 2014. "Influence of Dirt Accumulation on Performance of PV Panels." *Energy Procedia* 50: 50–56. https://doi.org/10.1016/j.egypro.2014.06.006.

Alternate Link 3hi: Environmental Dust → Electricity Produced

Description of Relationship

PV panels allowed to accumulate dust show reduced energy output of between 1% and 11.5% per month (relative to clean panels) in the absence of rain. Rainfall reduces the annual average loss of energy output due to soiling to less than 3% (Caron and Littmann 2013).[6]

Summary of Evidence

Studies in the United States have generally found soiling loss rates of <5%/month, kept lower in many cases by periodic rainfall (Sarver et al. 2013). A study in California found that energy output for panels in agricultural areas was reduced by up to 11% per month of dust accumulation but that these high soiling rates were offset by frequent rains. In this study, even very light (1 mm) rainfalls and, in some cases, accumulation of dew on the panels were enough to reduce losses from soiling to less than 1% (Caron and Littmann 2013). This range of effect is consistent with the magnitude of effects suggested by links 3h and 3i, which would produce a monthly reduction in energy of 0.2% to 7.5% based on the soiling rates found to occur in the United States (1–50 mg dust/m^2/day) and a 5% loss rate per gram of dust/m^2.

Likely negligible link: This link is likely to be negligible for solar energy development in the southwestern United States due to low soiling rates.

Other Factors

Location: Soiling rates vary by surrounding land use, soil type, and climate (e.g., soiling rates were higher on solar panels in agricultural areas in California than those in desert areas) (Caron and Littmann 2013). Rainfall can offset high soiling rates and limit energy losses due to soiling (see link 3h).

Technology: Most studies quantifying the effect of dust on energy production show similar low rates of soiling on photovoltaics and other types of solar energy technology in the United States (Sarver et al. 2013).

Sources

Caron, J.R., and B. Littmann. 2013. "Direct Monitoring of Energy Lost Due to Soiling on First Solar Modules in California." *Journal of Photovoltaics* 3(1): 336–340.

Sarver, T., A. Al-Qaraghuli, and L.L. Kazmerski. 2013. "A Comprehensive Review of the Impact of Dust on the Use of Solar Energy: History, Investigations, Results, Literature, and Mitigation Approaches." *Renewable and Sustainable Energy Reviews* 22: 698–733. http://dx.doi.org/10.1016/j.rser.2012.12.065.

4h: Traffic → Lost Time

Description of Relationship

An increase in traffic volume on a given road can result in congestion and an average increase in time spent traveling (lost time) for people traveling on a road with additional traffic due to a solar facility.

Temporary link: This link is temporary because it results from a temporary link (see link 4a).

Summary of Evidence

Once the additional traffic volume associated with a solar facility is estimated (see link 4a), its impact on local roads can be assessed through a variety of methods. The potential impact of additional traffic volume on travel time is influenced by a variety of factors, including expected sources of vehicles traveling to the site, site access points, existing road traffic volumes and capacities, timing of additional traffic, and other sources of congestion such as road work zones.

The many factors that influence traffic volume's effect on travel time mean that modeling must be done for a particular case to determine the likely outcome. Generic volume delay functions, such as the BPR delay model, can be used to determine whether significant travel time impacts are likely, but they may lack accuracy due to simplification (Mtoi and Moses 2014).

[6] This link replaces both link 3h and link 3i; it connects environmental dust directly to energy loss as a function of exposure time rather than using dust accumulation on solar panels as an intermediate step (links 3h and 3i). Both approaches were included because a significant amount of evidence was found for all three links, and the two approaches yield consistent results. This combination link does not have a strength of evidence rating because it is not included in the conceptual model diagram, but it provides additional evidence for the relationships in links 3h and 3i.

Follow-up with traffic simulation is recommended if initial models suggest that additional traffic volume would cause congestion and increase travel time (see Kotusevski and Hawick 2009 for a review of traffic simulation software).

A variety of traffic models and simulations provide methods to assess the likely impacts of additional traffic volume on surrounding roads; their accuracy depends on the specific method used. The LOS Engineering, Inc., 2010 and 2011 traffic studies provide examples of relatively simple analyses conducted for traffic effects from the construction of solar energy facilities.

Likely negligible link: This link is likely to be negligible for solar energy development on BLM lands due to their remote nature and low surrounding populations.

Strength of Evidence

Fair: Due to the large number of local variables that influence traffic flow and travel time, no general relationship can be stated between traffic volume and lost time. An increase in traffic volume certainly has the potential to increase time spent in traffic, but in many cases the additional traffic caused by the construction and operation of a solar energy facility will not be sufficient to cause congestion or longer travel times.

Predictability: As described above, traffic models can be used to predict likely effects from additional traffic volume at a particular site.

Sources

Kotusevski, G., and K.A. Hawick. 2009. "A Review of Traffic Simulation Software." *Research Letters in the Information and Mathematical Sciences* 13: 35–54.

LOS Engineering, Inc. 2010. Imperial Solar Energy Center West Traffic Impact Analysis. https://eplanning.blm.gov/epl-front-office/projects/nepa/66156/80544/93666/FAppBISECw_Traffic.pdf.

———. 2011. Centinela Solar Energy Draft Traffic Impact Analysis. http://centinelasolar.com/DocsInfo/Generating%20Facility/Imperial%20County%20Documents/Environmental%20Impact%20Report/Draft%20EIR/17%20App%20C-traffic-analysis.pdf.

Mtoi, E.T., and R. Moses. 2014. "Calibration and Evaluation of Link Congestion Functions: Applying Intrinsic Sensitivity of Link Speed as a Practical Consideration to Heterogeneous Facility Types within Urban Network." *Journal of Transportation Technologies* 4: 141–149.

4i: Lost Time → Cost of Disruption

Description of Relationship

Economic cost of congestion = ((Travel time at free-flow speed) – (Travel time with congestion)) * Traffic volume * Value of time

Temporary link: This link is temporary because it results from a temporary link (see link 4h).

Summary of Evidence

Time spent in traffic has an economic value that can be estimated by multiplying the increase in travel time due to traffic (difference between free-flow travel time and travel time with congestion) by the number of vehicles affected (traffic volume) and the value of time (Goodwin 2004). The value of time is the most uncertain variable in this equation; because most travel (commuting, errands, and personal travel) is done on an individual's own time and not for business purposes, the value of increased time on the road likely varies for each person. One study of willingness to pay a toll to reduce commute times found that commuters are willing to pay 14%–26% of their gross hourly wage to reduce travel time by one hour; other studies have found WTP for travel time reduction by one hour between 50% and 60% of gross hourly wage (Calfee and Winston 1998). A revealed preference study, in which drivers chose between a free and a toll road, found that the value of travel time was 72% of the average hourly wage (Lam and Small 2001).

Likely negligible link: This link is likely to be negligible for solar energy development on BLM lands due to their remoteness.

Strength of Evidence

Moderate: It is clear from a variety of studies that people place value on the time they spend in traffic and are generally willing to pay to spend less time in traffic.

Predictability: The equation described above can be used to calculate the value of time lost in traffic, but the hourly value of travel time, a key variable in this relationship, is uncertain and varies by individual. Several studies that assessed willingness to pay for shortened travel times found a range of values, but no studies were found that examined travel time values as a function of other factors.

Sources

Calfee, J., and C. Winston. 1998. "The Value of Automobile Travel Time: Implications for Congestion Policy." *Journal of Public Economics* 69: 83–102.

Goodwin, P. 2004. The Economic Costs of Road Traffic Congestion. ESRC Transport Studies Unit, University College London.

Lam, T.C., and K.A. Small. 2001. "The Value of Time and Reliability: Measurement from a Value Pricing Experiment." *Transportation Research Part E*: 231–251.

6g: Heat → Habitat

Description of Relationship

Increased temperatures can change habitat suitability for certain wildlife species.

Summary of Evidence

Most research on the influence of small changes in temperature on wildlife habitat are related to incubation temperatures for reptiles. Temperature influences how long reptile embryos take to develop (and therefore the timing hatching), and it can affect traits including sex, body size, and growth rate, depending on the species (Warner and Andrews 2002). In laboratory and field studies, reptiles have been shown to select nesting sites with temperatures suitable for embryonic development (Warner and Andrews 2002; Doody et al. 2006). Therefore, temperature changes that make additional habitat suitable for nesting are beneficial to reptiles, whereas temperature changes that make habitat less suitable for nesting are disadvantageous.

Likely negligible link: This link is likely to be negligible because the direction of the effect is uncertain, the effect is localized, and the small expected temperature changes are likely to affect only a few species.

Strength of Evidence

Low: Some laboratory and field studies exist for individual species, but due to the specificity of habitat requirements, no general relationship can be stated. Both positive and negative effects of heat on habitat suitability are possible, depending on the species' requirements.

Other Factors

Location: The location of a solar energy facility determines the wildlife species that will be affected by temperature changes.

Technology: The type of solar energy technology determines the amount of heat produced (see link 6e).

Sources

Doody, J.S., E. Guarino, A. Georges, B. Corey, G. Murray, and M. Ewert. 2006. "Nest Site Choice Compensates for Climate Effects on Sex Ratios in a Lizard with Environmental Sex Determination." *Evolutionary Ecology* 20: 307–330.

Warner, D.A., and R.M. Andrews. 2002. "Nest-site Selection in Relation to Temperature and Moisture by the Lizard *Sceloporus undulates*. *Herpetologica* 58(4): 399–407.

6i: Habitat → Grazing

Description of Relationship

Solar development on land previously used for grazing will result in the cancellation of grazing permits for the developed area.

Summary of Evidence

The environmental impact statements for solar energy zones on BLM land include livestock grazing as a resource that will be affected by solar development; the number of permits and animal unit months (AUMs, a common measure of grazing) that would be lost due to development is listed for each SEZ. Of the BLM's 17 SEZs, 13 contain some land currently authorized for grazing (BLM, n.d.). For example, solar development in the Antonito Southeast SEZ would result in the cancellation of three seasonal grazing allotments representing a total of 575 AUMs (BLM 2017). The actual amount of grazing lands lost to a solar development project will depend on the location of the project relative to public grazing lands within the SEZ.

Likely negligible link: This link is likely to be negligible for solar energy development on BLM lands due to the low numbers of grazing permits involved.

Strength of Evidence

High: The relationship between habitat loss due to solar development on BLM lands and the loss of grazing opportunities on those lands is straightforward.

Predictability: The loss of grazing opportunities from a particular solar development project can be determined from maps of the facility location and existing grazing land allotments.

Other Factors

Location: As stated above, the amount of grazing land lost to solar development depends on the location of a solar energy project relative to grazing land allotments.

Technology: The type of solar energy technology will influence the total amount of land that will be occupied by the facility and therefore unavailable for grazing (see link 9a).

Sources

BLM (Bureau of Land Management). N.d. "Solar Energy Zones." Solar Energy Development Programmatic EIS Information Center. http://solareis.anl.gov/sez/index.cfm. Accessed July 25, 2017.

———. 2017. Regional Mitigation Strategy for the Colorado Solar Energy Zones: Final Report. http://blmsolar.anl.gov/documents/docs/FINAL_CO_SRMS_Jan_2017.pdf.

6j: Grazing → Grazing Permit Value

Description of Relationship

The BLM's revenue from grazing permits is currently $1.87/AUM (BLM 2017).

BLM grazing lands are valuable to ranchers due to a combination of economy-of-scale cost savings and increased ranch value; the value of a BLM grazing permit to a rancher changes over time and has been assessed by multiple researchers with a wide range of results.

Summary of Evidence

The grazing fee, which is the amount BLM receives for grazing permits, is adjusted annually and was set at $1.87/AUM for 2017 (BLM 2017). Revenue lost due to cancelled grazing permits can be calculated by multiplying this fee by the total AUMs previously supported on the land removed from grazing.

Grazing permits can be transferred with a ranch property and therefore contribute to property value. There are several theories about the reason for this value: grazing permits on federal lands may allow the rancher to raise cattle more cheaply than on private land, larger ranches may confer economy-of-scale cost savings, and ranchers may value exclusive access to public lands for recreational uses (Stern 1998; Rimbey et al. 2007). A review of studies estimating grazing permit values on BLM lands found estimates ranging from $0–$220/AUM; these studies were conducted in locations throughout the western United States from 1950 to 1994 and used a variety of estimation techniques (Stern 1998). A more recent study using a hedonic value model found BLM permit values of $128/AUM in New Mexico and $112/AUM in the Great Basin (Rimbey et al. 2007). A 2010 hedonic value model for ranches in New Mexico estimated the value of a BLM grazing permit at about $250/AUM (Torell et al. 2010). An assessment of potential impacts to ranchers of various sage grouse management policies estimated that grazing permits on BLM-managed lands are valued at $150–350/AUM (Torell et al. 2014).

Likely negligible link: This link is likely to be negligible for solar energy development on BLM lands due to the low numbers of grazing permits involved.

Strength of Evidence

Moderate: Although the BLM revenue lost from cancelled grazing permits can be easily calculated as described above, the value of grazing land to ranchers is less certain and is not directly linked to the number of livestock that the land could support. Studies have used a variety of approaches, including hedonic value models, to assess the value of grazing permits to ranchers, but results are inconsistent and vary by location and with other ranch characteristics.

Predictability: The hedonic value models described above can be used to predict the value of grazing permits in the context in which the model was developed (e.g. New Mexico and Great Basin ranches for the Rimbey et al. 2007 model), but they are not applicable to other contexts.

Other Factors

Location: The location of a ranch has been shown to influence grazing permit values (Rimbey et al. 2007). The location of a specific solar development project determines the amount of land removed from grazing (see link 6i).

Technology: The type of solar energy technology will influence the total amount of land that will be unavailable for grazing (see link 9a).

Other: The proportion of a ranch's land consisting of BLM land influences the value of a BLM grazing permit ($/AUM) (Rimbey et al. 2007).

Sources

BLM (Bureau of Land Management). 2017. "BLM and Forest Service Announce 2017 Grazing Fee." U.S. Department of the Interior Bureau of Land Management. https://www.blm.gov/press-release/blm-and-forest-service-announce-2017-grazing-fee.

Rimbey, N.R., L.A. Torell, and J.A. Tanaka. 2007. "Why Grazing Permits Have Economic Value." *Journal of Agricultural and Resource Economics* 32(1): 20–40.

Stern, B.S. 1998. Permit Value: A Hidden Key to the Public Land Grazing Dispute. Unpublished master's thesis. The University of Montana, Missoula, MT. http://rangenet.org/directory/stern/thesis/chapter3.html#ESTIMATIONS. Accessed July 25, 2017.

Torell, L.A., B. Dixon, and D. McCullom. 2010. *The Market Value of Ranches and Grazing Permits in New Mexico, 1996 to 2010.* New Mexico State University Research Report 779. http://aces.nmsu.edu/pubs/research/economics/RR779/welcome.html#.

Torell, L.A., J.A. Tanaka, J.P. Ritten, N.R. Rimbey, D.T. Taylor, and T.K. Foulke. 2014. Ranch-level Economic Impacts of Altering Grazing Policies on Federal Land to Protect the Greater Sage-Grouse. University of Wyoming Extension, B-1258A. http://www.wyoextension.org/agpubs/pubs/B1258A.pdf.

7a: Solar Development → Transmission Lines

Description of Relationship

A new solar energy facility requires XX miles of transmission lines.

Summary of Evidence

Solar energy facilities must be connected to high-voltage transmission lines so that electricity generated at the facility can be distributed. New transmission lines between the solar energy facility and existing transmission lines are constructed; the length of new transmission lines is determined by the distance between the solar energy facility and the existing transmission lines (Patton et al. 2013).

Likely negligible link: This link is likely to be negligible for solar energy development on BLM lands because the only impact resulting from it is negligible (see link 7b).

Strength of Evidence

High: All solar energy facilities need to be connected to transmission lines for electricity distribution; unless a facility is built very close to an existing transmission line, new lines will need to be constructed.

Predictability: Although the length of transmission lines required cannot be estimated generally, the transmission line length for a specific solar energy facility can be determined, during project planning, on the basis of the location of the project and existing transmission lines.

Other Factors

Location: As stated above, location is the key determining factor for transmission line requirements.

Technology: Technology has no effect (assumed).

Sources

Patton, T., L. Almer, H. Hartmann, and K.P. Smith, eds. 2013. An Overview of Potential Environmental, Cultural, and Socioeconomic Impacts and Mitigation Measures for Utility-scale Solar Energy Development. Environmental Science Division, Argonne National Laboratory.

7b: Transmission Lines → Animal Deaths

Description of Relationship

Approximately 23.2 birds are killed by collisions each year per kilometer of transmission line.

Summary of Evidence

A meta-analysis attempted to assess both collision and electrocution mortality for transmission and distribution lines, but due to a lack of data it could estimate only mortality rates for collision with transmission lines and electrocution on distribution lines (Loss et al. 2014). Without an estimate of mortality from electrocution on transmission lines, the mortality rate listed in the "Description of Relationship" section underestimates bird mortality from transmission lines. As a rudimentary approximation, the estimated mortality rate from electrocution on distribution lines could be used (median 0.030 deaths/pole; 95% confidence interval 0.005–0.062 deaths/pole). The studies included in the meta-analysis were biased by habitat type (most collision studies were conducted in wetlands) and sampling design (few studies took into account seasonal differences or carcass losses, for example, by scavenging, that could cause underestimation of mortality) (Loss et al. 2014).

Likely negligible link: This link is likely to be negligible for solar energy development on BLM lands due to the low magnitude of the effect and the inclusion of energy transmission infrastructure as a criterion for the designation of solar energy zones, which should minimize the length of new transmission lines.

Strength of Evidence

Fair: The primary source of evidence for this relationship is a meta-analysis of 14 studies of bird mortality from collisions with transmission lines (Loss et al. 2014). This analysis used established methods and was well-documented, but data gaps and biases in the design limit its applicability to the southwestern United States. The analysis included studies with a wide range of estimates for collision-related mortality (95% confidence interval: 9.3–66.4 mortalities/kilometer of transmission line).

Other Factors

Location: The location of transmission lines relative to bird populations and migration routes determines the number and species of birds that may encounter the transmission lines.

Technology: Technology has no effect (assumed).

Bird species: Some species' behavior and physiology make them relatively vulnerable to collisions (Silva et al. 2014). Therefore, the composition of the bird community in the area surrounding a solar facility may influence transmission line mortality rates at the facility.

Sources

Loss, S.R., T. Will, and P.P. Marra. 2014. "Refining Estimates of Bird Collision and Electrocution Mortality at Power Lines in the United States." *PLoS ONE* 9(7): e101565.

Silva, J.P., J.M. Palmeirim, R. Alcazar, R. Correia, A. Delgado, and F. Moreira. 2014. "A Spatially Explicit Approach to Assess the Collision Risk between Birds and Overhead Power Lines: A Case Study with the Little Bustard." *Biological Conservation* 170: 256–263.

8b: Roads → Animal Deaths

Description of Relationship

The probabilities of an individual animal being killed during one road crossing and over a one-year period can be calculated from the equations described in link 4j.

Summary of Evidence

See link 4j for a summary of the evidence related to estimating road mortality probabilities. This link uses the same evidence as 4j, but the focus here is on changes to road mortality due to an increase in the length of roads present in a given area, which will increase the number of road crossings that an individual attempts each year and therefore its probability of being killed on a road over a one-year period, whereas link 4j focuses on the impacts of an increase in traffic on existing roads.

An alternative approach is to estimate road mortality rate as the number of individuals killed per unit length of road each day. If this number is known, the change in mortality due to new roads can be calculated by multiplying the number of individuals killed per unit road length per day by the total length of new roads. Many studies have attempted to calculate road mortality rates per unit length of road for groups of species. These studies are very location specific because they depend on the type of habitat near the road, the local wildlife community, and road-related variables (road width, traffic volume). They are also susceptible to biases in carcass detection and removal rates, and they are generally thought to underestimate mortality rates, depending on their sampling technique (Teixeira et al. 2013). For these reasons, these studies have low general applicability, but they can give a general idea of the magnitude of road mortality rates. Studies of total vertebrate road mortality estimated rates of 2.02 kills/km/day (Indiana) and 1.05 kills/km/day (Saguaro National Park) (Glista et al. 2007; Gerow et al. 2010). Studies that broke mortality down by taxonomic group found mortality rates of 1.91 kills/km/day (herpetofauna, Indiana), 0.07 kills/km/day (mammals, Indiana), 0.062 kills/km/day (snakes, Sonoran Desert), 0.04 kills/km/day (birds, Indiana), and 0.026 kills/km/day (mammals, New York) (Glista et al. 2007; Rosen and Lowe 1993; Barthelmess and Brooks 2010).

Field surveys can provide good estimates of wildlife mortality on roads at a particular site. A study of vertebrate road mortality in Saguaro National Park provides a good example of methods for roadkill surveys, including estimates of roadkill persistence and detectability, and the study calculates annual mortality estimates from survey data (Gerow et al. 2010).

Likely negligible link: This link is likely to be negligible for solar energy development in the southwestern United States due to low traffic volumes on roads built specifically for solar energy facilities and the exclusion of many wildlife species from solar energy facilities with fencing (see link 9b). Larger impacts are expected from increases in traffic volumes on existing roads during facility construction (see link 4j).

Strength of Evidence

Moderate: A variety of field studies (including some in the southwestern United States) and predictive models demonstrate that roads can be a relatively large cause of mortality for many types of wildlife. Specific estimates of mortality per unit length of road are location specific and have limited general applicability.

Predictability: One predictive model, which has been validated by several field studies with varying results and which has been used by several researchers in this field, provides the basis for the "Description of Relationship" section in link 4j.

Other Factors

Species: As discussed above, species' movement patterns and velocities influence their susceptibility to road mortality. Temporal patterns of activity can also affect road mortality; diurnal species are more likely to cross roads during high-traffic periods than nocturnal species (Hels and Buchwald 2001). This pattern should be reflected by the traffic volume variable in the vehicle collision model.

Sources

Barthelmess, E.L., and M.S. Brooks. 2010. "The Influence of Body Size and Diet on Road-Kill Trends in Mammals." *Biodiversity Conservation* 19: 1611–1629.

Gerow, K., N.C. Kline, D.E. Swann, and M. Pokorny. 2010. "Estimating Annual Vertebrate Mortality on Roads at Saguaro National Park, Arizona." *Human-Wildlife Interactions* 4(2): 283–292.

Gibbs, J.P., and W.G. Shriver. 2002. "Estimating the Effects of Road Mortality on Turtle Populations." *Conservation Biology* 16(6): 1647–1652.
Gibbs, J.P., and W.G. Shriver. 2005. "Can Road Mortality Limit Populations of Pool-breeding Amphibians?" *Wetlands Ecology and Management* 3: 281–289.
Glista, D.J., T.L. DeVault, and J.A. DeWoody. 2007. "Vertebrate Road Mortality Predominantly Impacts Amphibians." *Herpetological Conservation and Biology* 3(1): 77–87.
Hels, T., and E. Buchwald. 2001. "The Effect of Road Kills on Amphibian Populations." *Biological Conservation* 99: 331–340.
Litvaitis, J.A., and J.P. Tash. 2008. "An Approach toward Understanding Wildlife-Vehicle Collisions." *Environmental Management* 42: 688–697.
Roe, J.H., J. Gibson, and B.A. Kingsbury. 2006. "Beyond the Wetland Border: Estimating the Impact of Roads for Two Species of Water Snakes." *Biological Conservation* 130(2): 161–168.
Rosen, P.C., and C.H. Lowe. 1994. "Highway Mortality of Snakes in the Sonoran Desert of Southern Arizona." *Biological Conservation* 68: 143–148.
Row, J.R., G. Blouin-Demers, and P.J. Weatherhead. 2007. "Demographic Effects of Road Mortality in Black Ratsnakes (*Elaphe obsoleta*). *Biological Conservation* 137: 117–124.
Teixeira, F.Z., A.V.P. Coelho, I.B. Esperandio, and A. Kindel. 2013. "Vertebrate Road Mortality Estimates: Effects of Sampling Methods and Carcass Removal." *Biological Conservation* 157:317–323.

9h: Sedimentation → Cost of Municipal Water

Description of Relationship

Sedimentation of drinking water sources can increase the cost of municipal water treatment.

Summary of Evidence

There is no drinking water standard for sediment specifically, but the EPA's national primary drinking water regulations prohibit turbidity (cloudiness) greater than 1 Nephelometric Turbidity Unit (NTU) at all times, and no more than 0.3 NTUs in 95% of samples for any month, because turbidity can interfere with disinfection. Sediment can contribute to cloudiness and may cause raw water to exceed this standard. Although most suspended solids are effectively removed by standard water treatment practices (coagulation, flocculation, sedimentation and filtration) (EPA, n.d.), increased sediment loads could result in longer required run times for clarification and filtration, which could increase the cost of water treatment (EPA, n.d.). Four studies that assessed the effect of turbidity on drinking water treatment costs found that a 1% increase in turbidity is associated with a 0.07%–0.3% increase in water treatment costs (Freeman et al. 2008).

Likely negligible link: This link is likely to be negligible for solar energy development in the southwestern United States because the arid ecosystems have few surface waterways that are used for drinking water.

Strength of Evidence

Low: Because there is no drinking water standard for sediment and sediment is generally removed by standard water treatment, it is difficult to tell how frequently or under what circumstances sedimentation may cause increased water treatment costs. There is some evidence available for the order of magnitude of the effect of turbidity on water treatment costs, but it is based on only a few studies, and costs vary widely by location and treatment type.

Sources

EPA (U.S. Environmental Protection Agency). n.d. Conventional Treatment. Drinking Water Treatability Database. https://iaspub.epa.gov/tdb/pages/treatment/treatmentOverview.do?treatmentProcessId=1934681921.
Freeman, J., R. Madsen, & K. Hart. 2008. "Statistical Analysis of Drinking Water Treatment Plant Costs, Source Water Quality, and Land Cover Characteristics." The Trust for Public Land. https://www.tpl.org/sites/default/files/cloud.tpl.org/pubs/water-landuse-water-whitepaper.pdf.

9l: Biological Soil Crust → Infiltration

Description of Relationship

The presence of biological soil crust can increase or decrease infiltration rates.

Summary of Evidence

Infiltration rates are influenced by how quickly water moves over the soil surface and how permeable the surface is to water. Biological soil crusts can increase the roughness of the soil surface, which slows water down and promotes pooling, increasing the infiltration rate. Certain components of biological crusts absorb large amounts of water and expand when wet, which can increase hydraulic conductivity and further increase surface roughness but which may also partially seal the soil surface and restrict infiltration (Belnap et al. 2001; Chamizo et al. 2016). Therefore, the net effect of soil crusts on infiltration is dependent on local factors (Belnap et al. 2001). Overall, the effects of biological soil crusts on infiltration are likely much smaller than compaction-related effects on infiltration (see link 9p) (Belnap and Lange 2003).

The removal of biological crusts can result in the formation of physical soil crusts from raindrop impacts, which tend to decrease infiltration rates relative to biological crusts or bare soil (Chamizo et al. 2016).

Soil erosion models that incorporate infiltration include the Limburg Soil Erosion Model (LISEM), a widely used spatial model that can include aspects of desert soils such as biological soil crust (Rodríguez-Cabellero et al. 2015). Although the model requires a substantial amount of local data and geospatial information system knowledge to run, it can be used to assess infiltration effects from changes to biological soil crust and has been found to perform adequately in predicting infiltration in case studies (Rodríguez-Caballero et al. 2015).

Likely negligible link: This link is likely to be negligible due to the very small magnitude of observed effects of biological soil crusts on infiltration.

Strength of Evidence

Low: Studies that examined the effect of biological soil crusts on infiltration have found inconsistent results, with soil crusts infiltrating the rate of infiltration in some areas and decreasing the rate of infiltration in others; other studies have found no effect of soil crusts on infiltration. No meta-analyses related to this relationship were found.

Predictability: The LISEM spatial model can be adapted to include biological soil crusts and has been found to adequately (but not perfectly) predict infiltration and runoff in arid ecosystems.

Other Factors

Climate: Biological soil crusts tend to have rough surfaces in cold deserts due to frost-heaving; these rough surfaces slow water movement more than the smooth surfaces of soil crusts in hot deserts (Belnap et al. 2001).

Crust development: In semiarid regions, infiltration generally increases with greater biological crust development and biomass (Chamizo et al. 2016).

Crust components: The species that make up a biological soil crust influence its effect on infiltration. Some lichens are hydrophobic and can seal the soil surface when they form large patches, decreasing infiltration. Mosses are capable of absorbing large amounts of water, as are cyanobacterial sheaths and some cyanolichens, which may promote infiltration (Chamizo et al. 2016).

Soil factors: The level of soil moisture prior to a precipitation event can affect the extent to which biological crusts facilitate infiltration; dry biological crusts had much higher infiltration rates than previously-wetted crusts (Chamizo et al. 2016).

Sources

Belnap, J., J.H. Kaltenecker, R. Rosentreter, J. Williams, S. Leonard, and D. Eldridge. 2001. Biological Soil Crusts: Ecology and Management. U.S. Department of the Interior, Technical Reference 1730-2.

Chamizo, S., J. Belnap, D.J. Eldridge, Y. Cantón, and O.M. Issa. 2016. “The Role of Biocrusts in Arid Land Hydrology.” In *Biological Soil Crusts: An Organizing Principle in Drylands*, edited by B. Weber, B. Budel, and J. Belnap, 321–346. Switzerland: Springer International Publishing.

Rodríguez-Caballero, E., Y. Cantón, and V. Jetten. 2015. “Biological Soil Crust Effects Must Be Included to Accurately Model Infiltration and Erosion in Drylands: An Example from Tabernas Badlands.” *Geomorphology* 241: 331–342.

9r: Infiltration → Water Storage

Description of Relationship

A fraction of the water that infiltrates into the soil is stored in aquifers.

Summary of Evidence

Water that infiltrates into the soil can evaporate, be taken up by plants, or percolate into groundwater, from which it can move into surface waters or contribute to groundwater storage in an aquifer (Arnold et al. 1993). A review of groundwater recharge studies in arid and semi-arid regions estimated that between 0.1% and 5% of precipitation recharges groundwater (Scanlon et al. 2006), but no studies were found that examined the proportion of infiltrated water that becomes recharge.

Groundwater recharge models range from simple water balance models to complex simulations, but all suffer from inaccuracy in the data available for input parameters, which leads to high uncertainty in the resulting recharge estimate (Gee and Hillel 1988; Scanlon et al. 2006). High spatial variability in recharge rates due to small-scale variability in soils and topography makes it difficult to validate models even when field measurements can be taken.

Likely negligible link: This link is likely to be negligible for solar energy development in the southwestern United States because solar energy facilities are sited to avoid disturbing high-recharge areas, which minimizes their potential effect on groundwater storage.

Strength of Evidence

Fair: Because water must infiltrate the soil before reaching groundwater, there is clearly a relationship between the two processes. However, many location-specific factors determine the fate of infiltrated water, and no studies were found that assessed the relationship between water infiltration and groundwater recharge.

Predictability: Models to predict groundwater recharge exist, but they are data intensive and are often inaccurate, especially at the small spatial scales that would be required for assessment of recharge effects from a solar energy project.

Other Factors

Landscape: Groundwater recharge is influenced by landscape location, with high recharge rates concentrated beneath ephemeral streams and lakes in arid regions (Scanlon et al. 2006). Solar energy facilities are designed to avoid disturbing these areas, and therefore they are not expected to have a substantial effect on groundwater recharge rates (Patton et al. 2013).

Soils: Coarse-textured soils allow infiltrated water to drain to an aquifer faster, while fine-textured soils hold water in the root zone for a longer period, increasing the proportion of water that is taken up by plants (Gee and Hillel 1988). The depth to groundwater is reached influences the time for water to reach groundwater; deeper water tables allow more time for infiltrated water to be taken up by plants or to evaporate before it recharges groundwater (Shanafield and Cook 2014).

Vegetation: Vegetation takes up water from the soil and reduces water available for groundwater recharge; studies in North American deserts have shown that no recharge occurs in vegetated areas (Scanlon et al. 2006).

Sources

Arnold, J.G., P.M. Allen, and G. Bernhardt. 1993. "A Comprehensive Surface-Groundwater Flow Model." *Journal of Hydrology* 142: 47–69.

Gee, G.W., and D. Hillel. 1988. "Groundwater Recharge in Arid Regions: Review and Critique of Estimation Methods." *Hydrological Processes* 2: 255–266.

Patton, T., L. Almer, H. Hartmann, and K.P. Smith, eds. 2013. An Overview of Potential Environmental, Cultural, and Socioeconomic Impacts and Mitigation Measures for Utility-scale Solar Energy Development. Environmental Science Division, Argonne National Laboratory.

Scanlon, B.R., K.E. Keese, A.L. Flint, L.E. Flint, C.B. Gaye, W.M. Edmunds, and I. Simmers. 2006. "Global Synthesis of Groundwater Recharge in Semiarid and Arid Regions." *Hydrological Processes* 20: 3335–3370.

Shanafield, M., and P.G. Cook. 2014. "Transmission Losses, Infiltration and Groundwater Recharge through Ephemeral and Intermittent Streambeds: A Review of Applied Methods." *Journal of Hydrology* 511: 518–529.

9s: Water Storage → Natural Ecosystems/Flora

Description of Relationship

Increased depth to the water table and decreased stream flow cause stress in desert plants.

Summary of Evidence

A decline in the amount of water stored as groundwater can cause increased depth to water table and decreased stream flow. For plants that rely on groundwater as a water source, this decline results in water stress and can cause death. The greatest effects may be evident near surface waterways in arid and semi-arid regions, which are often able to support plant communities, including wetland-associated plants, due to shallow water tables. Field studies have shown that depth to groundwater is a key factor influencing riparian vegetation community composition along the San Pedro River in Arizona and the viability of mesquite stands along desert streams (Stromberg et al. 1992, Stromberg et al. 1996). On the basis of modeling and historic data, researchers believe that additional groundwater withdrawals in the Great Basin and Mojave Deserts would have similar effects on riparian plants in desert springs (Patten et al. 2008). Many introduced plant species are less sensitive to changes in groundwater depth than native plants, so decreased groundwater storage could enhance their competitive advantage over native species (Stromberg et al. 1996).

Likely negligible link: This link is likely to be negligible because it results from negligible links (see links 9r and 10b).

Strength of Evidence

Fair: Field studies have shown the importance of groundwater depth to plant communities in arid riparian areas. Effects of reduced water storage at a particular location would vary depending on the plant species present and background environmental conditions.

Other Factors

Species: Plant species vary in their responses to groundwater decline due to differences in rooting depth and tolerance to water stress (Stromberg et al. 1996).

Sources

Patten, D.T., L. Rouse, and J.C. Stromberg. 2008. "Isolated Spring Wetlands in the Great Basin and Mojave Deserts, USA: Potential Response of Vegetation to Groundwater Withdrawal." *Environmental Management* 41: 398–413.

Stromberg, J.C., J.A. Tress, S.D. Wilkins, and S.D. Clark. 1992. "Response of Velvet Mesquite to Groundwater Decline." *Journal of Arid Environments* 23(1): 45–58.

Stromberg, J.C., R. Tiller, and B. Richter. 1996. "Effects of Groundwater Decline on Riparian Vegetation of Semiarid Regions: The San Pedro, Arizona." *Ecological Applications* 6(1): 113–131.

9t: Water Storage → Water Availability

Description of Relationship

Less water stored as groundwater means less water is available for human use.

Summary of Evidence

Because there are few persistent sources of surface water in arid and semi-arid regions, people rely on groundwater sources to a larger degree than in other hydroclimatic regions (Scanlon et al. 2006). With the exception of Colorado, southwestern states use relatively more groundwater (as a percentage of total water use) than the national average (Arizona, 42%; California, 33%; Colorado, 14%; New Mexico, 50%; Nevada, 46%; Utah, 25%; national average, 22%) (Maupin et al. 2014). In addition, groundwater resources in the southwest United States are being used faster than they can be replenished, resulting in overall depletion of groundwater (Konikow 2013). Therefore, less water stored as groundwater means that less water is available for use in the long term.

Likely negligible link: This link is likely to be negligible because it results from negligible links (see links 9r and 10b).

Strength of Evidence

High: The statistics on groundwater use and depletion in the United States were compiled from the best available data and models by the USGS; they clearly show the importance of groundwater as a water source and that groundwater quantity is linked to water availability for human use.

Sources

Konikow, L.F. 2013. Groundwater Depletion in the United States (1900–2008). United States Geological Survey Scientific Investigations Report 2013-5079. https://pubs.usgs.gov/sir/2013/5079/SIR2013-5079.pdf.

Maupin, M.A., J.F. Kenny, S.S. Hutson, J.K. Lovelace, N.I. Barber, and K.S. Linsey. 2014. Estimated Use of Water in the United States in 2010. U.S. Geological Survey Circular 1405. http://dx.doi.org/10.3133/cir1405.

Scanlon, B.R., K.E. Keese, A.L. Flint, L.E. Flint, C.B. Gaye, W.M. Edmunds, and I. Simmers. 2006. "Global Synthesis of Groundwater Recharge in Semiarid and Arid Regions." *Hydrological Processes* 20: 3335–3370.

9u: Water Availability → Cost of Municipal Water

Description of Relationship

A decrease in water availability by XX% results in increased municipal water costs of XX%.

Summary of Evidence

Less available water increases the cost for both the extraction and treatment of groundwater for municipal use. The depth to the water table determines the distance that groundwater must be pumped in order to reach the surface and is a key factor in the unit cost of groundwater pumping (Dale 2016; Moore and Hedges 1960). In some cases, increased depth to water table can require modification of existing wells or drilling of new wells (Moran et al. 2014). Less water present in aquifers results in higher concentrations of existing pollutants, and in certain areas, withdrawal of fresh water from aquifers causes saltwater intrusion from underlying saline water (Foster and Chilton 2003). When pollutant levels approach or exceed drinking water standards, additional water treatment is needed to reduce pollutant concentrations. The type and cost of treatment required depends on the identity and concentration of the pollutants in question; no sources were found that provide an overview of water treatment technologies and the costs associated with each.

Likely negligible link: This link is likely to be negligible because it results from a negligible link (see link 9t).

Strength of Evidence

Fair: The effect of deeper water tables on the cost to extract water is relatively straightforward, but the necessity for and cost of modifications to wells is highly site dependent, and no general relationship can be stated. The effects on water treatment costs are much less certain; although multiple sources emphasize the high treatment costs of contaminated groundwater, no evidence was found that linked water availability to pollutant concentrations or treatment costs.

Other Factors

The location of a project determines the type of pollutants that could be present in groundwater (and therefore the cost to remove them) and the availability of alternate water sources (which can be a less-expensive alternative to groundwater treatment).

Sources

Dale, L. 2016. Clarifying and Quantifying Current and Near-term Groundwater Pumping Energy Use and Costs in California. Lawrence Berkeley National Laboratory 2016 EPIC Symposium.

Foster, S.S.D., and P.J. Chilton. 2003. "Groundwater: The Processes and Global Significance of Aquifer Degradation." *Philosophical Transactions of the Royal Society B: Biological Sciences* 358: 1957–1972.

Moore, C.V., and T.R. Hedges. 1960. "Irrigation Costs of Pumping in the San Joaquin Valley." *California Agriculture, October 1960*: 3-4.

Moran, T., J. Choy, and C. Sanchez. The Hidden Costs of Groundwater Overdraft. *Understanding California's Groundwater*. Water in the West at Stanford Woods Institute for the Environment and the Bill Lane Center for the American West. http://waterinthewest.stanford.edu/groundwater/overdraft/.

9v: Water Availability → Irrigated Crop Yield

Description of Relationship

A decrease in water availability by 10%, resulting in decreased irrigation by 10%, causes the yield of XX crop to decline by XX%.

Summary of Evidence

In general, when less water is available overall, less water is available for irrigation (see other factors for exceptions). A large proportion of crops grown in the western United States is dependent on irrigation for water; when less water is available for irrigation, the yield of these crops decreases. Models are available that predict yields for a variety of crops under different environmental and irrigation scenarios, but these models vary in the validity of their results and their applicability to different types of agricultural systems (Kloss et al. 2012). AquaCrop, a model developed by the United Nations Food and Agriculture Organization (FAO) that predicts yields under various irrigation conditions, has been parameterized for a variety of crops and regions, and researchers are continuing to extend the model to new systems (Steduto et al. 2009; Vanuytrecht et al. 2014).

Likely negligible link: This link is likely to be negligible because it results from a negligible link (see link 9t).

Strength of Evidence

Moderate: The effect of a change in water availability on the ability of farmers to irrigate crops depends on local factors related to water sources and allocation (see other factors), but any decrease in irrigation is likely to have a negative impact on the yield of irrigated crops, especially in water-limited areas like the southwest.

Predictability: Models to predict the effect of irrigation changes on crop yields are available, but their validity varies by crop type and other environmental variables.

Other Factors

Location: The geographical location in which the change in water availability occurs determines the local water sources and water use policies that influence an individual farmer's ability to use water for irrigation (Schlenker et al. 2007).

Technology: Technology has no effect (assumed).

Other: Agricultural management strategies, including planting of low-water-demand crops, use of efficient irrigation systems, and water reuse, can help to minimize effects of lower water availability for irrigation, but not all farmers have the means to implement these strategies (Pereira et al 2002).

Sources

Kloss, S., R. Pushpalatha, K.J. Kamoyo, and N. Schutze. 2012. "Evaluation of Crop Models for Simulating and Optimizing Deficit Irrigation Systems in Arid and Semi-arid Countries under Climate Variability." *Water Resource Management* 26: 997–1014.

Pereira, L.S., T. Oweis, and A. Zairi. 2002. "Irrigation Management under Water Scarcity." *Agricultural Water Management* 57: 175–206.

Schlenker, W., W.M. Hanemann, and A.C. Fisher. 2007. "Water Availability, Degree Days, and the Potential Impact of Climate Change on Irrigated Agriculture in California." *Climatic Change* 81: 19–38.

Steduto, P., T.C. Hsiao, D. Raes, and E. Fereres. 2009. "AquaCrop—The FAO Crop Model to Simulate Yield Response to Water: I. Concepts and Underlying Principles." *Agronomy Journal* 101(3): 426–437.

Vanuytrecht, E., D. Raes, P. Steduto, T. Hsiao, E. Fereres, K.H. Lee, …, and P.M. Moreno. 2014. "AquaCrop: FAO's Crop Water Productivity and Yield Response Model." *Environmental Modelling and Software* 62: 351–360.

9w: Irrigated Crop Yield → Value of Irrigated Crops

Description of Relationship

A decline in yield of XX crop by XX kg/hectare causes a loss in market value of $XX.

Summary of Evidence

The USDA releases an annual report with the market values for crops grown in the United States, averaged nationally and by state (USDA 2017). This information can be used to calculate the loss in market value due to irrigation changes by multiplying the decline in yield by the unit price for the crop in question.

Likely negligible link: This link is likely to be negligible because it results from a negligible link (see link 9v).

Strength of Evidence

High: The relationship between crop yield changes and market value is straightforward; market value losses can be calculated on the basis of the USDA's annual summary of crop values.

Other Factors

Location: The USDA's annual summary of crop values gives average values by state, but additional variation in crop values within a state may exist.

Technology: Technology has no effect (assumed).

Source

USDA (U.S. Department of Agriculture). 2017. Crop Values 2016 Summary. http://usda.mannlib.cornell.edu/usda/current/CropValuSu/CropValuSu-02-24-2017_revision.pdf. Accessed July 31, 2017.

10a: Solar Development → Water Use

Description of Relationship

Over the course of its lifecycle, a PV solar plant consumes 11–226 gallons of water/MWh. Concentrating solar power plants consume 80–170 gallons of water/MWh for the upstream and downstream components of their lifecycles; water consumption during operations varies by technology type (Table 10).

Table 10. Water consumption for the operation of a concentrating solar power plant

CSP technology type	Minimum water consumption (gal/MWh)	Maximum water consumption (gal/MWh)
Dish stirling	5	5
Fresnel	1000	1000
Power tower: cooling tower	740	860
Power tower: dry cooling	26	26
Power tower: hybrid cooling	90	250
Trough: cooling tower	560	1900
Trough: dry cooling	32	140
Trough: hybrid cooling	110	350

Source: Meldrum et al. (2013).

Summary of Evidence

Water is required for several parts of the solar power plant lifecycle, including manufacturing of PV panels, dust suppression during construction, and (for some concentrating solar power technologies) cooling towers (Sinha 2013). Estimates for the amount of water withdrawn and consumed by solar PV power plants vary widely; one meta-analysis found that the upstream and downstream water use of a PV plant with crystalline silicone panels (including raw materials, manufacturing, construction, and transportation, but not operations) ranged from 1 to 1600 gallons/MWh withdrawn and 10 to 210 gallons/MWh consumed (Meldrum et al. 2013). Other types of panels, including thin-film, are estimated to withdraw slightly less water than crystalline silicon panels and to consume far less (5–7 gallons/MWh). However, because PV technology and manufacturing are rapidly evolving, more research is needed into the upstream water use of PV plants.

An operating solar PV plant uses very little water: 1 to 26 gallons/MWh (due to data limitations, water withdrawal and consumption couldn't be separated for PV operations) (Meldrum et al. 2013).

Concentrating solar power plants use much more water than PV plants and are the most water-intensive forms of electricity production, consuming up to 1,000 gallons/MWh (Meldrum et al. 2013), in part due to their use of water-requiring chemicals and need for mirror washing. Many of these plants also dispose of water by allowing it to evaporate, so essentially all of the water they withdraw is consumed.

Likely negligible link: This link is likely to be negligible for solar energy development due to low water-use volumes by operating solar plants, especially PV plants, which are currently the most popular type of utility-scale solar energy technology. This impact could become important if multiple high-water-use concentrating solar power plants are built in the same area.

Strength of Evidence

Moderate: There have been some studies of lifecycle water use by solar energy facilities, including one meta-analysis that followed accepted methods for identifying, screening, and summarizing studies. Specific water use estimates are limited by the number of available studies for many solar technologies (just one study for several CSP technologies; fewer than five studies for all CSP technologies except trough cooling tower and trough dry cooling systems; fewer than five studies for all PV technologies except for flat panel operations), but these studies show that solar development of any technology type does use water during manufacturing, construction, and operations.

Other Factors

Solar Technology: Water use during concentrating solar power operations depends on the specific type of concentrating solar power technology in use; plants with cooling towers use the most water, whereas those with dry-cooling systems use much less (Meldrum et al. 2013).

The amount of water required for manufacturing PV panels varies by panel technology; for example, cadmium telluride panels require less electricity to manufacture and are more efficient than crystalline silicon panels, meaning that less glass and steel is required for mounting; grid electricity, glass, and steel are all water intensive to produce (Sinha 2013).

Sources

Meldrum, J., S. Nettles-Anderson, G. Heath, and J. Macknick. 2013. "Life Cycle Water Use for Electricity Generation: A Review and Harmonization of Literature Estimates." *Environmental Research Letters* 8. stacks.iop.org/ERL/8/015031.

Sinha, P. 2013. "Life Cycle Materials and Water Management for CdTe Photovoltaics." *Solar Energy Materials and Solar Cells* 119: 271–275. https://doi.org/10.1016/j.solmat.2013.08.022.

10b: Water Use → Water Storage

Description of Relationship

Increased use of groundwater can lower the water table, reduce aquifer capacity, and reduce surface water flows.

Increased use of surface water can reduce flows in waterways.

Summary of Evidence

Withdrawal of groundwater in excess of groundwater recharge rates causes the depth to water table to increase (Deacon et al. 2007; Leng et al. 2014). The removal of groundwater from aquifers can cause land subsidence, which reduces the total capacity of the underlying aquifer (Alley et al. 2002; de Graaf et al. 2017). Withdrawal of surface water directly reduces surface water flows. Groundwater and surface water systems are interconnected; depending on the specific hydrological conditions in an area, withdrawal of groundwater can reduce surface water flows, and withdrawal of surface water can increase the depth to the water table (Sophocleous 2002; Winter et al. 1998).

Specific hydrologic effects of groundwater withdrawal depend on site-specific characteristics (rates of groundwater withdrawal and recharge, soils, location of surface water relative to groundwater, topography) (Alley et al. 2002). Models have been developed to predict changes to groundwater and surface water due to groundwater withdrawal (de Graaf et al. 2017; Ercan et al. 2016).

Likely negligible link: This link is likely to be negligible because it results from a negligible link (see link 10a).

Strength of Evidence

Fair: The potential effects of water withdrawals are well-understood and have been documented in a variety of cases, but particular effects of withdrawals at a certain location are influenced by a variety of factors and must be estimated using models. Given the low water use of most solar energy facilities (see link 10a), it is likely that the increased groundwater withdrawals associated with these facilities has a limited impact on water storage in most cases.

Predictability: As described above, models are available to predict the effects of groundwater withdrawal on groundwater and surface water supplies.

Other Factors

Location: As described above, many location-specific factors influence the hydrological effects of increased water withdrawals.

Technology: The type of solar energy technology in use determines the amount of water required over its entire lifecycle and during operations (see link 10a).

Other: The source of water (groundwater or surface water; on-site or off-site) determines the type and location of the effects of increased water use; water is sometimes shipped to solar facilities during construction if there is not enough water available on-site, which displaces the effects of water withdrawal (Patton et al. 2013).

Sources

Alley, W.M., R.W. Healy, J.W. LaBaugh, and T.E. Reilly. 2002. "Flow and Storage in Groundwater Systems." *Science* 296: 1985–1990.

Deacon, J.E., A.E. Williams, C.D. Williams, and J.E. Williams. 2007. "Fueling Population Growth in Las Vegas: How Large-scale Groundwater Withdrawal Could Burn Regional Biodiversity." *BioScience* 57(8): 688–698.

de Graaf, I.E.M., R.L.P.H. van Beek, T. Gleeson, N. Moosdorf, O. Schmitz, E.H. Sutanudjaja, and M.F.P. Bierkens. 2017. "A Global-scale Two-layer Transient Groundwater Model: Development and Application to Groundwater Depletion." *Advances in Water Resources* 102: 53–67.

Ercan, A., E.C. Dogrul, and T.N. Kadir. 2016. "Investigation of the Groundwater Modelling Component of the Integrated Water Flow Model (IWFM)." *Hydrological Sciences Journal* 61(16): 2834–2848.

Leng, G., M. Huang, Q. Tang, H. Gao, and L.R. Leung. 2014. "Modeling the Effects of Groundwater-fed Irrigation on Terrestrial Hydrology Over the Conterminous United States." *Journal of Hydrometeorology*15: 957–972.

Patton, T., L. Almer, H. Hartmann, and K.P. Smith. 2013. An Overview of Potential Environmental, Cultural, and Socioeconomic Impacts and Mitigation Measures for Utility-scale Solar Energy Development. Argonne National Laboratory, Environmental Science Division.

Sophocleous, M. 2002. "Interactions Between Groundwater and Surface Water: The State of the Science." *Hydrogeology Journal* 10: 52-67.

Winter, T.C., J.W. Harvey, O.L. Franke, and W.M. Alley. 1998. "Ground and Surface Water: A Single Resource." *U.S. Geological Survey Circular* 1139. https://pubs.usgs.gov/circ/circ1139/pdf/circ1139.pdf.

National Ecosystem Services Partnership

The National Ecosystem Services Partnership (NESP) engages both public and private individuals and organizations to enhance collaboration within the ecosystem services community and to strengthen coordination of policy and market implementation and research at the national level. The partnership is an initiative of Duke University's Nicholas Institute for Environmental Policy Solutions and was developed with support from the U.S. Environmental Protection Agency and with donations of expertise and time from many public and private institutions. The partnership is led by Lydia Olander, director of the Ecosystem Services Program at the Nicholas Institute, and draws on the expertise of federal agency staff, academics, NGO leaders, and ecosystem services management practitioners.

Conceptual Model Series

The NESP Conceptual Model Series provides a collection of resources explaining why ecosystem services conceptual models (ESCMs) are useful for decision making, providing guidance for building ESCMs, and describing NESP's initial efforts to standardize and apply these models with federal agency partners. It includes application examples of ESCMs and associated evidence libraries. The series aims to provide practical guidance for those who wish to apply ESCMs as a tool for incorporating ecosystem services considerations into their decisions.

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