Assessing the Effects of Management Activities on Biodiversity and Carbon Storage on Public and Private Lands and Waters in the United States

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ABSTRACT

Natural and working lands (NWLs) provide many benefits to people, including storing greenhouse gases (GHGs), supporting biodiversity, and generating other ecosystem services. Management of NWLs can influence their condition and function and therefore the benefits they provide. This project surveys the synthesis literature to assess how different management actions on various types of NWLs affect biodiversity and GHG outcomes. This information can help to determine how to best manage these lands to contribute to both biodiversity and climate solutions in the United States.

INTRODUCTION

There are currently numerous efforts around the world to expand conserved and protected lands, with many governments, multilateral institutions, and nonprofits working toward a “30x30” goal—the conservation of 30% of lands and waters by 2030 (CBD 2022, National Climate Task Force 2021). There is wide acknowledgment that NWLs can contribute to these goals if managed sustainably, while simultaneously providing biodiversity, greenhouse gas (GHG) storage and sequestration, and other ecosystem services that support human welfare and well-being.

This project is meant to act as a starting point to assess how different forms of management on various types of NWLs contribute to or detract from biodiversity and GHG outcomes. Such an assessment can help identify how to best manage these lands to contribute to both biodiversity and climate solutions in the United States. We developed an approach and framework to conduct this assessment and completed a high-level literature review and expert consultation process to provide initial results. This work was inspired by a framework used to assess the benefits accrued through various levels of protection for marine protected areas (Grorud-Colvert et al. 2021). Though we limited this study’s scope to an exploration of biodiversity and GHG benefits provided by NWLs, we propose that this process could be adapted to examine the effects of management on other important ecosystem services, as well as how management affects equitable distribution of those services.

Our specific goals include:

- Identify a priority set of management activities that are common across US lands and waters and are likely to affect biodiversity, carbon storage and GHG emissions (collectively referred to as carbon), and equity.
- Identify a priority set of land/water systems (e.g., working and multiple use forests, freshwater) in which these activities are often managed.
- For each relationship, synthesize existing scientific literature and expert opinion to report an overall effect of the activity on biodiversity and carbon. A relationship is defined by a unique combination of an activity, a land/water system, and an effect on an outcome (biodiversity or carbon). For example, does forest thinning in working and multiple use forests have a positive, negative, neutral, or mixed impact on biodiversity?

- Indicate the confidence associated with the evidence for each overall relationship.
- Identify future research directions to strengthen this analysis in support of federal policy processes and decisions regarding conservation nationwide.

METHODS

Defining Project Scope and Framework

The project team worked in partnership with the US Department of Agriculture (USDA) to define the scope of work, identify research questions, develop an approach to assessing scientific evidence, and report results aligned with the needs of decision-makers. Throughout this research coproduction process, recommended as a best practice for ensuring effective and engaged scholarship (Beyond the Academy 2022), there were frequent and regular exchanges between the research teams and USDA staff, with input solicited from other federal partners through interagency processes.

The first step in this process was to develop a framework to organize the work by land or water system and management activity, allowing us to define searches based on combinations of these attributes. USDA identified an initial set of management activities and a list of priority land and water systems (Box 1) with input from other federal agency partners. The activities are commonly used by federal agencies and have potential effects on either carbon or biodiversity. The full list of activities within each land and water system is available in Appendix A. Codeveloping these lists enabled us to repeatedly revise them to be clearer and more specific, receive feedback, and revise again as we translated the language of federal agencies that manage activities into the language of academic researchers who study related topics in agriculture, natural resources, and the environment.

We originated a framework for compiling information across land and water systems, management activities, and outcomes, and developed a process that combined systematic rapid literature review with expert input, as described in the following section.

Box 1. Land and Water Systems

- Working and multiple use forests
- Croplands
- Grasslands*
- Freshwaters
- Coastal systems
- Marine systems

*The biodiversity assessment considered grasslands, rangelands, and pasture as a single system.

Rapid Literature Reviews

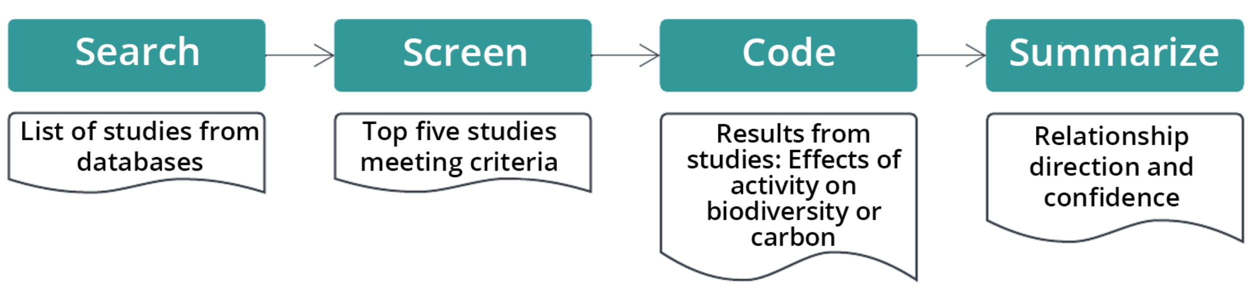
We performed a rapid literature review for each relationship, following a standardized process—search, screen, code, and summarize (Figure 1)—using the approach outlined by the Collaboration for Environmental Evidence (2022). We completed 92 rapid literature reviews for the effects of various management activities on carbon and 114 rapid literature reviews for biodiversity across multiple land and water systems. Because of the broad scope and short timeframe of this project, we focused on reviewing synthesis, meta-analysis, and review papers and limited the number of sources searched for relevant evidence (Lagisz et al. 2022).

Search: We conducted a separate search for each unique combination of land system, management activity, and outcome. We searched for literature synthesizing primary research in two academic databases (Web of Science and CAB Abstracts) using a search string developed for each relationship and saved the first 50 studies—ranked by relevance to search term—from each database for screening. We used a standard structure for each search string but modified and tested it iteratively until the search results were relevant to the relationships. The standard structure included search terms for activity, outcome, land or water system, and synthesis and meta-analysis studies. The output was a maximum of 100 scientific studies returned by our search strings (Appendix B).

Screen: We screened the studies' titles and abstracts to determine if they were meta-analyses or syntheses of primary research reporting the effect of the relevant management activity on either carbon or biodiversity. Studies also needed to be conducted in the focal land or water system, compare the effect of the activity to a control site where the activity did not occur, and include data from the United States or relevant to the US context. If more than five papers met these initial criteria, we selected the five most relevant papers for the relationship based on the specific variables reported, the geographic scope, and the recency of the paper. If fewer than five papers met the initial criteria, then we occasionally included results from a non-US relevant context, from a study with no control, or from a primary literature study (see Appendix C for more detail). The narrative summaries of the results describe where these exceptions were made. The output of this step was five or fewer relevant papers for coding.

Code: We extracted relevant information about the effect of the management activity on carbon or biodiversity and recorded it in a database. Information about the number of primary research papers synthesized in the meta-analysis or review, other variables influencing the relationship, and additional details about the paper were also recorded. We categorized each recorded result as representing a positive (e.g., increase in carbon sequestration or decrease in carbon emissions; increased biodiversity), negative (e.g., decrease in carbon sequestration or increase in carbon emissions; decreased biodiversity), neutral, or mixed effect on carbon or biodiversity. The outputs were a database for carbon with a total of 356 rows and a database for biodiversity with a total of 434 rows, where each row represents a relationship, or the effect of a management activity on a particular carbon pool or biodiversity taxa in a land or water system.

Figure 1. The four main steps in our rapid literature review process.



Note: Each step in a teal box generated the output listed below it in a white box, which fed into the following step.

Summarize: We identified the overall direction of effect (positive, negative, neutral, or mixed) by tallying the results of all coded papers for a relationship, weighted by the number of primary research papers synthesized in each paper. We flagged coded papers that were likely to use the same primary studies as inputs, and in these cases aimed to use only the more recent one in the summary process. At least two-thirds of results had to agree on a direction of effect for that direction to be selected; if less than two-thirds of results agreed, a "mixed" direction of effect was assigned.[1] The output was a table of arrows for each land or water system, containing a row of arrows for each individual activity examined with a narrative summary and reference list.

For the biodiversity results, we developed a program in R to process and analyze the database of coded relationships. This program allows us to generate results in a consistent and transparent manner and to update results automatically as new studies are added to our database. The program also helps to identify coding errors, gaps, and biases. We used R packages for cleaning data (e.g., the collection of packages within tidyverse) and plotting tables and figures (e.g., ggplot). We ran quality control tests to identify missing or incorrect data within coded relationships (such as data for sample sizes) and recoded papers when needed to generate a complete dataset.

We report the number and types of studies that contributed to each result directly below each arrow in our results tables as an indicator of confidence in the results. For carbon, we also classified our confidence in each result based on an expert assessment by the people who coded the constituent papers. Confidence ratings were adapted from the IPBES confidence matrix (IPBES 2016) based on the quantity and quality of evidence found and the level of agreement within the evidence.

Expert Workshops

After the rapid literature reviews were completed, we held a series of virtual workshops to obtain expert input on our process and preliminary results. Separate workshops were held for carbon and biodiversity discussions. See Appendix D for a list of experts who provided input at workshops or by email. Workshop participants provided feedback on the pros and cons of our approach and suggested potential future improvements to the methodology. They also reviewed the preliminary results for a subset of the management activities identified as priority by USDA and identified where the results aligned or did not align with their knowledge. In many cases, participants suggested additional studies to include in the summary and highlighted gaps or limitations in the current body of research. They also provided information about effects not captured in the literature review, such as direct effects of a management activity (e.g., reduced biomass due to timber harvest). Following the workshops, the project team used information from expert workshops to update the preliminary results, compile research gaps and limitations, and develop ideas for extensions and improvements for a potential second phase of this project. Carbon workshop participants highlighted the importance of understanding the timeframe over which studies took place after a management action was initiated and the control condition to which the effects of the management action was compared, so both of those elements were added to the carbon results.

[1] For example, if meta-analyses including 40 primary research papers showed a positive effect and 10 showed a negative effect, then we assigned a positive direction of effect. However, if meta-analyses including 30 primary research papers showed a positive effect and 20 showed a negative effect, then we assigned a mixed direction of effect.

FINDINGS

Results for Biodiversity and Carbon

For each land/water system, we summarize evidence in a table with arrows showing the direction of effects of each management activity on biodiversity or carbon. Arrows are provided for individual pools of carbon and taxonomic groups of species, according to the available evidence. For biodiversity, an overall arrow is also included, which is assigned using the same rules, but based on the pooled relationships across all assessed taxa.

In addition to these summary tables for each land/water system, we provide a separate summary for each relationship, including a single row of results arrows, as well as a narrative summary. The narrative summary provides additional details and context from the literature, including descriptions of key factors that influence the relationship, written by coders and augmented by our expert workshops. In the carbon results, details about the control condition and timeframe of studies are also provided alongside the narrative summary. We also provide references to all literature reviewed in the synthesis.

These results are presented in Appendices E and F. Click on the name of any management activity in Tables 1 and 2 to see results for specific management actions..

Table 1. Management actions included in the biodiversity and carbon results, land systems

	Land System		
	Working and Multiple Use Forests	**Croplands**	**Grasslands**
Biodiversity Results	Fertilization Grazing Herbicides Invasive species management Prescribed burn Reforestation Restoration from mining Riparian area management Soil stabilization Thinning Timber harvest Wildlife management	Constructed wetland Cover cropping Crop selection and diversification Fallow Fertilization for agriculture Herbicides for agriculture Land-use change Pesticides Prescribed burn Reforestation Riparian area management	Fertilization Grazing Habitat management Herbicides Invasive species management Oil and gas extraction Prescribed burn Reforestation
	Working and Multiple Use Forests	**Croplands**	**Grassland**
Carbon Results	Prescribed fire Thinning Herbicide application Timber harvest Reforestation Fertilization Grazing	Fertilizer management Herbicides Cover crops Crop selection and diversification Fallow Drainage management Reduced and no-tillage Biochar Land-use change to cropland Land-use change from cropland Reforestation Constructed wetland	Grazing (continuous and improved) Livestock management (nitrogen inhibitor application) Restoration Prescribed fire Fertilization

Click on the name of any management activity to see results for specific management actions.

Table 2. Management actions included in the biodiversity and carbon results, water systems

	Water system		
	Freshwater	**Coastal**	**Marine**
Biodiversity Results	Aquaculture Boating and shipping Diking Fish passage Green infrastructure Habitat restoration Recreation and tourism Spiritual experiences Subsistence harvest	Anchoring Aquaculture Boating and shipping Coastal development Dam removal Diking Dredging Fish passage Fishing Gray infrastructure Green infrastructure Habitat restoration Mining Oil and gas extraction Piers and docks Restoration River diversion Water discharge	Anchoring Aquaculture Boating and shipping Dredging Fishing Offshore wind Protected areas

	Freshwater	**Coastal**	**Marine**
Carbon Results	Aquaculture Draining and converting wetlands Extractive water use (wetland draining) Dams and reservoirs Green infrastructure (freshwater wetlands) Green infrastructure (peatlands) Restoration (wetlands) Restoration (peatlands) Wildlife management (dam removal)	Habitat restoration Fishing Aquaculture River diversion Anchoring Avoided habitat loss (salt marsh, mangrove, seagrass) Dredging Development Diking	Aquaculture Oil and gas extraction Protection Mining

Click on the name of any management activity to see results for specific management actions.

When interpreting these results, it is important to keep in mind that they emphasize the general effect of a management activity on carbon or biodiversity at the expense of site-specific variability. The effect in an individual location can be very different from the general effect shown in the results. Make sure to read the accompanying narrative summaries for additional information about how spatial, regional, environmental, and temporal context may influence the relationship; do not rely solely on the arrows in the results table to draw conclusions about the relationship.

The results are derived from a detailed coding database for each outcome (i.e., biodiversity and carbon storage). These coding databases record details on each study included in the assessment for anyone who would like more specific information than is available in the results documents, as well as information on the specific search strings used for the literature reviews.

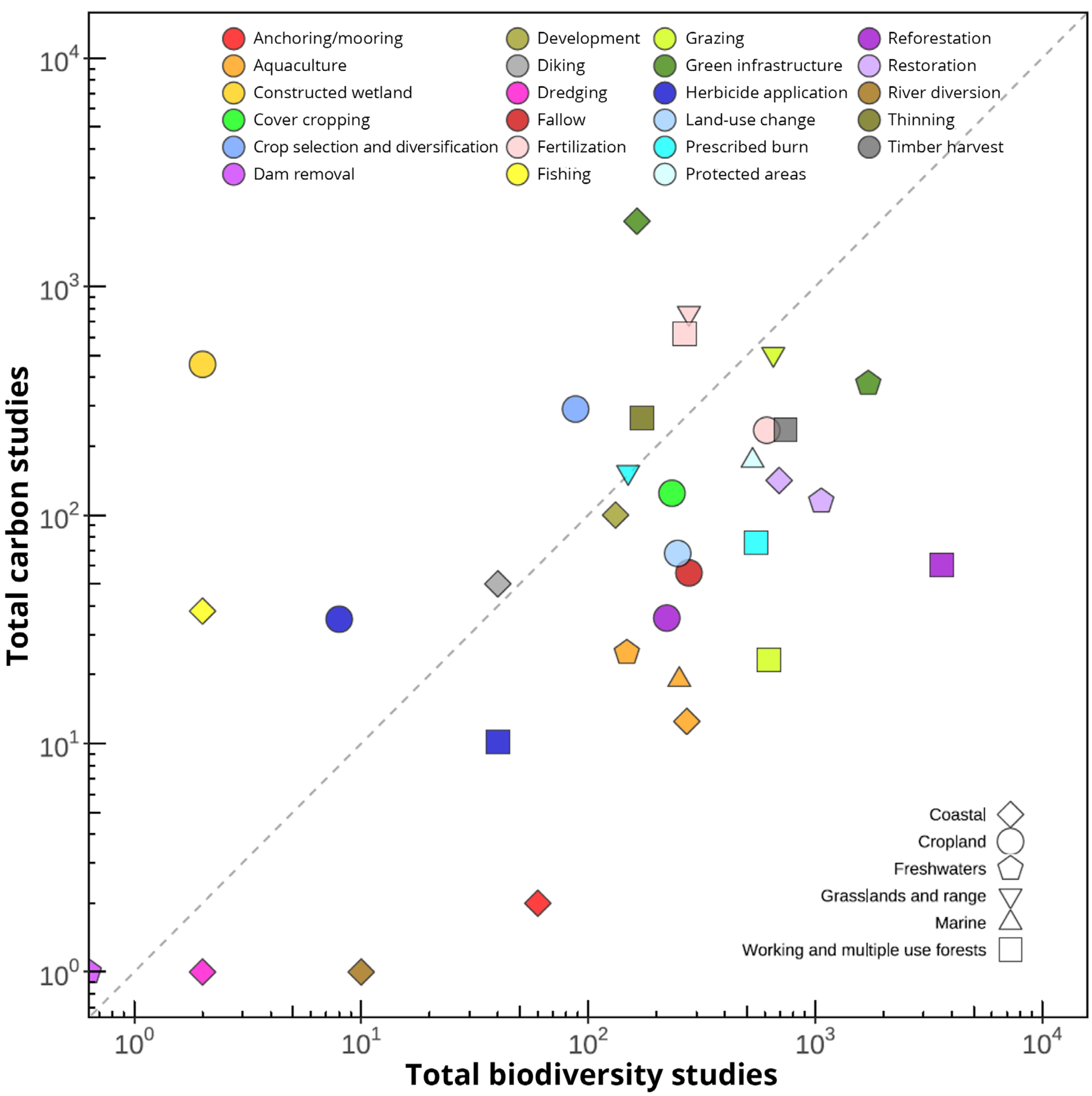
Comparing Biodiversity and Carbon

In addition to assessing evidence of how management actions impact biodiversity and carbon separately, we performed some preliminary comparisons between the two outcomes of interest. First, we compared the number of studies included in our review for biodiversity and carbon to assess whether the compiled evidence base is equally large for the two outcomes. Second, we compared the direction of impacts on biodiversity and carbon, to understand whether management activities have similar effects on the two outcomes.

The numbers of studies included in our review are summarized in Figure 2. Most relationships are supported by 10 or more studies for both biodiversity and carbon. Only seven relationships were represented by fewer than 10 studies for either outcome (e.g., constructed wetlands in cropland systems). The majority of symbols are below the diagonal dashed line, showing that our review tended to include more studies for biodiversity than for carbon. However, for 11 relationships, carbon studies outnumbered biodiversity studies (e.g., green infrastructure in coastal systems). Importantly, this figure reports the number of primary studies included in the synthesis papers we were able to review.

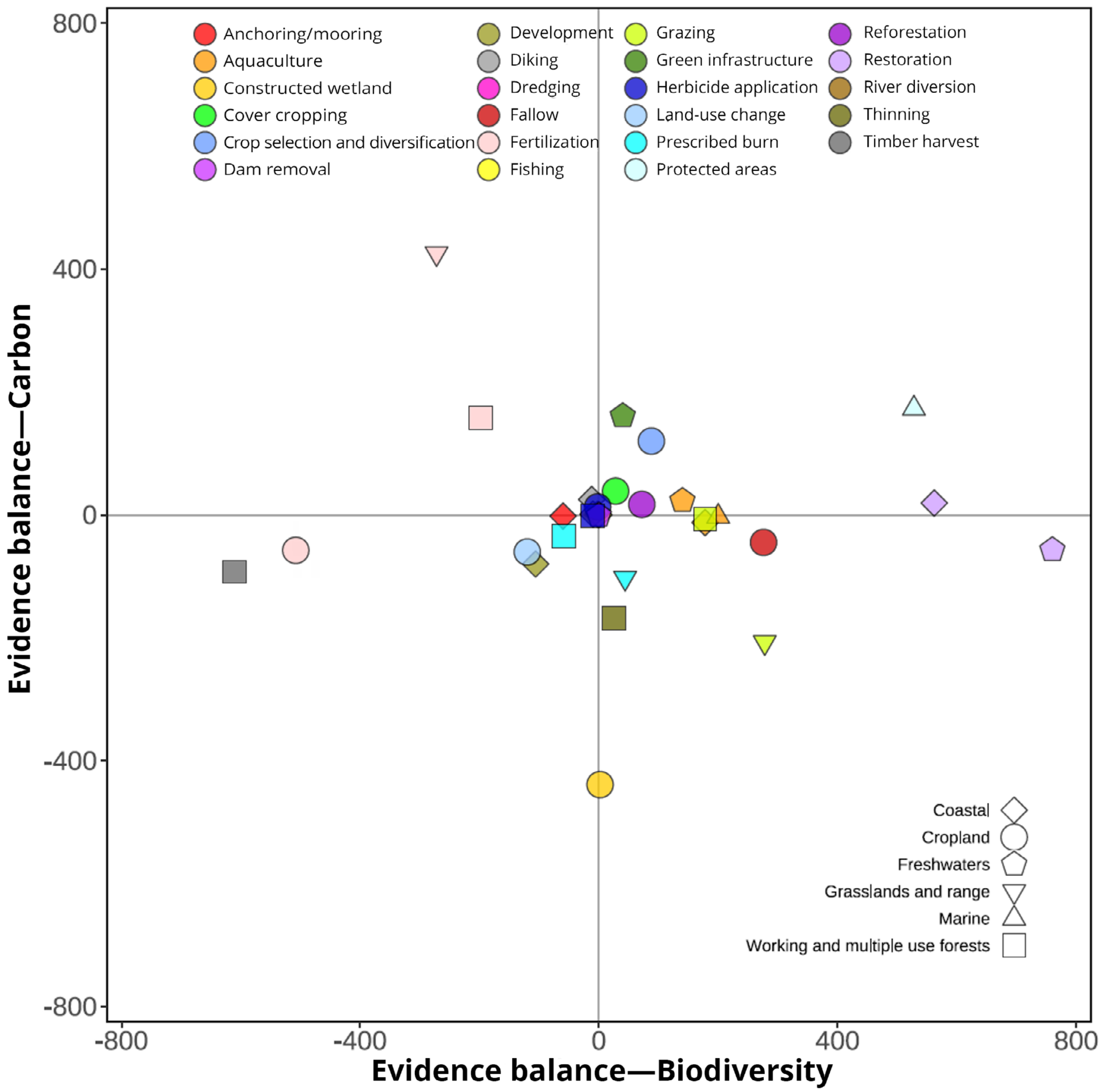
The agreement in direction of impacts between biodiversity and carbon is summarized in Figure 3. Most relationships cluster in the middle, indicating a mix of positive and negative impacts reported in the included studies. Relationships in the upper right quadrant have positive evidence balance (i.e., more positive than negative impacts reported) for both biodiversity and carbon. Examples include green infrastructure in freshwater systems and protected areas in marine systems. Relationships in the lower left quadrant have negative evidence balance for both biodiversity and carbon (e.g., timber harvest in forests, fertilization in croplands and land conversion to croplands, and development in coastal systems). The lower right and upper left quadrants indicate potential tradeoffs, where a given management activity may benefit one outcome but not the other. Relationships in the lower right quadrant include grazing in grassland systems, restoration in freshwater systems, fallow in cropland systems, prescribed burn in grasslands, and thinning in forests. Relationships in the upper left quadrant include fertilization in grasslands and forests. Again, this figure summarizes results from the papers we were able to review; adding more studies is likely to shift the position of symbols in Figure 3.

Figure 2. Comparing compiled evidence for biodiversity and carbon outcomes



Note: Each symbol represents a relationship (i.e., a unique combination of management activity and land/water system) and indicates the number of primary studies included in our review for biodiversity (horizontal axis) and carbon (vertical axis). Symbol shapes represent land/water systems, and colors represent management activities. The dashed diagonal line indicates equal numbers of studies for biodiversity and carbon outcomes.

Figure 3. Comparing impacts between biodiversity and carbon outcomes



Note: Each symbol represents a relationship (i.e., a unique combination of management activity and land/water system) and indicates the balance of evidence for biodiversity (horizontal axis) and carbon (vertical axis). Balance of evidence is defined as the number of positive impacts reported minus the number of negative impacts reported (mixed and neutral impacts are ignored). On each axis, 0 represents an equal number of positive and negative impacts. Symbol shapes represent land/water systems, and colors represent management activities. Note that two relationships with extreme values are not shown in this figure: coastal—green infrastructure (neutral evidence balance for biodiversity; positive for carbon) and forests—reforestation (positive evidence balance for biodiversity; neutral for carbon).

Suitability of Synthesis Literature for this Assessment

This process highlighted several considerations about the suitability of existing scientific literature, in particular syntheses and meta-analyses, for assessing the effects of management activities on carbon and biodiversity across the wide range of land and water systems and environmental conditions found in the United States. Published research tends to focus on effects within an individual land or water system, while impacts of management activities often cross system boundaries, such as GHG emissions occurring after fertilizer from croplands moves into freshwater systems. In addition, research frequently considers only one management intervention at a time, missing potential interactions between activities used in combination. This is particularly important for agricultural activities (e.g., cover cropping, fertilization, crop selection and diversification), which are rarely used on their own. The period of study after a management activity occurs is often limited compared to the timeframe during which effects can occur. Short-term effects on carbon or biodiversity may differ in magnitude or direction from medium- or long-term effects. In general, the limited scope (in land system, management activity, and time) of many studies obscures the more complex effects that management may cause, including trade-offs in effects across time and space.

Another issue arises from synthesis papers' tendency to report effects in terms of a percent change under the management activity compared to the control or the effect size of the management activity. These relative measures of change do not allow for direct comparison of results among carbon pools, which represent different proportions of the total carbon in the system, or comparison of biodiversity results among taxa, which have different numbers of species under control conditions. This precludes the assessment of the magnitude of change caused by a management activity on carbon or biodiversity unless all of the individual effects (among carbon pools or taxa) have the same direction. Quantitative synthesis of results across multiple meta-analyses would be required to make these assessments.

LIMITATIONS

Our rapid literature review and expert input approach allowed the project team to assess a broad range of management activities within a limited time frame, but also created some limitations that should be kept in mind when using the results.

The limited number of papers screened for each relationship may introduce bias by relying on academic databases to identify the most relevant papers, likely excluding gray literature and more recent studies that are less highly cited than older studies. Further, coding only five papers per relationship may bias results for well-studied fields such as agricultural management, for which there are many meta-analyses available. Our focus on syntheses of published literature means that the evidence summarized does not reflect the potential for climate change to alter the relationship between management activities and carbon or biodiversity in the future.

We did not evaluate the quality of syntheses or meta-analyses, so we do not have a standardized way to assess quality of evidence across relationships or compare the quality of evidence available for different management activities. In addition, this approach does not capture information about the intensity of management activities (e.g., the degree of forest thinning or the application rate of fertilizers), the magnitude of the effect of an activity on biodiversity or carbon, or thresholds observed for effects on these outcomes.

Finally, our approach is based on published scientific literature and expert input. It does not capture multiple sources of evidence, ways of knowing, or values for nature. Expert and community input would be strengthened by including more diverse perspectives and lived experiences.

FUTURE RESEARCH DIRECTIONS

We identified potential areas for future research, based on expert workshops and discussions of results from this phase of work.

Extend our approach to capture additional types of evidence. There are several ways we could expand our approach to capture more evidence to make the results more robust and cover a broader set of relevant management activities and land and water systems. The rapid literature review could be expanded to include more gray literature, government reports, additional studies based on recommendations from experts, and traditional sources of knowledge. This could occur across all activities, or only for targeted activities determined to be of high interest.

Add more management activities or specific ecosystem types. Expanding the set of activities covered (e.g., for fishing, include the subcategories of bottom trawling, gill netting, hook and line, etc.) and/or the set of land and water systems covered (e.g., expand to include lakes, working waters, or urban lands) to provide more specific information about management impacts on biodiversity and carbon.

Include information on magnitude of effect from the scientific literature, where possible. The initial assessment extracted targeted information from the scientific literature to rapidly review studies across many activities. To provide the best possible decision-relevant information, there could be value in adding more detailed information from the already-reviewed studies. In particular, if the data are available, assessing the magnitude of the effect of each activity on biodiversity and carbon would allow comparison across activities and better understanding of the overall effect of an activity where it is reported separately for different carbon pools or taxa. This information could be used to identify priorities for future research and inform federal processes focusing on the most impactful activities. Details on the intensity of the activity, thresholds, baselines used for comparisons, and how effects vary over time would also be important to consider as part of the magnitude assessment.

Develop a more robust system for determining confidence levels. In future phases of work, it will be important to settle on a common, defensible approach to evaluating the quality of evidence underlying each arrow, the quantity of evidence available, and the agreement among sources of evidence. The importance of doing this depends in part on how the information will be used. We could conduct more rigorous sensitivity analyses to test the robustness of our results, or further develop confidence levels through a Delphi method comparing results with expert insights.

Build a dynamic framework, dataset, and library to enable future updates. To grow the framework and create a dynamic platform to which others could contribute, we could expand our R code, written originally for the biodiversity outcomes, to automate the analysis for both biodiversity and carbon. This code performs all data cleaning, merging, tallying, analysis and graphic presentation in a transparent and repeatable form. Expanding to carbon would allow more consistent reporting between the two outcomes, would make error checking and correction more systematic, and would allow us to update findings in real time as new papers are assessed and coded. We could also design a user-friendly portal for accessing and exploring the data, and a way for others to easily contribute additional literature, with robust systems for quality assurance.

Engage experts and communities on how different management actions impact equitable access to nature and its benefit. Management activities affect people in many ways. Decisions about where different types of management activities occur can create, perpetuate, or alleviate inequitable conditions; for example, by determining where economic opportunities from timber harvest are available. In addition, impacts of management activities can affect different groups of people in different ways. Low-income communities may experience greater health impacts from smoke from prescribed burns if they are more likely to work outside and have less access to healthcare than higher-income communities. Because of these diverse impacts, it was not feasible to use a rapid literature review approach for equity similar to that used for assessing effects on carbon and biodiversity. An initial step to consider the equity effects of management actions is to develop a framework to identify what kind of information is needed and how it could be compiled. This would involve hosting discussions, convening environmental justice and equity scholars and practitioners, and engaging communities on this topic.

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APPENDIX A: LISTS OF MANAGEMENT ACTIVITIES INCLUDED IN RAPID LITERATURE REVIEWS

The following tables (A1–A4) show all management activities included in literature reviews. For activities listed under gaps, our search and screen methods did not lead to enough quality syntheses or meta-analyses to generate results. Clicking on an activity name in the preliminary results row of any of the tables will bring you to the results summary for that activity and land system.

Table A1. Management activities for land systems included in biodiversity literature review

	Land System		
	Working and Multiple Use Forests	**Croplands**	**Grasslands***
Preliminary Results	Fertilization Grazing Herbicides Invasive species management Prescribed burn Reforestation Restoration from mining Riparian area management Soil stabilization Thinning Timber harvest Wildlife management	Constructed wetland Cover cropping Crop selection and diversification Fallow Fertilization for agriculture Herbicides for agriculture Land-use change Pesticides Prescribed burn Reforestation Riparian area management	Fertilization Grazing Habitat management Herbicides Invasive species management Oil and gas extraction Prescribed burn Reforestation
Gaps	Mining Oil and gas extraction	Fertilization for restoration Herbicides for restoration Water extraction	Grazing infrastructure Mining Wildlife management

*The term "grasslands" can include both planted croplands and grazed pastures as well as perennial grasslands. We focus on perennial grasslands that may or may not be grazed by livestock. Croplands are considered as a separate land system.

Table A2. Management activities for water systems included in biodiversity literature review

	Water System		
	Freshwater	**Coastal**	**Marine**
Preliminary Results	Aquaculture Boating and shipping Diking Fish passage Green infrastructure Habitat restoration Recreation and tourism Spiritual experiences Subsistence harvest	Anchoring Aquaculture Boating and shipping Coastal development Dam removal Diking Dredging Fish passage Fishing* Gray infrastructure Green infrastructure Habitat restoration Mining Oil and gas extraction Piers and docks Restoration River diversion Water discharge	Anchoring Aquaculture Boating and shipping Dredging Fishing* Offshore wind Protected areas
Gaps	Dredging Filling Piers and docks River diversion Water discharge	Filling Public access	Habitat restoration

* Fishing includes a set of more specific activities that may be examined in future phases of this work but that were excluded in this phase due to time constraints, including:

- Bottom trawling
- Gill netting
- Longlining
- Trolling
- Traps and pots
- Nets
- Hook and line
- Spearfishing

Table A3. Management activities for land systems included in carbon literature review

	Land System		
	Working and Multiple Use Forests	**Croplands**	**Grasslands***
Preliminary Results	Prescribed fire Thinning Herbicide application Timber harvest Reforestation Fertilization Grazing	Fertilizer management Herbicides Cover crops Crop selection and diversification Fallow Drainage management Reduced and no-tillage Biochar Land-use change to cropland Land-use change from cropland Reforestation Constructed wetland	Grazing (continuous and improved) Livestock management (nitrogen inhibitor application) Restoration Prescribed fire Fertilization
Gaps	Invasive species management Soil stabilization Riparian buffer	Riparian buffers Prescribed burn Extractive water use	Invasive species management Riparian buffer Herbicide

*The term “grasslands” can include both planted croplands and grazed pastures as well as perennial grasslands. We focus on perennial grasslands that may or may not be grazed by livestock. Croplands are considered as a separate land system.

Table A4. Management activities for water systems included in carbon literature review

	Water System		
	Freshwater	**Coastal**	**Marine**
Preliminary Results	Aquaculture Draining and converting wetlands Extractive water use (wetland draining) Dams and reservoirs Green infrastructure (freshwater wetlands) Green infrastructure (peatlands) Restoration (wetlands) Restoration (peatlands) Wildlife management (dam removal)	Habitat restoration Fishing Aquaculture River diversion Anchoring Avoided habitat loss (salt marsh, mangrove, seagrass) Dredging Development Diking	Aquaculture Oil and gas extraction Protection Mining
Gaps	Boating and shipping Dredging Filling Dikes and levees Piers/docks/jetties/boat ramps Gray infrastructure: pilings Mineral extraction Water discharge	Boating/shipping Filling Thin-layer sediment placement Dam removal Mining Oil and gas extraction Water discharge Gray infrastructure Green infrastructure (oyster reef, dune, living shoreline)	Offshore wind energy Fishing Anchoring Restoration Boating/shipping Dredging

APPENDIX B: SEARCH STRINGS

Table B1. Search strings used in Web of Science and CAB Abstracts for rapid literature review

Land/Water System	Activity	Outcome	Search String
Coastal	Anchoring	Biodiversity	(coast* OR estuar* OR bay* OR nearshore* OR wetland* OR marsh*) AND ("boat anchor*" OR anchoring OR moor*) AND (biodiversity OR "biological diversity" OR "bio-diversity" OR "species richness") AND (review OR meta-analysis OR "meta analysis")
Coastal	Anchoring	Biodiversity	(coast* OR estuar* OR bay* OR nearshore* OR wetland* OR marsh*) AND ("boat anchor*" OR anchoring OR moor*) AND (biodiversity OR "biological diversity" OR "bio-diversity" OR "species richness")
Coastal	Aquaculture	Biodiversity	(biodiversity OR "biological diversity" OR "bio-diversity" OR "species richness") AND (aquaculture OR "net pen*" OR "fish farm" OR mariculture) AND (coast* OR estuar* OR bay* OR nearshore* OR wetland* OR marsh*) AND (review OR meta-analysis OR "meta analysis")
Coastal	Boating and Shipping	Biodiversity	(biodiversity OR "biological diversity" OR "bio-diversity" OR "species richness") AND (boat* OR ship* OR vessel) AND (coast* OR estuar* OR bay* OR nearshore* OR wetland* OR marsh*) AND (review OR meta-analysis OR "meta analysis")
Coastal	Coastal habitat restoration	Biodiversity	(restor*) AND (biodiversity OR "biological diversity" OR "bio-diversity" OR "species richness") AND (coast* OR estuar* OR bay* OR nearshore* OR wetland* OR marsh*) AND (review OR meta-analysis OR "meta analysis")
Coastal	Dam removal	Biodiversity	("dam remov*") AND (biodiversity OR "biological diversity" OR "bio-diversity" OR "species richness") AND (coast* OR estuar* OR bay* OR nearshore* OR wetland* OR marsh*) AND (review OR meta-analysis OR "meta analysis")
Coastal	Development	Biodiversity	("coastal development" OR "coastal construction" OR "coastal building") AND (biodiversity OR "biological diversity" OR "bio-diversity" OR "species richness") AND (coast* OR estuar* OR bay* OR nearshore* OR wetland* OR marsh*) AND (review OR meta-analysis OR "meta analysis")
Coastal	Diking	Biodiversity	(dike OR embankment OR "sea wall" OR seawall OR impoundment OR "tidal restrict*") AND (biodiversity OR "biological diversity" OR "bio-diversity" OR "species richness") AND (coast* OR estuar* OR bay* OR nearshore* OR wetland* OR marsh*) AND (review OR meta-analysis OR "meta analysis")

Land/Water System	Activity	Outcome	Search String
Coastal	Diking	Biodiversity	(dike OR embankment OR "sea wall" OR seawall OR impoundment OR "tidal restrict*") AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (coast* OR estuar* OR bay* OR nearshore* OR wetland* OR marsh*)
Coastal	Dredging	Biodiversity	dredg* AND sediment AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (coast* OR estuar* OR bay* OR nearshore* OR wetland* OR marsh*) AND (review OR meta-analysis OR "meta analysis") NOT fish*
Coastal	Dredging	Biodiversity	dredg* AND sediment AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (coast* OR estuar* OR bay* OR nearshore* OR wetland* OR marsh*) NOT fish*
Coastal	Filling	Biodiversity	fill* AND sediment AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (coast* OR estuar* OR bay* OR nearshore* OR wetland* OR marsh*) AND (review OR meta-analysis OR "meta analysis")
Coastal	Filling	Biodiversity	fill* AND sediment AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (coast* OR estuar* OR bay* OR nearshore* OR wetland* OR marsh*)
Coastal	Fish Passage	Biodiversity	("fish pass*" OR "fish ladder" OR fishway* OR "fish screen*") AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (coast* OR estuar* OR bay* OR nearshore* OR wetland* OR marsh*) AND (review OR meta-analysis OR "meta analysis")
Coastal	Fishing	Biodiversity	(fish* OR trawl* OR dredg* OR longlin* OR gillnet* OR "purse seine*") AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (coast* OR estuar* OR bay* OR nearshore* OR wetland* OR marsh*) AND (review OR meta-analysis OR "meta analysis")
Coastal	Fishing	Biodiversity	(fish* OR trawl* OR dredg* OR longlin* OR gillnet* OR "purse seine*") AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (coast* OR estuar* OR bay* OR nearshore* OR wetland* OR marsh*)

Land/Water System	Activity	Outcome	Search String
Coastal	Gray Infrastrusture	Biodiversity	("gray infrastructure" OR "sea wall*" OR seawall* OR berm* OR "flood gate*" OR dike* OR breakwater* OR revetment* OR bulkhead*) AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (coast* OR estuar* OR bay* OR nearshore* OR wetland* OR marsh*) AND (review OR meta-analysis OR "meta analysis")
Coastal	Green Infrastructure	Biodiversity	(build OR built OR creat* OR restor*) AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (coast* OR estuar* OR bay* OR nearshore* OR wetland* OR marsh*) AND (review OR meta-analysis OR "meta analysis")
Coastal	Habitat Restoration	Biodiversity	(restor*) AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (coast* OR estuar* OR bay* OR nearshore* OR wetland* OR marsh*) AND (review OR meta-analysis OR "meta analysis")
Coastal	Mining	Biodiversity	(mining) AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (coast* OR estuar* OR bay* OR nearshore* OR wetland* OR marsh*) AND (review OR meta-analysis OR "meta analysis")
Coastal	Oil and gas extraction	Biodiversity	(oil OR gas) AND (extraction OR drilling OR frack*) AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (coast* OR estuar* OR bay* OR nearshore* OR wetland* OR marsh*) AND (review OR meta-analysis OR "meta analysis")
Coastal	Piers, docks, jetty, boat ramp	Biodiversity	(pier* OR dock* OR jetty OR jetties OR "boat ramp*") AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (coast* OR estuar* OR bay* OR nearshore* OR wetland* OR marsh*) AND (review OR meta-analysis OR "meta analysis")
Coastal	Piers, docks, jetty, boat ramp	Biodiversity	(pier* OR dock* OR jetty OR jetties OR "boat ramp*") AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (coast* OR estuar* OR bay* OR nearshore* OR wetland* OR marsh*)
Coastal	Public access	Biodiversity	(visit* OR "public access" OR "public use") AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (coast* OR estuar* OR bay* OR nearshore* OR wetland* OR marsh*)

Land/Water System	Activity	Outcome	Search String
Coastal	Public access	Biodiversity	(recreat* OR touris* OR ecotouris* OR visit* OR "public access" OR "public use") AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (coast* OR estuar* OR bay* OR nearshore* OR wetland* OR marsh*)
Coastal	Restoration (thin layer sediment placement)	Biodiversity	("sediment plac*" OR "thin layer" OR "sediment deposition") AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (coast* OR estuar* OR bay* OR nearshore* OR wetland* OR marsh*) AND (review OR meta-analysis OR "meta analysis")
Coastal	Restoration (thin layer sediment placement)	Biodiversity	("sediment plac*" OR "thin layer" OR "sediment deposition") AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (coast* OR estuar* OR bay* OR nearshore* OR wetland* OR marsh*)
Coastal	River diversion	Biodiversity	("river div*") AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (coast* OR estuar* OR bay* OR nearshore* OR wetland* OR marsh*) AND (review OR meta-analysis OR "meta analysis")
Coastal	Water discharge	Biodiversity	("water discharge" OR "wastewater discharge" OR "agricultural runoff" OR "stormwater discharge") AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (coast* OR estuar* OR bay* OR nearshore* OR wetland* OR marsh*) AND (review OR meta-analysis OR "meta analysis")
Cropland	Constructed wetland	Biodiversity	(“constructed wetland*” OR “treatment wetland*” OR “artificial wetland*”) AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (cropland OR agricultur*) AND (review OR meta-analysis OR "meta analysis")
Cropland	Constructed wetland	Biodiversity	(“constructed wetland*” OR “treatment wetland*” OR “artificial wetland*”) AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (cropland OR agricultur*)
Cropland	Cover cropping	Biodiversity	"cover crop*" AND (biodiversity OR "biological diversity") AND (cropland OR agricultur*) AND (review OR meta-analysis OR "meta analysis")
Cropland	Crop selection and diversification	Biodiversity	"crop selection" OR "crop divers*" AND (biodiversity OR "biological diversity") AND (cropland OR agricultur*) AND (review OR meta-analysis OR "meta analysis")

Land/Water System	Activity	Outcome	Search String
Cropland	Extractive water use	Biodiversity	("extractive water use" OR "water withdraw*" OR "water extract*" OR "groundwater extract*" OR aquifer) AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (cropland OR agricultur*) AND (review OR meta-analysis OR "meta analysis")
Cropland	Extractive water use	Biodiversity	("extractive water use" OR "water withdraw*" OR "water extract*" OR "groundwater extract*" OR aquifer) AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (cropland OR agricultur*)
Cropland	Fallow	Biodiversity	(fallow* OR "set-aside" OR "set aside") AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (cropland OR agricultur*) AND (review OR meta-analysis OR "meta analysis")
Cropland	Fertilization	Biodiversity	fertiliz* AND (biodiversity OR "biological diversity") AND (cropland OR agricultur*) AND (review OR meta-analysis OR "meta analysis")
Cropland	Fertilization (restoration)	Biodiversity	(fertiliz* AND restor*) AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (cropland OR agricultur*) AND (review OR meta-analysis OR "meta analysis")
Cropland	Fertilization (restoration)	Biodiversity	(fertiliz* AND restor*) AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (cropland OR agricultur*)
Cropland	Herbicide application	Biodiversity	herbicid* AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (cropland OR agricultur*) AND (review OR meta-analysis OR "meta analysis")
Cropland	Herbicide application	Biodiversity	herbicid* AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (cropland OR agricultur*)
Cropland	Herbicide application (restoration)	Biodiversity	(herbicid* AND restor*) AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (cropland OR agricultur*) AND (review OR meta-analysis OR "meta analysis")
Cropland	Herbicide application (restoration)	Biodiversity	(herbicid* AND restor*) AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (cropland OR agricultur*)

Land/Water System	Activity	Outcome	Search String
Cropland	Land-Use Change	Biodiversity	(“land use change*” OR "land-use change*" OR "land cover change*" OR "land-cover change*" OR conversion) AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (cropland OR agricultur*) AND (review OR meta-analysis OR "meta analysis")
Cropland	Pesticide	Biodiversity	pesticid* AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (cropland OR agricultur*) AND (review OR meta-analysis OR "meta analysis")
Cropland	Prescribed burn	Biodiversity	("prescribed burn*" OR "prescribed fire*" OR "managed fire*" OR "controlled burn*") AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (cropland OR agricultur*) AND (review OR meta-analysis OR "meta analysis")
Cropland	Prescribed burn	Biodiversity	("prescribed burn*" OR "prescribed fire*" OR "managed fire*" OR "controlled burn*") AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (cropland OR agricultur*)
Cropland	Reforestation	Biodiversity	(reforestation OR afforestation OR "tree plant*" OR "forest restoration") AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (cropland OR agricultur*) AND (review OR meta-analysis OR "meta analysis")
Cropland	Riparian Area Management	Biodiversity	"riparian" AND (biodiversity OR "biological diversity") AND (cropland OR agricultur*) AND (review OR meta-analysis OR "meta analysis")
Freshwaters	Aquaculture	Biodiversity	(aquaculture* OR “fish farm*” OR aquafarm* OR pisciculture* OR “net pen*”) AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (freshwater* OR river* OR stream* OR lake* OR pond* OR wetland* OR peatland* OR marsh*) AND (review OR meta-analysis OR "meta analysis")
Freshwaters	Aquaculture	Biodiversity	(aquaculture* OR “fish farm*” OR aquafarm* OR pisciculture* OR “net pen*”) AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (freshwater* OR river* OR stream* OR lake* OR pond* OR wetland* OR peatland* OR marsh*)

Land/Water System	Activity	Outcome	Search String
Freshwaters	Boating and Shipping	Biodiversity	(boat* OR ship* OR vessel) AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (freshwater* OR river* OR stream* OR lake* OR pond* OR wetland* OR peatland* OR marsh*) AND (review OR meta-analysis OR "meta analysis")
Freshwaters	Boating and Shipping	Biodiversity	(boat* OR ship* OR vessel) AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (freshwater* OR river* OR stream* OR lake* OR pond* OR wetland* OR peatland* OR marsh*)
Freshwaters	Dam removal	Biodiversity	("dam remov*") AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (freshwater* OR river* OR stream* OR lake* OR pond* OR wetland* OR peatland* OR marsh*) AND (review OR meta-analysis OR "meta analysis")
Freshwaters	Dam removal	Biodiversity	("dam remov*") AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (freshwater* OR river* OR stream* OR lake* OR pond* OR wetland* OR peatland* OR marsh*)
Freshwaters	Diking	Biodiversity	(dike* OR levee*) AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (freshwater* OR river* OR stream* OR lake* OR pond* OR wetland* OR peatland* OR marsh*) AND (review OR meta-analysis OR "meta analysis")
Freshwaters	Diking	Biodiversity	(dike* OR levee*) AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (freshwater* OR river* OR stream* OR lake* OR pond* OR wetland* OR peatland* OR marsh*)
Freshwaters	Dredging	Biodiversity	dredg* AND sediment AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (freshwater* OR river* OR stream* OR lake* OR pond* OR wetland* OR peatland* OR marsh*) AND (review OR meta-analysis OR "meta analysis")
Freshwaters	Dredging	Biodiversity	dredg* AND sediment AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (freshwater* OR river* OR stream* OR lake* OR pond* OR wetland* OR peatland* OR marsh*)
Freshwaters	Filling	Biodiversity	fill* AND sediment AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (freshwater* OR river* OR stream* OR lake* OR pond* OR wetland* OR peatland* OR marsh*) AND (review OR meta-analysis OR "meta analysis")

Land/Water System	Activity	Outcome	Search String
Freshwaters	Filling	Biodiversity	fill* AND sediment AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (freshwater* OR river* OR stream* OR lake* OR pond* OR wetland* OR peatland* OR marsh*)
Freshwaters	Fish Passage	Biodiversity	("fish pass*" OR "fish ladder" OR fishway* OR "fish screen*") AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (freshwater* OR river* OR stream* OR lake* OR pond* OR wetland* OR peatland* OR marsh*) AND (review OR meta-analysis OR "meta analysis")
Freshwaters	Fish Passage	Biodiversity	("fish pass*" OR "fish ladder" OR fishway* OR "fish screen*") AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (freshwater* OR river* OR stream* OR lake* OR pond* OR wetland* OR peatland* OR marsh*)
Freshwaters	Green Infrastructure	Biodiversity	(build OR built OR creat* OR restor*) AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (freshwater* OR river* OR stream* OR lake* OR pond* OR wetland* OR peatland* OR marsh*) AND (review OR meta-analysis OR "meta analysis")
Freshwaters	Green Infrastructure	Biodiversity	(build OR built OR creat* OR restor*) AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (freshwater* OR river* OR stream* OR lake* OR pond* OR wetland* OR peatland* OR marsh*)
Freshwaters	Habitat Restoration	Biodiversity	(restor*) AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (freshwater* OR river* OR stream* OR lake* OR pond* OR wetland* OR peatland* OR marsh*) AND (review OR meta-analysis OR "meta analysis")
Freshwaters	Habitat Restoration	Biodiversity	(restor*) AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (freshwater* OR river* OR stream* OR lake* OR pond* OR wetland* OR peatland* OR marsh*)
Freshwaters	Piers, docks, jetty, boat ramp	Biodiversity	(pier* OR dock* OR jetty OR jetties OR “boat ramp*”) AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (freshwater* OR river* OR stream* OR lake* OR pond* OR wetland* OR peatland* OR marsh*) AND (review OR meta-analysis OR "meta analysis")

Land/Water System	Activity	Outcome	Search String
Freshwaters	Piers, docks, jetty, boat ramp	Biodiversity	(pier* OR dock* OR jetty OR jetties OR “boat ramp*”) AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (freshwater* OR river* OR stream* OR lake* OR pond* OR wetland* OR peatland* OR marsh*)
Freshwaters	Recreation and tourism	Biodiversity	(recreat* OR touris* OR ecotouris*) AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (freshwater* OR river* OR stream* OR lake* OR pond* OR wetland* OR peatland* OR marsh*) AND (review OR meta-analysis OR "meta analysis")
Freshwaters	River diversion	Biodiversity	("river div*") AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (freshwater* OR river* OR stream* OR lake* OR pond* OR wetland* OR peatland* OR marsh*) AND (review OR meta-analysis OR "meta analysis")
Freshwaters	River diversion	Biodiversity	("river div*") AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (freshwater* OR river* OR stream* OR lake* OR pond* OR wetland* OR peatland* OR marsh*)
Freshwaters	Spiritual or traditional experiences	Biodiversity	(spirit* OR religio* OR sacred OR ceremon* OR "cultural value*") AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (freshwater* OR river* OR stream* OR lake* OR pond* OR wetland* OR peatland* OR marsh*) AND (review OR meta-analysis OR "meta analysis")
Freshwaters	Spiritual or traditional experiences	Biodiversity	(spirit* OR religio* OR sacred OR ceremon* OR "cultural value*") AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (freshwater* OR river* OR stream* OR lake* OR pond* OR wetland* OR peatland* OR marsh*)
Freshwaters	Subsistence harvest	Biodiversity	(subsistence) AND (harvest* OR forag* OR gather* OR hunt* OR fish* OR trap*) AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (freshwater* OR river* OR stream* OR lake* OR pond* OR wetland* OR peatland* OR marsh*) AND (review OR meta-analysis OR "meta analysis")
Freshwaters	Water discharge	Biodiversity	("water discharge" OR "wastewater discharge" OR "agricultural runoff" OR "stormwater discharge") AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (freshwater* OR river* OR stream* OR lake* OR pond* OR wetland* OR peatland* OR marsh*) AND (review OR meta-analysis OR "meta analysis")

Land/Water System	Activity	Outcome	Search String
Freshwaters	Water discharge	Biodiversity	("water discharge" OR "wastewater discharge" OR "agricultural runoff" OR "stormwater discharge") AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (freshwater* OR river* OR stream* OR lake* OR pond* OR wetland* OR peatland* OR marsh*)
Grasslands and range	Fertilization (restoration)	Biodiversity	(fertiliz* AND restor*) AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (grassland* OR rangeland* OR pasture*) AND (review OR meta-analysis OR "meta analysis")
Grasslands and range	Grazing	Biodiversity	graz* AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (grassland* OR rangeland* OR pasture*) AND (review OR meta-analysis OR "meta analysis")
Grasslands and range	Habitat or vegetation management	Biodiversity	(“habitat management” OR “vegetation management”) AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (grassland* OR rangeland* OR pasture*) AND (review OR meta-analysis OR "meta analysis")
Grasslands and range	Habitat or vegetation management	Biodiversity	(habitat OR vegetation) AND management AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (grassland* OR rangeland* OR pasture*) AND (review OR meta-analysis OR "meta analysis")
Grasslands and range	Herbicide application (restoration)	Biodiversity	(herbicid* AND restor*) AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (grassland* OR rangeland* OR pasture*) AND (review OR meta-analysis OR "meta analysis")
Grasslands and range	Herbicide application (restoration)	Biodiversity	(herbicid* AND restor*) AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (grassland* OR rangeland* OR pasture*)
Grasslands and range	Infrastructure operation & management	Biodiversity	(pipeline* OR “permanent fenc*” OR “electric fenc” OR “stream cross*” OR laneway* OR “watering station*” OR gate* OR road* OR drain*) AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (grassland* OR rangeland* OR pasture*) AND (review OR meta-analysis OR "meta analysis")
Grasslands and range	Infrastructure operation & management	Biodiversity	(pipeline* OR “permanent fenc*” OR “electric fenc” OR “stream cross*” OR laneway* OR “watering station*” OR gate* OR road* OR drain*) AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (grassland* OR rangeland* OR pasture*)

Land/Water System	Activity	Outcome	Search String
Grasslands and range	Invasive Species Management	Biodiversity	("invasive species" OR "exotic species" OR "nonnative species" OR invasive) AND (control OR removal OR management) AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (grassland* OR rangeland* OR pasture*) AND (review OR meta-analysis OR "meta analysis")
Grasslands and range	Mining	Biodiversity	mining AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (grassland* OR rangeland* OR pasture*) AND (review OR meta-analysis OR "meta analysis")
Grasslands and range	Mining	Biodiversity	mining AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (grassland* OR rangeland* OR pasture*)
Grasslands and range	Oil and gas extraction	Biodiversity	(oil OR gas) AND (extraction OR drilling OR frack*) AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (grassland* OR rangeland* OR pasture*) AND (review OR meta-analysis OR "meta analysis")
Grasslands and range	Oil and gas extraction	Biodiversity	(oil OR gas) AND (extraction OR drilling OR frack*) AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (grassland* OR rangeland* OR pasture*)
Grasslands and range	Prescribed burn	Biodiversity	("prescribed burn*" OR "prescribed fire*" OR "managed fire*" OR "controlled burn*") AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (grassland* OR rangeland* OR pasture*) AND (review OR meta-analysis OR "meta analysis")
Grasslands and range	Reforestation	Biodiversity	(reforestation OR afforestation OR "tree plant*" OR "forest restoration") AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (grassland OR rangleland OR pasture) AND (review OR meta-analysis OR "meta analysis")
Grasslands and range	Wildlife management	Biodiversity	(“wildlife management” OR reintroduc* OR “population management” OR “disease management” OR culling OR transloc* OR "population control") AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (grassland* OR rangeland* OR pasture*) AND (review OR meta-analysis OR "meta analysis")

Land/Water System	Activity	Outcome	Search String
Marine	Anchoring	Biodiversity	(ocean* OR marin* OR maritime OR offshore OR EEZ) AND ("boat anchor*" OR anchoring OR "vessel anchor*" OR moor*) AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (review OR meta-analysis OR "meta analysis")
Marine	Aquaculture	Biodiversity	(ocean* OR marin* OR maritime OR offshore OR EEZ) AND (aquaculture OR "net pen*" OR "fish farm" OR mariculture) AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (review OR meta-analysis OR "meta analysis")
Marine	Boating and Shipping	Biodiversity	(ocean* OR marin* OR maritime OR offshore OR EEZ) AND (boat* OR ship* OR vessel) AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (review OR meta-analysis OR "meta analysis")
Marine	Dredging	Biodiversity	dredg* AND sediment AND (ocean* OR marin* OR maritime OR offshore OR EEZ) AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (review OR meta-analysis OR "meta analysis")
Marine	Dredging	Biodiversity	dredg* AND sediment AND (ocean* OR marin* OR maritime OR offshore OR EEZ) AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness")
Marine	Fishing	Biodiversity	(ocean* OR marin* OR maritime OR offshore OR EEZ) AND (fish* OR trawl* OR dredg* OR longlin* OR gillnet* OR "purse seine*") AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (review OR meta-analysis OR "meta analysis")
Marine	Habitat Restoration	Biodiversity	(restor*) AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (ocean* OR marin* OR maritime OR offshore OR EEZ) AND (review OR meta-analysis OR "meta analysis")
Marine	Habitat Restoration	Biodiversity	(restor*) AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (ocean* OR marin* OR maritime OR offshore OR EEZ)
Marine	Offshore wind	Biodiversity	(wind) AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (ocean* OR marin* OR maritime OR offshore OR EEZ) AND (review OR meta-analysis OR "meta analysis")

Land/Water System	Activity	Outcome	Search String
Marine	Protection	Biodiversity	(protect* OR "protected area" OR "reserve" OR "preserve" OR "no-take" OR park) AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND (ocean* OR marin* OR maritime OR offshore OR EEZ) AND (review OR meta-analysis OR "meta analysis")
Working and multiple use forests	Fuels Management	Biodiversity	effect AND ("prescribed burn*" OR "prescribed fire" OR "managed fire" OR "controlled burn*") AND (biodiversity) AND forest AND (review OR meta-analysis OR "meta analysis")
Working and multiple use forests	Fuels Management	Biodiversity	TS = (("prescribed burn*" OR "prescribed fire" OR "managed fire" OR "controlled burn*") AND (biodiversity OR "bio-diversity" OR "species richness") AND (review OR meta-analysis OR "meta analysis"))
Working and multiple use forests	Grazing	Biodiversity	graz* AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND forest AND (review OR meta-analysis OR "meta analysis")
Working and multiple use forests	Herbicide application	Biodiversity	herbicid* AND (biodiversity OR "species richness" OR "bio-diversity") AND forest AND (review OR meta-analysis OR "meta analysis")
Working and multiple use forests	Mining	Biodiversity	mining AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND forest AND (review OR meta-analysis OR "meta analysis")
Working and multiple use forests	Mining	Biodiversity	mining AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND forest
Working and multiple use forests	Oil and gas extraction	Biodiversity	(oil OR gas) AND (extraction OR drilling OR frack*) AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND forest AND (review OR meta-analysis OR "meta analysis")
Working and multiple use forests	Reforestation	Biodiversity	(reforestation OR afforestation OR "tree plant*" OR "forest restoration") AND (biodiversity OR "species richness" OR "bio-diversity" OR "biological diversity") AND forest AND (review OR meta-analysis OR "meta analysis")
Working and multiple use forests	Soil stabilization	Biodiversity	("soil stabilization" OR "erosion control") AND (biodiversity OR "species richness" OR "bio-diversity" OR "biological diversity") AND forest AND (review OR meta-analysis OR "meta analysis")
Working and multiple use forests	Thinning	Biodiversity	thin* AND forest AND (biodiversity OR "bio-diversity" OR "species richness") AND (review OR meta-analysis OR "meta analysis"))

Land/Water System	Activity	Outcome	Search String
Working and multiple use forests	Wildlife population management	Biodiversity	(“wildlife management” OR reintroduc* OR “population management” OR “disease management” OR culling OR transloc* OR "population control") AND (biodiversity OR “biological diversity” OR "bio-diversity" OR "species richness") AND forest AND (review OR meta-analysis OR "meta analysis")
Coastal	Anchoring	Carbon	effect AND carbon AND (coast* OR estuar* OR bay* OR nearshore* OR wetland) AND (“boat anchor*” OR anchoring OR moor*)
Coastal	Aquaculture	Carbon	effect AND (aquaculture OR “net pen*” OR “fish farm” OR mariculture) AND carbon AND (coast* OR estuar* OR bay* OR nearshore*) AND (review OR meta-analysis OR “meta analysis”)
Coastal	Boating and shipping	Carbon	effect AND (boat* OR ship* OR vessel) AND (carbon OR emission*) AND (coast* OR estuar* OR bay* OR nearshore* OR wetland) AND (review OR meta-analysis OR “meta analysis”)
Coastal	Boating and shipping	Carbon	(boat* OR ship* OR vessel) AND (carbon OR emission*) AND (coast* OR estuar* OR bay* OR nearshore* OR wetland) AND (review OR meta-analysis OR “meta analysis”)
Coastal	Dam removal	Carbon	effect AND (“dam remov*”) AND carbon AND (coast* OR estuar* OR bay* OR nearshore*) AND (review OR meta-analysis OR “meta analysis”)
Coastal	Development	Carbon	effect AND (“coastal development” OR “coastal construction” OR “coastal building”) AND carbon AND (coast* OR estuar* OR bay* OR nearshore*) AND (review OR meta-analysis OR “meta analysis”)
Coastal	Diking	Carbon	effect AND (dike OR embankment OR “sea wall” OR seawall OR impoundment OR “tidal restrict*”) AND carbon AND (coast* OR estuar* OR bay* OR nearshore*) AND (review OR meta-analysis OR “meta analysis”)
Coastal	Dredging	Carbon	effect AND dredg* AND sediment AND carbon AND (coast* OR estuar* OR bay* OR nearshore*) AND (review OR meta-analysis OR “meta analysis”) NOT fish*
Coastal	Filling	Carbon	effect AND fill* AND sediment AND carbon AND (coast* OR estuar* OR bay* OR marsh) AND (review OR meta-analysis OR “meta analysis”)
Coastal	Fishing	Carbon	effect AND (fish* OR trawl* OR dredg* OR longlin* OR gillnet* OR “purse seine*”) AND (carbon) AND (coast* OR estuar* OR bay* OR nearshore*) AND (review OR meta-analysis OR “meta analysis”)

Land/Water System	Activity	Outcome	Search String
Coastal	Gray infrastructure	Carbon	effect AND (“gray infrastructure” OR “sea wall*” OR seawall* OR berm* OR “flood gate*” OR dike* OR breakwater* OR revetment* OR bulkhead*) AND carbon AND (coast* OR estuar* OR bay* OR nearshore*) AND (review OR meta-analysis OR “meta analysis”)
Coastal	Green infrastructure	Carbon	effect AND (marsh OR “salt marsh” OR “tidal marsh”) AND (build OR built OR creat* OR restor*) AND carbon AND (coast* OR estuar* OR bay* OR nearshore*) AND (review OR meta-analysis OR “meta analysis”)
Coastal	Green infrastructure	Carbon	effect AND mangrove* AND (build OR built OR creat* OR restor*) AND carbon AND (coast* OR estuar* OR bay* OR nearshore*) AND (review OR meta-analysis OR “meta analysis”)
Coastal	Green infrastructure	Carbon	effect AND (“oyster reef*” OR oyster) AND (build OR built OR creat* OR restor*) AND carbon AND (coast* OR estuar* OR bay* OR nearshore*) AND (review OR meta-analysis OR “meta analysis”)
Coastal	Green infrastructure	Carbon	effect AND dune* AND (build OR built OR creat* OR restor*) AND carbon AND (coast* OR estuar* OR bay* OR nearshore*) AND (review OR meta-analysis OR “meta analysis”)
Coastal	Green infrastructure	Carbon	effect AND “living shoreline*” AND carbon AND (coast* OR estuar* OR bay* OR nearshore*) AND (review OR meta-analysis OR “meta analysis”)
Coastal	Green infrastructure	Carbon	effect AND (seagrass* OR “sea grass*”) AND (build OR built OR creat* OR restor*) AND carbon AND (coast* OR estuar* OR bay* OR nearshore*) AND (review OR meta-analysis OR “meta analysis”)
Coastal	Mining	Carbon	effect AND mining AND carbon AND (coast* OR estuar* OR bay* OR nearshore*) AND (review OR meta-analysis OR “meta analysis”)
Coastal	Oil and gas extraction	Carbon	effect AND (oil OR gas) AND (extraction OR drilling OR frack*) AND carbon AND (coast* OR estuar* OR bay* OR nearshore*) AND (review OR meta-analysis OR “meta analysis”)
Coastal	Piers, docks, jetties, boat ramps	Carbon	effect AND (pier* OR dock* OR jetty OR jetties OR “boat ramp*”) AND carbon AND (coast* OR estuar* OR bay* OR nearshore*) AND (review OR meta-analysis OR “meta analysis”)

Land/Water System	Activity	Outcome	Search String
Coastal	Restoration	Carbon	effect AND (“sediment plac*” OR “thin layer” OR “sediment deposition”) AND carbon AND (coast* OR estuar* OR bay* OR marsh) AND (review OR meta-analysis OR “meta analysis”)
Coastal	Restoration	Carbon	effect AND (“coastal habitat” OR marsh OR mangrove OR oyster OR dune*) AND restor* AND carbon AND (coast* OR estuar* OR bay* OR nearshore*) AND (review OR meta-analysis OR “meta analysis”)
Coastal	River diversion	Carbon	effect AND (“river div*”) AND carbon AND (coast* OR estuar* OR bay* OR nearshore*) AND (review OR meta-analysis OR “meta analysis”)
Coastal	Water discharge	Carbon	effect AND (“water discharge” OR “wastewater discharge” OR “agricultural runoff” OR “stormwater discharge”) AND carbon AND (coast* OR estuar* OR bay* OR nearshore*) AND (review OR meta-analysis OR “meta analysis”)
Cropland	Biochar	Carbon	effect AND biochar AND (carbon OR “greenhouse gas”) AND (cropland OR agricultur*) AND (review OR meta-analysis OR “meta analysis”)
Cropland	Constructed wetland	Carbon	effect AND (“constructed wetland*” OR “treatment wetland*” OR “artificial wetland*”) AND (carbon OR “greenhouse gas*”) AND (cropland OR agricultur*) AND (review OR meta-analysis OR “meta analysis”)
Cropland	Cover cropping	Carbon	effect AND “cover crop*” AND (carbon OR “greenhouse gas”) AND (cropland OR agricultur*) AND (review OR meta-analysis OR “meta analysis”)
Cropland	Crop selection and diversification	Carbon	effect AND (“crop selection” OR “crop divers*”) AND (carbon OR “greenhouse gas”) AND (cropland OR agricultur*) AND (review OR meta-analysis OR “meta analysis”)
Cropland	Drainage management	Carbon	effect AND (“drainage management” OR ditch* OR “tile drain” OR “grass buffer*” OR “field buffer” OR buffer* OR “field border*” OR “buffer strip*”) AND (carbon OR “greenhouse gas”) AND (cropland OR agricultur*) AND (review OR meta-analysis OR “meta analysis”)
Cropland	Extractive water use	Carbon	effect AND (“extractive water use” OR “water extract*” OR “groundwater extract*”) AND (carbon OR “greenhouse gas*”) AND (cropland OR agricultur*) AND (review OR meta-analysis OR “meta analysis”)
Cropland	Fallow	Carbon	effect AND fallow* AND (carbon OR “greenhouse gas”) AND (cropland OR agricultur*) AND (review OR meta-analysis OR “meta analysis”)

Land/Water System	Activity	Outcome	Search String
Cropland	Fertilization	Carbon	effect AND fertiliz* AND (carbon OR “greenhouse gas”) AND (cropland OR agricultur*) AND (review OR meta-analysis OR “meta analysis”)
Cropland	Herbicides	Carbon	effect AND herbicid* AND (carbon OR “greenhouse gas”) AND (cropland OR agricultur*) AND (review OR meta-analysis OR “meta analysis”)
Cropland	Land-use change	Carbon	effect AND (“land use change” OR “conversion”) AND (carbon OR “greenhouse gas”) AND (cropland OR agricultur*) AND (review OR meta-analysis OR “meta analysis”)
Cropland	Land-use change	Carbon	effect AND (“restor*” OR “conversion” OR “natural*”) AND (carbon OR “greenhouse gas”) AND (cropland OR agricultur*) AND (review OR meta-analysis OR “meta analysis”)
Cropland	Prescribed burn	Carbon	effect AND (“prescribed burn*” OR “prescribed fire” OR “managed fire” OR “controlled burn*”) AND (carbon OR “greenhouse gas”) AND (cropland OR agricultur*) AND (review OR meta-analysis OR “meta analysis”)
Cropland	Reforestation	Carbon	effect AND (reforestation OR afforestation OR “tree plant*” OR “forest restoration”) AND (carbon OR “greenhouse gas”) AND (cropland OR agricultur*) AND (review OR meta-analysis OR “meta analysis”)
Cropland	Riparian buffers	Carbon	effect AND “riparian buffer” AND (carbon OR “greenhouse gas”) AND (cropland OR agricultur*) AND (review OR meta-analysis OR “meta analysis”)
Cropland	Tillage	Carbon	effect AND (till*) AND (carbon OR “greenhouse gas”) AND (cropland OR agricultur*) AND (review OR meta-analysis OR “meta analysis”)
Freshwaters	Aquaculture	Carbon	effect AND aquaculture AND carbon AND (freshwater* OR river* OR stream* OR lake* OR pond* OR wetland* OR peatland* OR marsh*) AND (review OR meta-analysis OR “meta analysis”)
Freshwaters	Boating and Shipping	Carbon	effect AND (boat* OR ship*) AND carbon AND (freshwater* OR river* OR stream* OR lake* OR pond* OR wetland* OR peatland* OR marsh*) AND (review OR meta-analysis OR “meta analysis”)
Freshwaters	Development	Carbon	effect AND (development OR construction OR building OR “land use change*” OR conversion) AND carbon AND (freshwater* OR river* OR stream* OR lake* OR pond* OR wetland* OR peatland* OR marsh*) AND (review OR meta-analysis OR “meta analysis”)

Land/Water System	Activity	Outcome	Search String
Freshwaters	Diking	Carbon	effect AND (dike* OR levee*) AND carbon AND (freshwater* OR river* OR stream* OR lake* OR pond* OR wetland* OR peatland* OR marsh*) AND (review OR meta-analysis OR “meta analysis”)
Freshwaters	Draining wetlands	Carbon	effect AND (drain* OR dry OR dried OR “water withdraw*”) AND (carbon OR “greenhouse gas*”) AND (freshwater* OR river* OR stream* OR lake* OR pond* OR wetland* OR peatland* OR marsh*) AND (review OR meta-analysis OR “meta analysis”)
Freshwaters	Dredging	Carbon	effect AND dredg* AND sediment AND carbon AND (freshwater* OR river* OR stream* OR lake* OR pond* OR wetland* OR peatland* OR marsh*) AND (review OR meta-analysis OR “meta analysis”)
Freshwaters	Filling	Carbon	effect AND fill* AND sediment AND carbon AND (freshwater* OR river* OR stream* OR lake* OR pond* OR wetland* OR peatland* OR marsh*) AND (review OR meta-analysis OR “meta analysis”)
Freshwaters	Gray infrastructure	Carbon	effect AND (pile* OR piling*) AND carbon AND (freshwater* OR river* OR stream* OR lake* OR pond* OR wetland* OR peatland* OR marsh*) AND (review OR meta-analysis OR “meta analysis”)
Freshwaters	Gray infrastructure	Carbon	effect AND dam* AND carbon AND (freshwater* OR river* OR stream* OR lake* OR pond* OR wetland* OR peatland* OR marsh*) AND (review OR meta-analysis OR “meta analysis”)
Freshwaters	Green infrastructure	Carbon	effect AND (marsh* OR wetland* OR peatland*) AND (build OR built OR creat* OR restor*) AND (carbon OR “greenhouse gas*”) AND (review OR meta-analysis OR “meta analysis”)
Freshwaters	Mining	Carbon	(mine OR mines OR mining OR “mineral extraction”) AND (carbon OR “greenhouse gas*”) AND (freshwater* OR river* OR stream* OR lake* OR pond* OR wetland* OR peatland* OR marsh*) AND (review OR meta-analysis OR “meta analysis”)
Freshwaters	Piers, docks, jetty, boat ramp	Carbon	effect AND (pier* OR dock* OR jetty OR jetties OR “boat ramp*”) AND carbon AND (freshwater* OR river* OR stream* OR lake* OR pond* OR wetland* OR peatland* OR marsh*) AND (review OR meta-analysis OR “meta analysis”)

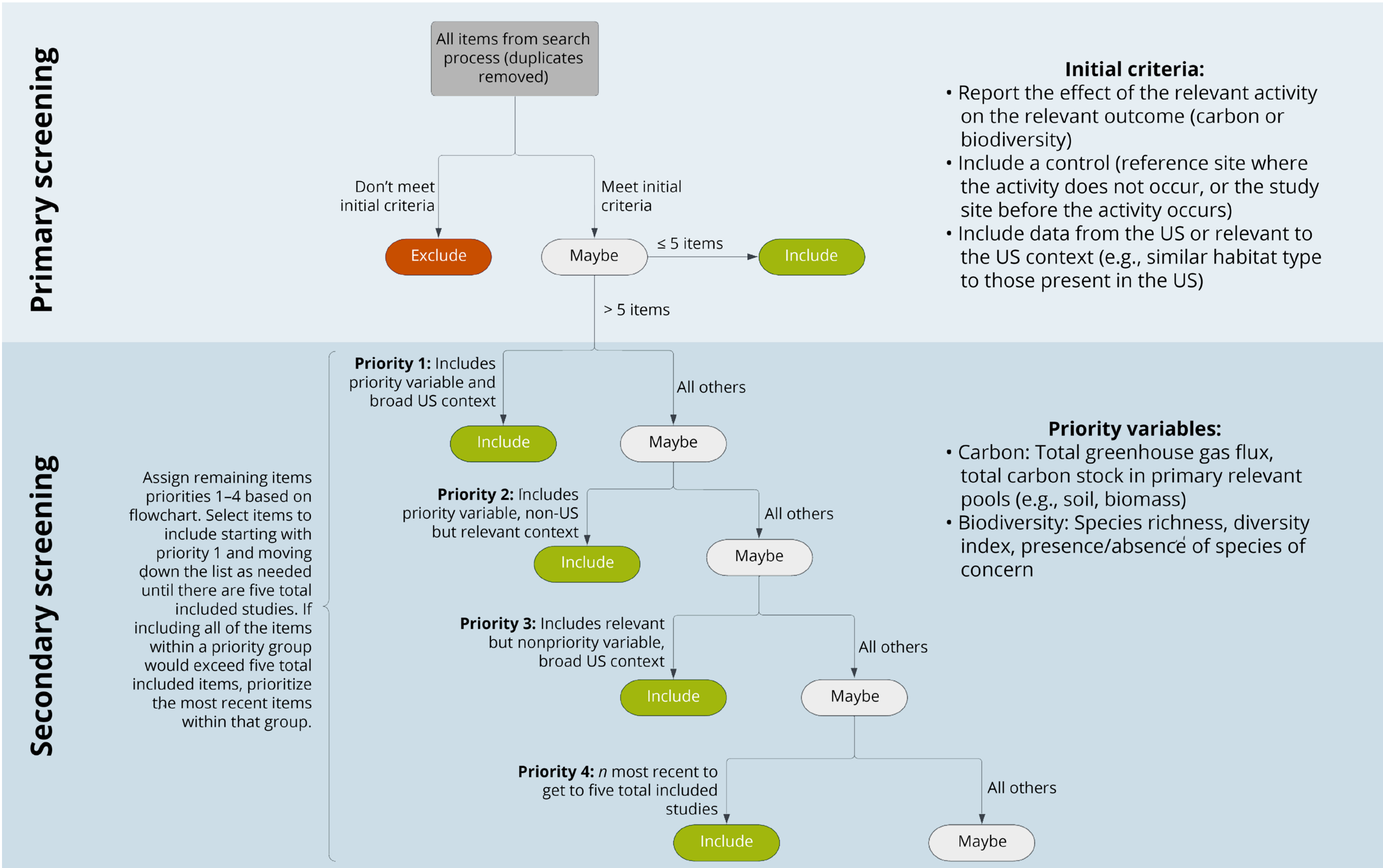
Land/Water System	Activity	Outcome	Search String
Freshwaters	Water discharge	Carbon	effect AND (“water discharge” OR “wastewater discharge” OR “agricultural runoff” OR “stormwater discharge”) AND carbon AND (freshwater* OR river* OR stream* OR lake* OR pond* OR wetland* OR peatland* OR marsh*) AND (review OR meta-analysis OR “meta analysis”)
Freshwaters	Wildlife population management	Carbon	“dam remov*” AND carbon AND (freshwater* OR river* OR stream* OR lake* OR pond* OR wetland* OR peatland* OR marsh*) AND (review OR meta-analysis OR “meta analysis”)
Grasslands and range	Fertilization and herbicides	Carbon	effect AND fertiliz* AND carbon AND (grassland* OR rangeland*) AND (review OR meta-analysis OR “meta analysis”)
Grasslands and range	Fertilization and herbicides	Carbon	effect AND herbicide* AND carbon AND (grassland* OR rangeland*) AND (review OR meta-analysis OR “meta analysis”)
Grasslands and range	Fuels management	Carbon	effect AND (“prescribed burn*” OR “prescribed fire” OR “managed fire” OR “controlled burn*”) AND carbon AND (grassland* OR rangeland*) AND (review OR meta-analysis OR “meta analysis”)
Grasslands and range	Grazing	Carbon	effect AND graz* AND carbon AND (grassland* OR rangeland*) AND (review OR meta-analysis OR “meta analysis”)
Grasslands and range	Invasive species management	Carbon	effect AND (“invasive species” OR “exotic species” OR “nonnative species” OR invasive) AND (control OR removal OR management) AND carbon AND (grassland* OR rangeland*) AND (review OR meta-analysis OR “meta analysis”)
Grasslands and range	Livestock management	Carbon	effect AND livestock AND (management OR manure) AND carbon AND (grassland* OR rangeland*) AND (review OR meta-analysis OR “meta analysis”)
Grasslands and range	Restoration	Carbon	effect AND restor* AND (native OR planting) AND carbon AND (grassland* OR rangeland*) AND (review OR meta-analysis OR “meta analysis”)
Grasslands and range	Riparian buffers	Carbon	effect AND “riparian buff*” AND carbon AND (grassland* OR rangeland*) AND (review OR meta-analysis OR “meta analysis”)
Marine	Anchoring	Carbon	effect AND carbon AND (ocean* OR marin* OR maritime OR offshore OR EEZ) AND (“boat anchor*” OR “vessel anchor*” OR moor*)
Marine	Anchoring (cable)	Carbon	effect AND carbon AND (ocean* OR marin* OR maritime OR offshore OR EEZ) AND (anchor OR “cable anchor” OR “cable”)

Land/Water System	Activity	Outcome	Search String
Marine	Aquaculture	Carbon	effect AND (aquaculture OR mariculture OR “net pen*” OR “fish farm”) AND carbon AND (ocean* OR marin* OR maritime OR offshore OR EEZ) AND (review OR meta-analysis OR “meta analysis”)
Marine	Boating	Carbon	effect AND (boat* OR ship* OR vessel) AND (carbon OR emission*) AND (ocean* OR marin* OR maritime OR offshore OR EEZ) AND (review OR meta-analysis OR “meta analysis”)
Marine	Diking	Carbon	effect AND (dike OR diking) AND carbon AND (ocean* OR marin* OR maritime OR offshore OR EEZ) AND (review OR meta-analysis OR “meta analysis”)
Marine	Dredging	Carbon	effect AND (dredg*) AND (carbon AND sediment) AND (ocean* OR marin* OR maritime OR offshore OR EEZ)
Marine	Filling	Carbon	effect AND (fill*) AND (sediment OR sand*) AND carbon AND (ocean* OR marin* OR maritime OR offshore OR EEZ) AND (review OR meta-analysis OR “meta analysis”)
Marine	Fishing	Carbon	effect AND (fishing OR trawl* OR dredg* OR longlin* OR gillnet* OR “purse seine*”) AND (carbon) AND (ocean* OR marin* OR maritime OR offshore OR EEZ)
Marine	Mining	Carbon	effect AND (mining OR “deep sea mining” OR “seabed mining” OR “deep-sea mining”) AND carbon AND (ocean* OR marin* OR maritime OR offshore OR EEZ) AND (review OR meta-analysis OR “meta analysis”)
Marine	Mining	Carbon	(“seabed mining” OR “deepsea mining” OR “deep-sea mining”) AND carbon
Marine	Offshore wind	Carbon	effect AND (wind) AND carbon AND (ocean* OR marin* OR maritime OR offshore OR EEZ) AND (review OR meta-analysis OR “meta analysis”)
Marine	Oil and gas extraction	Carbon	effect AND (oil OR gas) AND (extract* OR drill* OR infrastructure) AND carbon AND (ocean* OR marin* OR maritime OR offshore OR EEZ) AND (review OR meta-analysis OR “meta analysis”)
Marine	Protection	Carbon	effect AND (protect* OR “protected area” OR “reserve” OR “preserve” OR “no-take” OR park) AND carbon AND (ocean* OR marin* OR maritime OR offshore OR EEZ) AND (review OR meta-analysis)
Marine	Restoration	Carbon	effect AND (restoration) AND carbon AND (ocean* OR marin* OR maritime OR offshore OR EEZ) AND (review OR meta-analysis)

Land/Water System	Activity	Outcome	Search String
Working and multiple use forests	Fertilization	Carbon	effect AND fertiliz* AND (biomass) AND forest AND (review OR meta-analysis OR “meta analysis”)
Working and multiple use forests	Fertilization and herbicides	Carbon	effect AND (fertiliz*) AND (carbon) AND forest AND (review OR meta-analysis OR “meta analysis”)
Working and multiple use forests	Fertilization and herbicides	Carbon	effect AND herbicide* AND carbon AND forest AND (review OR meta-analysis OR “meta analysis”)
Working and multiple use forests	Fuels management	Carbon	effect AND (“prescribed burn*” OR “prescribed fire” OR “managed fire” OR “controlled burn*”) AND (carbon OR “greenhouse gas*”) AND forest AND (review OR meta-analysis OR “meta analysis”)
Working and multiple use forests	Grazing	Carbon	effect AND grazing AND carbon AND forest AND (review OR meta-analysis OR “meta analysis”)
Working and multiple use forests	Invasive species management	Carbon	effect AND (“invasive species” OR “exotic species” OR “nonnative species” OR invasive) AND (control OR removal OR management) AND carbon AND forest AND (review OR meta-analysis OR “meta analysis”)
Working and multiple use forests	Mineral extraction	Carbon	effect AND mining AND carbon AND forest AND (review OR meta-analysis OR “meta analysis”)
Working and multiple use forests	Oil and gas extraction	Carbon	effect AND ((oil OR gas) AND (extraction OR drilling) OR frack*) AND carbon AND forest AND (review OR meta-analysis OR “meta analysis”)
Working and multiple use forests	Prescribed burn	Carbon	effect AND (“prescribed burn*” OR “prescribed fire” OR “managed fire” OR “controlled burn*”) AND (biomass) AND forest AND (review OR meta-analysis OR “meta analysis”)
Working and multiple use forests	Reforestation	Carbon	effect AND (reforestation OR afforestation OR “tree plant*” OR “park maint*” OR “vegetation manag*” OR fertiliz* OR pesticide OR “species choice”) AND (carbon) AND forest AND (review OR meta-analysis OR “meta analysis”)
Working and multiple use forests	Riparian buffers	Carbon	effect AND “riparian buff*” AND carbon AND forest AND (review OR meta-analysis OR “meta analysis”)
Working and multiple use forests	Soil stabilization	Carbon	effect AND (“soil stabilization” OR seeding OR reseeding OR “erosion control”) AND (carbon) AND forest AND (review OR meta-analysis OR “meta analysis”)
Working and multiple use forests	Soil stabilization	Carbon	effect AND (“soil stabilization” OR “erosion control”) AND (carbon) AND forest AND (review OR meta-analysis OR “meta analysis”)

Land/Water System	Activity	Outcome	Search String
Working and multiple use forests	Soil stabilization	Carbon	effect AND (“soil stabilization” OR seeding OR reseeding OR “erosion control”) NOT “mast seed*” AND (carbon) AND forest AND (review OR meta-analysis OR “meta analysis”)
Working and multiple use forests	Thinning	Carbon	effect AND thin* AND carbon AND forest AND (review OR meta-analysis OR “meta analysis”)
Working and multiple use forests	Thinning	Carbon	effect AND thin* AND (biomass) AND forest AND (review OR meta-analysis OR “meta analysis”)
Working and multiple use forests	Timber harvest	Carbon	effect AND (“timber harvest*” OR “timber extract*” OR logging OR thin*) AND (carbon) AND forest AND (review OR meta-analysis OR “meta analysis”)
Working and multiple use forests	Wildlife management	Carbon	effect AND (“wildlife management” OR reintroduc* OR “population management” OR “disease management” OR culling OR transloc* OR “population control”) AND (carbon OR “greenhouse gas*”) AND forest AND (review OR meta-analysis OR “meta analysis”)
Working and multiple use forests	Wildlife management	Carbon	effect AND (“wildlife management” OR reintroduc* OR “population management” OR “disease management” OR culling OR transloc* OR “population control”) AND (carbon OR “greenhouse gas*”) AND forest

APPENDIX C: SCREENING FLOWCHART



APPENDIX D: EXPERTS WHO PARTICIPATED IN OCTOBER 2022 WORKSHOPS

Biodiversity workshop participants:

Lindsay Rosa, Defenders of Wildlife

Lou Ballard, US Fish and Wildlife Service

Ken Bagstad, US Geological Survey

Jacob Malcolm, Office of Policy Analysis, US Department of the Interior

Brendan Fisher, University of Vermont

Elena Bennett, McGill University

Robin Abell, Conservation International

Mark Monaco, National Oceanic and Atmospheric Administration, National Centers for Coastal Ocean Science

Jessica Hellman, University of Minnesota Institute on Environment

Robin Naidoo, World Wildlife Federation—US

Ciara Raudsepp Hearne, Wildlife Conservation Society Canada

Colby Loucks, World Wildlife Federation

Caitlin Littlefield, Conservation Science Partners

Meredith Holm, US Fish and Wildlife Service

Carbon workshop participants:

Jason James, Exponent Inc.

Chris Woodall, US Forest Service-Forest Inventory and Analysis Program

Jennifer Le, Bureau of Ocean Energy Management

Kristin Byrd, US Geological Survey

Allison Eagle, Environmental Defense Fund

Bryan Stevenson, Soil Health Institute

Steve DelGrosso, US Department of Agriculture

Tyler Lark, University of Wisconsin

David Hoover, US Department of Agriculture-Agricultural Research Service

Jim Holmquist, Smithsonian Environmental Research Center

Additional participants requested to remain anonymous.

APPENDIX E: EFFECTS OF MANAGEMENT ACTIVITIES ON BIODIVERSITY—RESULTS TABLES

Overview

This document presents results for the effects of management activities on biodiversity in three land systems (working and multiple use forests, croplands, and grasslands and rangelands) and three water systems (freshwaters, coastal, and marine), and includes:

- Note about using these results
- Key to interpreting results
- Summary tables for each land and water system with symbols showing the effects of activities on biodiversity
- Detailed results and a narrative for each activity in the summary tables

The R code developed to clean data and generate output figures is available upon request and will be made publicly available.

Note to Users

Please keep in mind the following considerations when interpreting or using these results. The Limitations section in this report includes additional details and caveats.

- These results show the direction of the effect (i.e., positive or negative) of a management activity on biodiversity, but not the magnitude of the effect. Therefore, they should not be used to compare across activities in terms of which has a relatively greater effect. In addition, care should be taken not to assume the overall effect of an activity when the reported individual effects within specific taxa have different directions or when information is missing for certain taxa.
- When we did not find enough information to produce results for a relationship, it does not mean the activity does not have an effect on biodiversity, though it may indicate a gap in existing research. When an activity has mixed results, it could have positive, negative, or no effect. This may be due to variation based on other factors (which we include in the narrative summaries when available), or the studies summarized in our results had conflicting findings.
- These results are based on evidence from broad synthesis and meta-analysis papers, and therefore obscure important local-scale factors that could change the direction of the effect. The results should not be used to predict the outcome of a management activity in any particular location without a thorough understanding of local factors.
- These results summarize studies that vary in terms of how they measure the effects of management activities over time. In some cases, results may vary substantially over different timeframes, and the included studies often do not cover a long enough period to see long-term results.

Key to Interpreting Results

In each summary table:

- *A row* represents a relationship reported in the scientific literature about the effect of an activity on biodiversity in a water or land system.
- *A column* represents results for a specific taxon. The “all” column refers to a paper reporting an effect on all biodiversity. The “overall” category refers to an overall relationship based on weighted vote counting results across taxa.
- *Number of each type of study* underpinning the arrows is included with R for Review, M for Meta-Analysis, and P for Primary study.
- *Arrow color* corresponds to arrow direction.
- *Arrow direction* indicates the effect of an activity on biodiversity in the following way:

Symbol	Effect of Activity on Biodiversity	Interpretation
↑	Positive	The activity increases biodiversity
↓	Negative	The activity decreases biodiversity
↔	Neutral	The activity has no significant effect on biodiversity
↑↓	Mixed	The results may increase, decrease, or have no effect on biodiversity, according to the literature
[empty cell]	Uncertain	Our methods did not generate enough information to determine the effect

Biodiversity in Working and Multiple Use Forests

The following results show the effects of activities on biodiversity in working and multiple use forests. We define working and multiple use forests as forests where timber harvest is permitted.

There were several additional activities for which we did not find enough information in the literature to generate results. These knowledge gaps include:

- Mining
- Oil and gas extraction

Working and Multiple Use Forests: All Activities

	Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
Fertilization	↓	R:1 M:0 P:0 ↑↓					R:1 M:3 P:0 ↓				
Grazing	↑↓	R:0 M:3 P:0 ↓	R:0 M:2 P:0 ↔	R:0 M:1 P:0 ↓	R:0 M:1 P:0 ↔		R:0 M:4 P:0 ↑↓	R:0 M:2 P:0 ↔	R:0 M:1 P:0 ↔		
Herbicides	↔	R:0 M:1 P:0 ↔	R:0 M:1 P:0 ↔	R:0 M:1 P:0 ↔	R:0 M:1 P:0 ↓		R:0 M:1 P:2 ↑↓				
Invasive species management	↑↓	R:0 M:1 P:0 ↑					R:1 M:1 P:0 ↑↓	R:0 M:1 P:0 ↑			R:0 M:1 P:0 ↓
Prescribed burn	↔	R:0 M:2 P:0 ↔	R:0 M:1 P:0 ↔	R:0 M:1 P:0 ↔	R:0 M:1 P:0 ↔		R:0 M:2 P:0 ↑↓			R:0 M:1 P:0 ↓	R:0 M:1 P:0 ↔
Reforestation	↑	R:0 M:2 P:0 ↑	R:0 M:2 P:0 ↑	R:0 M:1 P:0 ↑	R:0 M:2 P:0 ↑		R:1 M:3 P:0 ↑	R:0 M:2 P:0 ↑	R:0 M:1 P:0 ↑↓		
Restoration for mining	↑									R:0 M:0 P:1 ↑	R:0 M:1 P:0 ↑
Riparian area management	↑↓	R:0 M:1 P:0 ↑	R:0 M:1 P:0 ↔		R:0 M:1 P:0 ↔				R:0 M:1 P:0 ↑		
Soil stabilization	↑↓						R:0 M:1 P:2 ↑↓				
Thinning	↔	R:0 M:1 P:0 ↑	R:0 M:1 P:0 ↔	R:0 M:1 P:0 ↔	R:0 M:1 P:0 ↔		R:1 M:2 P:0 ↔	R:1 M:1 P:0 ↑↓			R:0 M:1 P:0 ↔
Timber harvest	↓	R:0 M:2 P:0 ↓	R:0 M:1 P:0 ↔		R:0 M:1 P:0 ↓		R:0 M:2 P:0 ↓	R:0 M:1 P:0 ↓	R:0 M:1 P:0 ↔		
Wildlife management	↔						R:0 M:1 P:0 ↔	R:0 M:1 P:0 ↔			

Working and Multiple Use Forests: Fertilization

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↓	R:1 M:0 P:0 ↑↓					R:1 M:3 P:0 ↓				

Fertilization had negative effects on forest biodiversity (De Schrijver et al. 2011; Ma et al. 2021; Midolo et al. 2019; Sullivan and Sullivan 2018). Most of this research was focused on nitrogen addition; meta-analyses revealed decreases in species richness of plants (Ma et al. 2020; Midolo et al. 2019) and soil invertebrates (Ma et al. 2020). However, one meta-analysis found nonsignificant decrease in plant richness (De Schrijver et al. 2011) and a vote counting review found that the evidence was mixed for birds and plants (Sullivan and Sullivan 2018).

Working and Multiple Use Forests: Grazing

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↑↓	R:0 M:3 P:0 ↓	R:0 M:2 P:0 ↔	R:0 M:1 P:0 ↓	R:0 M:1 P:0 ↔		R:0 M:4 P:0 ↑↓	R:0 M:2 P:0 ↔	R:0 M:1 P:0 ↔		

Grazing had mixed impacts on biodiversity in working and multiple use forests (Felton et al. 2010; Bernes et al. 2018; Barzan et al. 2021; Li and Jiang 2021; Huaranca et al. 2022). Bird species richness and abundance were, in general, not affected by grazing (Felton et al. 2010; Barzan et al. 2021; Li and Jiang 2021); however, Barzan et al. (2021) reported a significant negative impact of high- or low- (but not moderate-) intensity grazing in neotropical and afrotropical regions only. No impact of grazing was found on the species abundance or richness of mammals, amphibians, or reptiles, except when comparing timber plantations to pastures grazed with no remnant vegetation, in which case reptile and amphibian species richness was reduced (Felton et al. 2010; Li and Jiang 2021). Overall, grazing had neutral effects on invertebrate species richness (Felton et al. 2010; Li and Jiang 2021) and negative effects on the abundance of lepidopterans and spiders, but not carabids (Bernes et al. 2018). Mixed effects of grazing on plants were reported. There was no impact on the species richness of understory vegetation, while woody vegetation showed a negative response and ground plants, shrubs, forbs, and bryophytes responded positively (Felton et al. 2010; Bernes et al. 2018; Li and Jiang 2021; Huaranca et al. 2022). It is likely that grazing produced variable changes in plant species richness due to multiple interacting direct (increased light to the herbaceous or ground layer; trampling disturbance) and indirect impacts (shifts in competitive and protective relationships within vegetation).

Working and Multiple Use Forests: Herbicides

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↔	R:0 M:1 P:0 ↔	R:0 M:1 P:0 ↔	R:0 M:1 P:0 ↔	R:0 M:1 P:0 ↓		R:0 M:1 P:2 ↑↓				

Herbicide application had neutral effects on forest biodiversity (Bataineh et al. 2014; Greene et al. 2016; Stokey et al. 2021). A meta-analysis of loblolly pine forest management (Greene et al. 2016) found that amphibian diversity declined with herbicide application, while plant, bird, reptile and mammal diversity was unaffected. Further studies of plant diversity reveal contrasting response, with two field studies showing neutral (Bataineh et al. 2014) and negative effects (Stokey et al. 2021) for plant species richness, although the effect of herbicides were dependent on other management strategies (e.g., herbicide application intensity, herbivore exclusion).

Working and Multiple Use Forests: Invasive Species Management

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↑↓	R:0 M:1 P:0 ↑					R:1 M:1 P:0 ↑↓	R:0 M:1 P:0 ↑			R:0 M:1 P:0 ↓

Invasive species management has mixed effects on biodiversity and depends on the type of invasive species being removed and the method in which it is done. Ecological benefits of invasive species removal have been documented (Prior et al. 2017). For example, Byrom et al. (2016) found positive effects on birds, insects, and plants when invasive possums were removed in New Zealand. However, there can also be unintended consequences of species removal, and impacts may depend upon the trophic level to which the invasive species belongs (Ballari et al. 2016). Chemical control of invasive species can also negatively impact leaf litter arthropod communities (Hartshorn 2021).

Working and Multiple Use Forests: Prescribed Burn

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↔	R:0 M:2 P:0 ↔	R:0 M:1 P:0 ↔	R:0 M:1 P:0 ↔	R:0 M:1 P:0 ↔		R:0 M:2 P:0 ↑↓			R:0 M:1 P:0 ↓	R:0 M:1 P:0 ↔

In general, prescribed burning has no effect on species richness across all taxa (Pastro et al. 2014; Crowder et al. 2012; Eales et al. 2018). However, some studies, depending on plant type and region, show that plant species richness can increase after prescribed burns (Willms et al. 2017; Eales et al. 2018). For example, Willms et al. (2017) found that nonnative plant richness increased after burns in the eastern US.

Working and Multiple Use Forests: Reforestation

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↑	R:0 M:2 P:0 ↑	R:0 M:2 P:0 ↑	R:0 M:1 P:0 ↑	R:0 M:2 P:0 ↑		R:1 M:3 P:0 ↑	R:0 M:2 P:0 ↑	R:0 M:1 P:0 ↑↓		

Forest restoration has mixed effects on biodiversity, across taxa (Crouzeilles et al. 2015; Wang et al. 2021; Felton et al. 2010; Bremer and Farley 2010). In many cases, forest restoration can increase biodiversity (Crouzeilles et al. 2015; Wang et al. 2021), but researchers also point to factors that impact the outcome and cause mixed impacts on biodiversity, such as the presence of remnant habitat (Felton et al. 2010), restored forest age, whether the area was originally forested or not, presence of native versus exotic species, and others. (Bremer and Farley 2010).

Working and Multiple Use Forests: Restoration from Mining

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↑									R:0 M:0 P:1 ↑	R:0 M:1 P:0 ↑

Literature with relevant information on mining have demonstrated positive impacts on biodiversity with mining restoration in working and multiple use forests. In a field study about recovery from copper mining, ectomycorrhizal fungi appeared to have increased species richness and abundance as forest succession also increased (Huang et al. 2015). In a meta-analysis, it was stated that species richness in an area will increase over time as a result of forest succession and recovery from the mining process. The recovery speed depends on the biome, the mining process, and the extent of the mining operation, but overall, species richness and diversity of plants and animals have shown positive improvements over time (T. Li et al. 2022).

Working and Multiple Use Forests: Riparian Area Management

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↑↓	R:0 M:1 P:0 ↑	R:0 M:1 P:0 ↔		R:0 M:1 P:0 ↔				R:0 M:1 P:0 ↑		

From the data available, it can be stated that riparian area management in working and multiple use forests positively impacts biodiversity for most taxa. In a meta-analysis, it was found that edge species of birds were benefited for restoration of the riparian area and the buffer provided them with preferable habitat types. The riparian buffer also gives birds a place to go when forced out from logging or habitat removal for farming in other areas (Marczak et al. 2010). Arthropods appeared to benefit in terms of richness and abundance with the returning forest buffer.

Working and Multiple Use Forests: Soil Stabilization

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↑↓						R:0 M:1 P:2 ↑↓				

Soil stabilization had mixed effects on plant diversity (Dodson et al. 2010; Tisserant et al. 2021; Wang et al. 2021). In a meta-analysis of roadside slope restoration Wang et al. (2021) found neutral, negative, and positive effects of soil stabilization on plant diversity. These varying responses were dependent on the different roadside restoration techniques (e.g., seed spraying, species selection, substrate amelioration). Likewise, the two field studies (Dodson et al. 2010; Tisserant et al. 2021) found technique-dependent responses.

Working and Multiple Use Forests: Thinning

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↔	R:0 M:1 P:0 ↑	R:0 M:1 P:0 ↔	R:0 M:1 P:0 ↔	R:0 M:1 P:0 ↔		R:1 M:2 P:0 ↔	R:1 M:1 P:0 ↑↓			R:0 M:1 P:0 ↔

Thinning has neutral effects on biodiversity in working and multiple use forests (Fontaine and Kennedy 2012; Verschuyl et al. 2011; Duguid and Ashton 2013; Willms et al. 2017; Ranius et al. 2018). Bird species diversity has been shown to increase significantly in response to thinning (Verschuyl et al. 2011; Fontaine and Kennedy 2012), and positive or neutral effects were reported on small mammals. For reptiles and amphibian species diversity, no significant response to thinning was observed (Verschuyl et al. 2011); whereas for insects and invertebrates, thinning resulted in either decreased biodiversity (Ranius et al. 2018) or had no significant impact (Verschuyl et al. 2011; Ranius et al. 2018). Mixed effects of thinning on plant species diversity were also reported (Duguid and Ashton 2013; Ranius et al. 2018); however, the species richness of nonnative plants was found to significantly increase after thinning treatments (Willms et al. 2017). Increase in nonnative plant species due to disturbance is well-established, and these results suggest that thinning may create conditions for nonnative plant species.

Working and Multiple Use Forests: Timber Harvest

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↓	R:0 M:2 P:0 ↓	R:0 M:1 P:0 ↔		R:0 M:1 P:0 ↓		R:0 M:2 P:0 ↓	R:0 M:1 P:0 ↓	R:0 M:1 P:0 ↔		

Timber harvest had generally negative effects on forest biodiversity (Chaudhary et al. 2016; Clark and Covey 2012; LaManna and Martin 2017; Prieto-Benítez et al. 2011; Thorn et al. 2018). For birds, LaManna and Martin (2017) found that logging in either pure conifer or deciduous forests types tended to reduce bird species richness on average, but logging in mixed conifer–deciduous forests resulted in no net change in species richness, in part confirming negative responses of bird diversity reported in two other meta-analyses (Chaudhary et al. 2016; Thorn et al. 2018). Chaudhary and colleagues' (2016) meta-analysis also found negative responses for amphibians, insects, and plant species richness. Reduced plant species richness was also reported in the meta-analysis by Clark and Covey (2012). Finally, Prieto-Benítez et al. (2011) found reduced spider species richness from logging.

Working and Multiple Use Forests: Wildlife Management

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↔						R:0 M:1 P:0 ↔	R:0 M:1 P:0 ↔			

A meta-analysis (Bernes et al. 2018) reports no effect of ungulate herbivore exclusion on the species richness of arthropods (beetles, lepidoptera, spiders) and plants. The response of plants did vary depending on growth form.

Biodiversity in Croplands

The following results show the effects of activities on biodiversity in croplands.

There were several additional activities for which we did not find enough information in the literature to generate results. These knowledge gaps include:

- Fertilization for restoration
- Herbicides for restoration
- Water extraction

Cropland: All Activities

	Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
Constructed wetland	↑					R:0 M:0 P:1 ↑					
Cover cropping	↔								R:0 M:1 P:0 ↔		R:0 M:1 P:0 ↑
Crop selection and diversification	↑									R:0 M:1 P:0 ↑	R:0 M:1 P:0 ↑
Fallow	↑	R:1 M:2 P:1 ↑					R:0 M:1 P:1 ↑	R:0 M:1 P:0 ↑	R:0 M:1 P:0 ↑		
Fertilization for agriculture	↓				R:0 M:1 P:0 ↓				R:0 M:3 P:0 ↓	R:0 M:1 P:0 ↓	
Herbicides for agriculture	↔						R:1 M:0 P:0 ↓		R:0 M:1 P:0 ↔		
Land-use change	↑↓	R:0 M:1 P:0 ↑	R:0 M:0 P:1 ↓				R:0 M:1 P:1 ↑	R:0 M:2 P:0 ↓			R:0 M:1 P:0 ↔
Pesticides	↓				R:0 M:1 P:0 ↓		R:0 M:0 P:1 ↓	R:0 M:0 P:1 ↓			R:1 M:0 P:0 ↑↓
Prescribed burn	↔										R:0 M:1 P:0 ↔
Reforestation	↔		R:1 M:0 P:0 ↔					R:0 M:1 P:0 ↑			R:0 M:2 P:0 ↑
Riparian area management	↑										R:0 M:1 P:0 ↑

Cropland: Constructed Wetland

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↑					R:0 M:0 P:1 ↑					

A field study (Davis and Moore 2016) found positive effects on native fish species richness in Australia. Compared to ditch and generic water recycling pits, constructed wetlands harbored greater fish richness, which was comparable to remnant floodplain wetlands.

Cropland: Cover Cropping

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↔								R:0 M:1 P:0 ↔		R:0 M:1 P:0 ↑

The application of cover crops has no effect of species richness of nematodes (non-insect invertebrates), but has been shown to increase their abundance (Puissant et al. 2021). Cover crops reduce nutrient and soil erosion and increase belowground plant biomass, thus increasing the amount of carbon and soil nutrients available to nematodes. We have no data on the effects of cover cropping on other taxa.

Cropland: Crop Selection and Diversification

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↑									R:0 M:1 P:0 ↑	R:0 M:1 P:0 ↑

Crop diversification had positive effects for biodiversity (Venter et al. 2016; Beillouin et al. 2021; McDaniel et al. 2014). Two meta-analyses of soil microbes found greater overall microbial diversity and biomass in diversified agriculture when compared to monocultures (Venter et al. 2016; McDaniel et al. 2014). A second-order meta-analysis (i.e., analysis of meta-analyses) explored the biodiversity effects of multiple forms of diversification (Beillouin et al. 2021), including agroforestry, intercropping, and cultivar mixture. They report generally positive effects across all taxa, drawing from 95 meta-analyses integrating 5,156 experiments conducted over 84 experimental years.

Cropland: Fallow

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↑	R:1 M:2 P:1 ↑					R:0 M:1 P:1 ↑	R:0 M:1 P:0 ↑	R:0 M:1 P:0 ↑		

Fallow or set-aside land had positive effects on biodiversity in croplands (van Buskirk and Willi 2004; Kovács-Hostyánszki and Báldi 2012; Mertz et al. 2021; Staggenborg and Anthes 2021). Most studies considered bird communities, and bird species richness and abundance was higher in secondary forest (Mertz et al. 2021), set-aside, and long-term agricultural fallow land (van Buskirk and Willi 2004, Kovács-Hostyánszki and Báldi 2012, Staggenborg and Anthes 2021), than land under conventional annual or perennial agricultural production. Insect and spider species richness was also significantly higher in set-aside land (van Buskirk and Willi 2004). Plant species richness was significantly higher in set-aside land; however, a chronosequence over 2–50 years of fallowing showed a progressive decrease in herbaceous plant diversity and increase in woody species diversity.

Cropland: Fertilization for Agriculture

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↓				R:0 M:1 P:0 ↓				R:0 M:3 P:0 ↓	R:0 M:1 P:0 ↓	

Fertilizers can negatively affect soil biodiversity. For example, inorganic fertilization has been shown to significantly reduce soil bacterial diversity (Dai et al. 2018) and reduce richness and diversity in soil nematodes (Puissant et al. 2021). Even organic fertilization has been found to significantly decrease mycorrhizal fungi species richness, though biomass increased (Jiang et al. 2021). Furthermore, fertilizer application can negatively affect growth rates of sensitive aboveground taxa, such as amphibians (Baker et al. 2013).

Cropland: Herbicides for Agriculture

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↔						R:1 M:0 P:0 ↓		R:0 M:1 P:0 ↔		

Herbicide application had negative impacts on biodiversity in croplands. Herbicide application decreases genetic diversity and species diversity, simplifies functional groups, and adds instability to wild plant communities in agroecosystems (Qi et al. 2016). Herbicides did not impact soil nematode communities, although pesticides and nematicides had negative effects (Puissant et al. 2021).

Cropland: Land-Use Change

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↑↓	R:0 M:1 P:0 ↑	R:0 M:0 P:1 ↓				R:0 M:1 P:1 ↑	R:0 M:2 P:0 ↓			R:0 M:1 P:0 ↔

Land use change had mixed, taxa-dependent effects on biodiversity (Tripathi et al. 2021; Nunez et al. 2021; Winfree et al. 2009; Donnison et al. 2021; Méndez-Rojas et al. 2021). Meta-analysis shows positive effects on bird and plant richness when arable land is converted to bio-energy crops (Donnison et al. 2021). Conversely, land-use change has a negative impact on the species richness of beetles (Méndez-Rojas et al. 2021) and bees (Winfree et al. 2009). Diverging results were found in an African field study (Tripathi et al. 2021), where plant richness increased along a land-use gradient while mammal richness decreased. Finally, a meta-analysis of how biodiversity is affected by the interaction between climate change and conversion to cropland revealed mixed responses across all taxa (Nunez et al. 2021) but, based on this study, it is challenging to consider the effects of land-use change in isolation.

Cropland: Pesticides

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↓				R:0 M:1 P:0 ↓		R:0 M:0 P:1 ↓	R:0 M:0 P:1 ↓			R:1 M:0 P:0 ↑↓

Pesticide use had negative effects on cropland biodiversity (Gunstone et al. 2021; de Snoo 1999; Baker et al. 2013). Meta-analysis revealed negative effects of pesticides and fertilizers on survival and growth of amphibians (Baker et al. 2013); however, richness effects were not reported. A field study from the Netherlands showed that unsprayed field margins harbored a greater richness of plants and insects (de Snoo 1999). Finally, the review by Gunstone et al. (2021) focused on soil invertebrates and found soil taxa abundance and richness were negatively affected in 25.8% and 41.7% and positively affected in 19.4% and 8.3% of 30 and 12 reviewed outcomes, respectively.

Cropland: Prescribed Burn

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↔	R:0 M:1 P:0 ↑					R:0 M:1 P:0 ↔	R:0 M:1 P:0 ↑↓			R:0 M:1 P:0 ↔

Prescribed burning has neutral effects on biodiversity in cropland ecosystems (Crowder et al. 2012). Although burning did not significantly alter species richness, it significantly increased species abundance and species evenness. These patterns for increasing overall abundance and evenness with no change in richness were consistent across taxonomic groupings and levels of taxonomic resolution (arthropods, birds, nonbird vertebrates, plants, and soil organisms).

Cropland: Reforestation

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↔		R:1 M:0 P:0 ↔					R:0 M:1 P:0 ↑			R:0 M:2 P:0 ↑

Reforestation of croplands had a positive effect on biodiversity (Ferreira et al. 2019; Mokondoko et al. 2022; Ren et al. 2017; Torralba et al. 2017). Studies often focused on comparing agroforestry systems to conventionally managed cropland (e.g., shade coffee versus sun coffee). Meta-analyses showed positive effects for bird, plant, and insect richness (Torralba et al. 2017; Mokondoko et al. 2022) and multitaxa diversity (Ren et al. 2017). A landscape analysis of mammalian use of forested habitats reports a neutral response (Ferreira et al. 2019).

Cropland: Riparian Area Management

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↑										R:0 M:1 P:0 ↑

Riparian area management has positive effects on biodividersity in croplands. A single meta-analysis (Lind et al. 2019) demonstrated benefits for multiple taxa, and highlighted the importance of the width of riparian buffer for creating positive effects.

Biodiversity in Grasslands, Rangeland, and Pastures

The following results show the effects of activities on biodiversity in grasslands, rangeland, and pastures.

There were several additional activities for which we did not find enough information in the literature to generate results. These knowledge gaps include:

- Grazing infrastructure
- Mining
- Wildlife management

Grasslands, Rangeland, and Pastures: All Activities

	Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
Fertilization	↓	R:1 M:0 P:0 ↑↓					R:1 M:2 P:0 ↓	R:1 M:0 P:0 ↑↓		R:0 M:1 P:0 ↓	
Grazing	↑↓	R:0 M:1 P:0 ↔					R:0 M:3 P:0 ↑↓	R:0 M:1 P:0 ↓		R:0 M:1 P:0 ↑	R:0 M:1 P:0 ↑
Habitat management	↑↓						R:0 M:1 P:2 ↔	R:0 M:1 P:0 ↑			
Herbicides	↑↓						R:0 M:1 P:1 ↑↓				
Invasive species management	↑↓						R:0 M:1 P:0 ↑↓				
Oil and gas extraction	↑↓	R:0 M:0 P:1 ↑↓					R:0 M:0 P:2 ↑↓				
Prescribed burn	↔	R:0 M:1 P:0 ↑					R:0 M:1 P:0 ↔	R:0 M:1 P:0 ↑↓			R:0 M:1 P:0 ↔
Reforestation	↓						R:1 M:0 P:0 ↓				

Grasslands, Rangeland, and Pastures: Fertilization

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↓	R:1 M:0 P:0 ↑↓					R:1 M:2 P:0 ↓	R:1 M:0 P:0 ↑↓		R:0 M:1 P:0 ↓	

Fertilization (restoration) had negative or mixed impacts on biodiversity in grassland ecosystems (Vickery et al. 2001; Jefferson 2005; Humbert et al. 2016; Liu et al. 2020; Wang et al. 2020). Effects depended on the type of fertilization. Addition of inorganic fertilizer decreased the number and diversity of grassland invertebrates, whereas organic fertilizers benefit invertebrates when applied at a moderate level (Vickery et al. 2001). Earthworm populations increase at moderate but decrease at high rates of both inorganic and organic fertilization. Fertilizer-related reductions in invertebrates are detrimental for grassland birds, but moderate use of organic fertilizer may benefit birds by increasing soil-dwelling invertebrates (Vickery et al. 2001). Species richness of plants is reduced by inorganic nitrogen (Humbert et al. 2016) and nitrogen and phosphorus (Wang et al. 2020) addition, and negative effects are exacerbated by dose and duration of additive nitrogen application. Species richness of plants may possibly be supported by low levels of organic fertilizer (farmyard manure) (Jefferson 2005). Bacterial taxonomic richness responds nonlinearly to increasing inorganic nitrogen input, decreasing precipitously after a threshold of approximately 28 g nitrogen m^2·y–1 (Liu et al. 2020).

Grasslands, Rangeland, and Pastures: Grazing

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↑↓	R:0 M:1 P:0 ↔					R:0 M:3 P:0 ↑↓	R:0 M:1 P:0 ↓		R:0 M:1 P:0 ↑	R:0 M:1 P:0 ↑

Grazing has mixed effects on biodiversity in grassland ecosystems (Scohier and Dumont 2012; Herrero-Jáuregui and Oesterheld 2018; Wang and Tang 2019; Barzan et al. 2021; Huaranca et al. 2022). Effects depended on grazing intensity, and the response of species richness and diversity generally agreed with the intermediate disturbance hypothesis in grasslands—they increased with light and moderate but decreased with high grazing intensities. The species richness of birds was not significantly impacted by grazing in grassland habitats (Barzan et al. 2021). Plant species richness and diversity was either not affected (Scohier and Dumon, 2012; Herrero-Jáuregui and Oesterheld 2018) or significantly increased (Wang and Tang 2019; Huaranca et al. 2022) by low to moderate stocking density, whereas increasing from moderate-high had negative impacts. Grazing had negative impacts on woody plant species (Huaranca et al. 2022). The species richness of arthropods significantly decreased in response to grazing at low and high intensities, but not moderate (Wang and Tang 2019), likely because of impacts on plant coverage. Plant species richness was increased in autumn-grazed pastures compared to ungrazed controls, suggesting that grazing period is important (Scohier and Dumont 2012). Species richness of microbes significantly increased in response to grazing but decreased at high grazing intensity (Wang and Tang 2019).

Grasslands, Rangeland, and Pastures: Habitat Management

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↑↓						R:0 M:1 P:2 ↔	R:0 M:1 P:0 ↑			

Vegetation management had mixed effects on biodiversity in grasslands (Humbert et al. 2012; McGranahan et al. 2013; Milberg et al. 2017). Meta-analysis found that delaying mowing had positive effects on invertebrate species richness and neutral effects on plant species richness (Humbert et al. 2012). Two field studies found that less frequent mowing (Milberg et al. 2017) or managing for heterogeneity (McGranahan et al. 2013) had neutral effects on plant species richness.

Grasslands, Rangeland, and Pastures: Herbicides

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↑↓						R:0 M:1 P:1 ↑↓				

Herbicide application (restoration) has mixed effects on biodiversity in grassland ecosystems (Kettenring and Adams 2011; Applestein et al. 2018); however, more evidence is needed, and the data are limited to impacts on plants. Herbicide application can effectively reduce invasive plants (Applestein et al. 2018) but may not be accompanied by increases in native species (Kettenring and Adams 2011). Control methods may result in an open niche, allowing novel invaders to establish. Herbicide use can directly or indirectly negatively affect nontarget native species (Kettenring and Adams 2011).

Grasslands, Rangeland, and Pastures: Invasive Species Management

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↑↓						R:0 M:1 P:0 ↑↓				

Invasive species management is complex, as there are many different techniques and combinations of techniques. Studies show that spread prevention is the most economical and ecological way to control invasive species (Marshall et al. 2011). However, there is mixed evidence on the impact of invasive species management on native communities. For example, in a meta-analysis (Farrell and Gornish 2019) on management of an invasive grass species, the most commonly studied treatment (herbicide) negatively impacted native plant communities, but other treatments such as seeding, fire, and herbicide with additional treatments increased abundance of native plants and had positive or neutral effects. More research is needed to look at the long-term impact of invasive species management on native populations (Farrell and Gornish 2019).

Grasslands, Rangeland, and Pastures: Oil and Gas Extraction

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↑↓	R:0 M:0 P:1 ↑↓					R:0 M:0 P:2 ↑↓				

Oil and gas extraction in grassland ecosystems had a seemingly overall negative impact on biodiversity for at least two specific taxa. From a field study, it was evident that areas with disturbances from extraction had an increased amount of nonnative plant species. Two of these nonnative species dominated the site in question (more than 50% of the area), which in turn decreases overall biodiversity (Bergquist et al. 2007). In a modeling study, increased species richness was only significant for grassland bird species when compared to decreased tree cover in extraction zones. Grasslands themselves showed a significant increased species richness when far from well sites or when far from disturbances (Maguire and Papes 2021). When closer to disturbances or areas of extraction, biodiversity of bird and plant taxa decreased.

Grasslands, Rangeland, and Pastures: Prescribed Burn

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↔	R:0 M:1 P:0 ↑					R:0 M:1 P:0 ↔	R:0 M:1 P:0 ↑↓			R:0 M:1 P:0 ↔

Prescribed burning had mixed effects on biodiversity in grasslands (Alba et al. 2015; Mason et al. 2021; Pastro et al. 2014). Meta-analyses report neutral responses for plants, butterflies and bees (Alba et al. 2015; Mason et al. 2021). The species richness of birds was found to increase after prescribed burns in temperate grasslands (Pastro et al. 2014).

Grasslands, Rangeland, and Pastures: Reforestation

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↓						R:1 M:0 P:0 ↓				

Based on one review study, conversion of natural grasslands to tree plantations has a significant negative impact on native flora and fauna, particularly specialist species (Bremer and Farley 2010).

Biodiversity in Freshwaters

The following results show the effects of activities on biodiversity in freshwaters.

There were several additional activities for which we did not find enough information in the literature to generate results. These knowledge gaps include:

- Dredging
- Filling
- Piers and docks
- River diversion
- Water discharge

Freshwaters: All Activities

	Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
Aquaculture	↑	R:0 M:1 P:0 ↑	R:0 M:1 P:0 ↓		R:0 M:1 P:0 ↓	R:0 M:1 P:0 ↑					R:0 M:1 P:0 ↑
Boating and shipping	↓								R:0 M:0 P:1 ↓		
Diking	↓										R:1 M:0 P:0 ↓
Fish passage	↑↓					R:3 M:0 P:0 ↑↓					
Green infrastructure	↑↓	R:1 M:0 P:0 ↑			R:1 M:0 P:0 ↔	R:1 M:0 P:0 ↓	R:0 M:0 P:1 ↑				R:1 M:0 P:0 ↑
Habitat restoration	↑	R:0 M:1 P:0 ↑			R:1 M:1 P:0 ↔	R:0 M:3 P:0 ↑	R:0 M:1 P:0 ↑	R:0 M:1 P:0 ↑	R:0 M:1 P:0 ↔		
Recreation and tourism	↓	R:1 M:0 P:0 ↓				R:0 M:0 P:1 ↓	R:0 M:0 P:1 ↓				
Spiritual experiences	↑					R:1 M:0 P:0 ↑					R:1 M:0 P:0 ↑
Subsistence harvest	↑↓	R:1 M:0 P:0 ↔				R:2 M:0 P:0 ↓					

Freshwaters: Aquaculture

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↑	R:0 M:1 P:0 ↑	R:0 M:1 P:0 ↓		R:0 M:1 P:0 ↓	R:0 M:1 P:0 ↑					R:0 M:1 P:0 ↑

Aquaculture has a positive impact on species richness for fish and birds, but negative impacts for mammals and amphibians (Barrett et al. 2018). In general, many fish species prefer aquaculture sites over natural habitats and, on average, fish farms are associated with a higher density and diversity of wild fish. However, the effects of aquaculture on fish abundance and diversity likely depend on the functional group being assessed and the positive effects found in the literature may result from a focus on generalist carnivores (Barrett et al. 2018). As the result of an increase in fish abundance, the species richness of birds and marine mammals, such as dolphins, that feed on fish is higher than reference sites.

Freshwaters: Boating and Shipping

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↓								R:0 M:0 P:1 ↓		

Evidence of the effects of boating and shipping on biodiversity is limited to one modeling study, which focuses on the fraction of potentially occurring mollusk species in response to change in river flow velocities (Koopman et al. 2018). As the result of changes in river flow velocity, Koopman et al. (2018) predict that shipping traffic has a negative impact on mollusk diversity, with community assemblages shifting toward flow-resistant species.

Freshwaters: Diking

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↓										R:1 M:0 P:0 ↓

Evidence for the impacts of diking on freshwater ecosystems is limited to one non–meta analysis review, but there is an overall perception that diking negatively impacts biodiversity. Artificial levees disconnect floodplains and their ecosystems and create separation of the input to the watershed and the surrounding area (Knox et al. 2022). The food web of floodplains are dependent on allochthonous and autochthonous carbon inputs, which are disrupted with the boundary of a levee.

Freshwaters: Fish Passage

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↑↓					R:3 M:0 P:0 ↑↓					

Fish passage infrastructure has mixed effects on fish biodiversity in freshwater ecosystems (P. Li et al. 2022; Bai et al. 2017; Kemp 2016). In general, fish passage construction opens up channels through which the fish can migrate when rivers are otherwise blocked by dams and increases river connectivity and aquatic biodiversity (P. Li et al. 2022). However, the success of these systems is very context-dependent, because some designs have detrimental effects on fish populations (Bai et al. 2017; Kemp 2016; Raut et al. 2018). For example, fish passage construction can kill fish through forcing overcrowding that causes injury (Bai et al. 2022), its success can vary by fish species (Kemp 2016), and its effectiveness is unknown across dam scales (Raut et al. 2018).

Freshwaters: Green Infrastructure

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↑↓	R:1 M:0 P:0 ↑			R:1 M:0 P:0 ↔	R:1 M:0 P:0 ↓	R:0 M:0 P:1 ↑				R:1 M:0 P:0 ↑

The implementation of green infrastructure into freshwater ecosystems has demonstrated positive impact on biodiversity. In a review on constructed wetlands, it was apparent that biodiversity increased overall because these wetlands were placed in a location where there was once nothing. The constructed wetlands are also important to make up for natural wetland loss (Zhang et al. 2020). Introducing more plants and green infrastructure to an ecosystem has shown to benefit biodiversity, especially in an urban area model where most green space is lacking (Rojas et al. 2022). In another review, there was some analysis on specific biodiversity relationships, but there were no numerical data or specific relationships on biodiversity in urban ponds. Overall, the presence of ponds in an urban environment seems to have either a neutral or positive impact on taxa diversity (Oertli and Parris 2019).

Freshwaters: Habitat Restoration

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↑	R:0 M:1 P:0 ↑			R:1 M:1 P:0 ↔	R:0 M:3 P:0 ↑	R:0 M:1 P:0 ↑	R:0 M:1 P:0 ↑	R:0 M:1 P:0 ↔		

Restoration had positive effects on biodiversity in freshwater ecosystems (Brown et al. 2012; Thomas et al. 2015; Sievers et al. 2018; Lu et al. 2019). The species richness of bird communities was significantly higher in restored compared to degraded wetlands (Sievers et al. 2018). Restoration did not significantly affect amphibian communities; however, in some studies, species richness was lower within agricultural wetlands than reference wetlands (Sievers et al. 2018), and others found that species richness or abundance of amphibians was greater in created or restored wetlands versus reference wetlands (Brown et al. 2012). River and wetland restoration had significant positive effects on fish species richness (Sievers et al. 2018; Lu et al. 2019), and most restoration projects featured an increase in species richness and diversity and a more pronounced increase in abundance (Thomas et al. 2015). Neutral (Sievers et al. 2018) or positive (Lu et al. 2019) effects of river restoration were observed on invertebrate communities, and species richness was lower in urban wetland areas. River restoration resulted in a significant increase in biodiversity of riparian plants (Lu et al. 2019). Positive effects on biodiversity depended on restoration technique, with channel reconfiguration and riparian buffer establishment having the most impact.

Freshwaters: Recreation and Tourism

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↓	R:1 M:0 P:0 ↓				R:0 M:0 P:1 ↓	R:0 M:0 P:1 ↓				

Recreation and tourism can negatively affect freshwater biodiversity, but the impact depends on the type of activity. Freshwater recreational fishing has been found to be associated with introduced nonnative aquatic species (Davis and Darling 2017) and, though there is limited research on the impacts of nonmotorized recreational activities, human disturbance from canoeing has been found to have negative impacts on a range of bird species (Steven et al. 2011).

Freshwaters: Spiritual Experiences

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↑					R:1 M:0 P:0 ↑					R:1 M:0 P:0 ↑

Spiritual and traditional experiences had positive effects on biodiversity in freshwater ecosystems. In India, temple-based fish sanctuaries prevent destructive fishing practices and sand mining and are informally managed to protect high fish densities (Jumani et al. 2022). In Laos and Thailand, fish communities in sanctuaries can attain higher species richness, density, and biomass, and can potentially serve as source populations for adjacent river reaches. Globally, cemeteries and churchyards have a considerable conservation role, as even in heavily transformed landscapes they often act as refuges for populations of rare and endangered species (Löki et al. 2019). As conservation and spirituality is tightly interwoven, restoring the eroded social and spiritual traditions of local communities would conserve these often last healthy and natural habitat patches of urban areas.

Freshwaters: Subsistence Harvest

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↑↓	R:1 M:0 P:0 ↔				R:2 M:0 P:0 ↓					

Subsistence harvest in freshwaters remains an important food procurement strategy for many populations around the world. However, it has the potential to negatively impact native biodiversity. For example, Brotherton et al. (2020) report declines in fish diversity as a result of fishing activities, and that offtake of waterbirds for recreation and subsistence harvest, while not affecting population growth, can have negative consequences as well. Furthermore, aquaculture has become an important aspect of combating global food insecurity. However, if poorly managed, it also has the potential to negatively affect ecosystems, as has been documented with introduced tilapia aquaculture around the world (Canonico et al. 2005).

Biodiversity in Coastal Systems

The following results show the effects of activities on biodiversity in coastal systems.

There were several additional activities for which we did not find enough information in the literature to generate results. These knowledge gaps include:

- Filling
- Public access

Coastal: All Activities

	Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
Anchoring	↓						R:1 M:1 P:0 ↓				
Aquaculture	↑	R:0 M:1 P:0 ↑	R:0 M:1 P:0 ↔		R:0 M:1 P:0 ↔	R:0 M:2 P:0 ↑			R:0 M:1 P:0 ↓		R:2 M:0 P:0 ↔
Boating and shipping	↓					R:1 M:0 P:0 ↓	R:0 M:1 P:0 ↓		R:0 M:0 P:1 ↔		R:1 M:0 P:0 ↑↓
Coastal development	↓					R:0 M:1 P:0 ↓	R:1 M:0 P:0 ↓				R:1 M:1 P:0 ↑↓
Dam removal	↑					R:0 M:0 P:3 ↑	R:0 M:0 P:1 ↑↓				
Diking	↑↓	R:0 M:1 P:0 ↔				R:0 M:1 P:0 ↔	R:0 M:1 P:0 ↓		R:0 M:1 P:1 ↑		
Dredging	↓								R:0 M:0 P:1 ↓		
Fish passage	↑↓					R:1 M:0 P:1 ↑↓					
Fishing	↔					R:0 M:0 P:1 ↔					
Gray infrastructure	↓	R:0 M:1 P:0 ↓					R:0 M:1 P:0 ↓				R:0 M:1 P:0 ↓
Green infrastructure	↑↓					R:0 M:1 P:0 ↔	R:0 M:1 P:0 ↑		R:0 M:1 P:0 ↑		R:0 M:1 P:0 ↑
Habitat restoration	↑	R:0 M:1 P:0 ↑				R:0 M:1 P:0 ↔	R:0 M:1 P:0 ↑		R:0 M:2 P:0 ↑↓		R:0 M:2 P:0 ↑

Coastal: All Activities *(Continuted)*

Mining	↓					R:0 M:0 P:2 ↓	R:0 M:0 P:1 ↔		R:0 M:0 P:3 ↓		
Oil and gas extraction	↓					R:0 M:0 P:1 ↑	R:1 M:0 P:0 ↓		R:0 M:0 P:1 ↓		R:1 M:0 P:1 ↓
Piers and docks	↓			R:0 M:0 P:1 ↓			R:0 M:1 P:0 ↓				R:2 M:0 P:0 ↓
Restoration	↑						R:1 M:0 P:0 ↑				
River diversion	↓					R:1 M:0 P:1 ↓			R:1 M:0 P:0 ↓		
Water discharge	↑↓										R:1 M:0 P:0 ↑↓

Coastal: Anchoring

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↓						R:1 M:1 P:0 ↓				

Anchoring and mooring have negative impacts on the abundance of coastal vegetation (Sagerman et al. 2020; Board et al. 2020). Chains used for anchoring and mooring abrade or uproot seagrass shoots, reducing seagrass cover and creating anchor pits (Board et al. 2020). As a result, this damage to seagrass tissue can increase their susceptibility to disease and decrease their ability to produce chlorophyll, further diminishing seagrass abundance. Scoured seagrass meadows are also associated with increased colonization by invasive species (Board et al. 2020). However, because of spatial correlation between mooring areas and high boat traffic, it is challenging to attribute these impacts specifically to mooring when they may be driven by other aspects of boat activity (Sagerman et al. 2020).

Coastal: Aquaculture

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↑	R:0 M:1 P:0 ↑	R:0 M:1 P:0 ↔		R:0 M:1 P:0 ↔	R:0 M:2 P:0 ↑			R:0 M:1 P:0 ↓		R:2 M:0 P:0 ↔

The overall effects of coastal aquaculture activities on biodiversity are positive, but depend on the type of species cultivated/raised (Theuerkauf et al. 2020), as well as the taxon (Barrett et al. 2018) and species (Martinez-Garcia et al. 2013; Forbes et al. 2022). Bivalve, particularly mussel and oyster cultures, and seaweed aquaculture have been associated with higher abundance and species richness (Theuerkauf et al. 2020). The presence of fish farms also has a positive effect on wild fish and bird species richness, but a neutral effect on mammal and amphibian species richness (Barrett et al. 2018). However, scientists warn that farmed species may introduce pathogens that harm wild species, and interbreeding between farmed and wild species may have negative consequences on wild populations (Hutchings et al. 2012). Furthermore, bottom-dwelling organisms can be negatively impacted by organic wastes and chemicals used in aquaculture (Hutchings et al. 2012). In a study of floating-cage cultures of sea bream off the Spanish coast, Martinez-Garcia et al. (2013) found that, due to fish waste, polychaetes (marine worms) abundance beneath net cages was significantly reduced, though some polychaetes species were more tolerant to fish farm pollution than others. Lastly, the impact of aquaculture depends on the management techniques employed. For example, Forbes et al. (2022) found that, while kelp farms can create habitats that enhance local biodiversity, harvesting of kelp forests makes it unlikely for there to be any beneficial outcomes.

Coastal: Boating and Shipping

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↓					R:1 M:0 P:0 ↓	R:0 M:1 P:0 ↓		R:0 M:0 P:1 ↔		R:1 M:0 P:0 ↑↓

While boating and shipping has an overall negative effect on biodiversity, this impact can vary depending on the size and type of vessel (e.g., motorized versus nonmotorized [Davenport and Davenport 2006]). Exotic and potentially harmful species can be transported inadvertently in ships (Burgin and Hardiman 2011; Darling et al. 2018). In Australia, recreational boating was associated with the introduction of exotic species that negatively impact native species by outcompeting them (Burgin and Hardiman 2011). Among vessels traveling along the Pacific coast of the US, overall species diversity was not significantly different between managed and unmanaged ballast water. However, ballast water exchange did result in the loss of some common benthic coastal taxa (e.g., decapods, mollusks, bryozoans, cnidaria) while potentially toxic species were picked up (Darling et al. 2018). Recreational boating can also negatively affect submerged plant vegetation, though impacts may be lessened through proper management of boat traffic and improved mooring infrastructure (Sagerman et al. 2020). Furthermore, in a recent case study along the Moroccan coast, noise pollution from boats can negatively impact endangered marine species (Chahouri et al. 2022).

Coastal: Coastal Development

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↓					R:0 M:1 P:0 ↓	R:1 M:0 P:0 ↓				R:1 M:1 P:0 ↑↓

There are mixed results on the impacts of coastal development on biodiversity, but most appear to be negative. In a meta-analysis on Louisiana coastal areas, human pollution and construction in and near Lake Pontchartrain has made the waterbody and its deltas unhealthy, with generally low taxonomic biodiversity (O'Connell et al. 2009). In a second meta-analysis, it was found that there was no difference in the biodiversity or abundance of organisms found along shorelines with breakwaters when compared with those along natural shorelines. Seawalls were found to encourage lower biodiversity and abundance of organisms than natural shorelines. Ripraps had no significant impacts on biodiversity of taxa (Gittman et al. 2016). In a review, it was stated that with coastal development comes increased turbidity, sediment removal/displacement, and pollution. These processes can destroy currently established seagrass meadows and can prevent new populations from establishing. With development of ports comes boats that can introduce new species established on their hulls. These species can be invasive and negatively impact biodiversity (Boudouresque et al. 2009). Another review stressed that development, along with a host of other problems, was forcing the extinction of many marine taxa (Riera et al. 2014).

Coastal: Dam Removal

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↑					↑ R:0 M:0 P:3	↑↓ R:0 M:0 P:1				

In general, dam removal increases connectivity of coastal waterways, and thus can increase habitat connectivity and fish biodiversity for both resident and migrant fish (Shaffer et al. 2017; Villamil and Locke 2021; Sun et al. 2021). Dam removal has mixed effects on plant biodiversity in coastal systems, leaving it largely unchanged (Foley et al. 2017).

Coastal: Diking

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↑↓	↔ R:0 M:1 P:0				↔ R:0 M:1 P:0	↓ R:0 M:1 P:0		↑ R:0 M:1 P:1		

Diking increases the species richness of invertebrates and the abundance of fish and shorebirds, but decreases the richness of plants (Debue et al. 2022). These heterogeneous effects result from the creation of new habitats, such as open water, mudflats, and salt marshes, that favor some taxa over others. Specifically, the loss of plant richness is caused by the replacement of nonhalophyte and non–flood tolerant species by halophyte species, which are less diverse. However, many of these studies focus on relatively short-term effects of diking and do not capture longer-term effects on biodiversity.

Coastal: Dredging

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↓								↓ R:0 M:0 P:1		

Evidence of impacts of dredging on biodiversity is limited. One study found that the disposal of dredged waste material in Chesapeake Bay had a negative effect on the species richness of benthic invertebrates (Schaffner et al. 2010). Compared with reference sites (i.e., where no disposal occurred), it takes about 1.5 years for species richness of disposal sites' to recover to predisposal conditions. We have no data on the effects of dredging on other taxa.

Coastal: Fish Passage

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↑↓					R:1 M:0 P:1 ↑↓					

Overall, fish passage infrastructure has mixed effects in coastal systems. In general, fishways are intended to create passage for migratory fish in otherwise blocked waterways (Marsden and Stuart 2019). However, the effectiveness varies greatly on the type of fish. For example, eel passage depends greatly on the design of fish passage systems—their upstream migration is, surprisingly, negatively impacted by certain fish passage designs (Tamario et al. 2018). Additionally, fish body size impacts the success of fish passage systems—older designs exclude passage of smaller-bodied fish and newer systems with improved hydraulic conditions allow passage of smaller fish (Marsden and Stuart 2019). Overall, existing research points to a need to better understand how to design fish passage systems for better passage of all types of fish.

Coastal: Fishing

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↔					R:0 M:0 P:1 ↔					

The impact of fishing on coastal environments was limited to one modeling study; the impacts were shown to be neutral (Grech and Coles 2011). The decreased amount of trawling in the modeled coastal system did not show significant changes in biodiversity during the time period of collected data. With decreased areas allowed for trawling, decreased licensed boats, and total decreased days trawled, habitats and aquatic animals may potentially have increased biodiversity, but did not show any immediate changes with the reduction of available trawling area. Fisheries would have to trawl at a much lower intensity and with more spatial distance between where they collect for there to be a significant difference in biodiversity.

Coastal: Gray Infrastructure

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↓	R:0 M:1 P:0 ↓					R:0 M:1 P:0 ↓				R:0 M:1 P:0 ↓

Coastal gray infrastructure, specifically hardened shorelines, has negative impacts on biodiversity. Compared with natural shorelines, biodiversity is 23% lower along shorelines with seawalls (Gittman et al. 2016). Shorelines with seawalls have also been found to have 45% fewer organisms than natural shorelines. These negative impacts are more severe for coastal plants and birds. Effect sizes diminish for shorelines with ripraps or breakwaters; however, there is less evidence for these other types of infrastructure. These biodiversity trends are consistent across all types of natural shorelines (i.e., rocky, soft sediment, biogenic).

Coastal: Green Infrastructure

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↑↓					R:0 M:1 P:0 ↔	R:0 M:1 P:0 ↑		R:0 M:1 P:0 ↑		R:0 M:1 P:0 ↑

Green infrastructure generally supports biodiversity outcomes, with specific evidence of positive effects on marine forest species (i.e., kelp, fucoids) and mollusks (coded as *noninsect invertebrates*). However, green infrastructure is a broad activity encapsulating several more specific activities, including kelp forest restoration, oyster reef restoration, creation of artificial reefs, and artificial intertidal rock pools. Several studies suggest that the impacts of green infrastructure on biodiversity are mediated by specific types of infrastructure or techniques used for restoration. For example, Earp et al. (2022) found that the magnitude of effect size was dependent on how restoration of kelp forests was achieved. Similarly, biodiversity in artificial tidal pools was varied based on the depth, volume, and area of pools (Bugnot et al. 2018).

Coastal: Habitat Restoration

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↑	R:0 M:1 P:0 ↑				R:0 M:1 P:0 ↔	R:0 M:1 P:0 ↑		R:0 M:2 P:0 ↑↓		R:0 M:2 P:0 ↑

Coastal habitat restoration has generally positive impacts on biodiversity, although these effects vary depending on the type of restoration. Across the five papers we considered, restoration activities included reduction in nutrient loading (McCrackin et al. 2016), oyster bed restoration (Smith et al. 2021), kelp forest restoration (Earp et al. 2022), construction of artificial reefs (Paxton et al. 2020), and invasive species removal (Ning et al. 2021). Understanding the specific dynamics of each of these forms of restoration is beyond the scope of analysis; however, time since intervention emerged as a common mediating variable. Furthermore, the control or baseline for comparison varied widely across studies and within meta-analyses and was also shown to have important effects on the reported outcomes. While it is safe to conclude that coastal restoration, as a broad category of activities, has positive effects on species, it is difficult to parse the underlying mechanisms without a more granular analysis of specific types of restoration.

Coastal: Mining

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↓					R:0 M:0 P:2 ↓	R:0 M:0 P:1 ↔		R:0 M:0 P:3 ↓		

Mining had negative effects on biodiversity in coastal ecosystems (Cuadrado et al. 2016; Hayward et al. 2016; Gambi et al. 2020; Tombokan et al. 2020; Vilar et al. 2022). Negative impacts resulting from metal-contaminated mine tailings and sedimentation were observed for fish species richness and biomass (Cuadrado et al. 2016; Vilar et al. 2022). Coral cover and species richness decreased in proximity to mining activities (Cuadrado et al. 2016; Hayward et al. 2016). Sulfide-contaminated mine tailings negatively affected nematode species composition, resulting in dominance of opportunistic species with high metal tolerance (Gambi et al. 2020). The effects of mine tailing discharge on meiofaunal biodiversity and composition were still evident approximately 30 years after the end of the mining activities. Heavy metal contamination from mining activities did not significantly affect the species richness of seaweeds, suggesting they may act as bioremediators (Tombokan et al. 2020).

Coastal: Oil and Gas Extraction

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↓					R:0 M:0 P:1 ↑	R:1 M:0 P:0 ↓		R:0 M:0 P:1 ↓		R:1 M:0 P:1 ↓

Oil and gas activities have largely negative effects on biodiversity in coastal ecosystems (Ellison and Farnsworth 1996; Ellis et al. 2012; Venegas-Li et al. 2018; Laroche et al. 2018). In mangrove ecosystems, petroleum pollutants result in tree defoliation, stand death, loss of associated animal species, increasing seedling mutation rates, and reduced system-wide species richness (Ellison and Farnsworth 1996). The species richness of microbial communities is affected by proximity to oil platforms and drilling sites, with diversity decreasing closer to the sites (Laroche et al. 2018). For marine species diversity as a whole, oil exploration and production resulted in a loss of benthic biodiversity and suspension-feeding communities, with the potential for large scale effects on sensitive communities such as deep-sea, coral, and vegetated habitats (Fraser and Russell 2012). Gas extraction structures have been shown to act as artificial reefs, attracting aggregations of fish species, and leading to higher levels of species richness and abundance near platforms compared to a short distance from them (Consoli et al. 2013). Given that 67% of hydrocarbon activities in the global oceans occur in areas that are among the top 10% for species richness and endemicity, only 15% of mapped marine species to date are free from threats from hydrocarbon activities (Venegas-Li et al. 2018).

Coastal: Piers and Docks

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↓			R:0 M:0 P:1 ↓			R:0 M:1 P:0 ↓				R:2 M:0 P:0 ↓

The impacts of piers, docks, jetties, and boat ramps have shown to have negative impacts on the biodiversity of coastal environments. The increased presence and travel of tourists around this world has forced the development of these structures, which has in turn degraded the environment to an unhealthy level (Davenport and Davenport 2005). In a field study on turtle hatchling migration, when released near a jetty, around 70% of the tagged hatchlings were predated before they reached the coast (Wilson et al. 2019). Hatchlings released farther from the jetty were only 23% predated. This is because predatory fish often collect near the jetties during the day. In a meta-analysis, it was shown that construction of docks over vegetated habitats resulted in a decreased overall amount of vegetation (Sagerman et al. 2019). In another review, there was evidence of urban infrastructure having negative impacts on biodiversity as constructed coastal habitats don't support intertidal and subtitle assemblages (Bulleri and Chapman 2009).

Coastal: Restoration

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↑						R:1 M:0 P:0 ↑				

The evidence on the impact of biodiversity in coastal environments from the restoration of sediment is limited to one review. This review focused on sediment movement in the Mississippi River. It was justified that, while trying to restore wetlands and deltas for coastal protection, sediment transfer from the Mississippi can also induce nutrient loading. This only benefits biodiversity of the plants and the wetland if they are able to take up the nitrogen and organic matter being deposited (Morris et al. 2013). Restoring the wetland at this point is more valued that then risk that nutrient loading brings.

Coastal: River Diversion

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↓					R:1 M:0 P:1 ↓			R:1 M:0 P:0 ↓		

Large-scale river diversion projects—when river water is redirected to supply irrigation systems, for hydroelectric power, or other uses—change freshwater discharge, salinity, and siltation levels in estuaries and coastal marine ecosystems, resulting in a negative effect on coastal populations of marine fish and epifauna (Drinkwater and Frank 1994; Rowell et al. 2008; Wilber and Bass 1998). Case studies on the historical impacts of the diversion of the Colorado River such that water no longer reaches the Gulf of California, as well as rediversion of river water back into Matagorda Bay, Texas, support this finding (Rowell et al. 2008; Wilber and Bass 1998). Joint management of river and marine estuary ecosystems is recommended (Drinkwater and Frank 1994; Rowell et al. 2008).

Coastal: Water Discharge

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↑↓										R:1 M:0 P:0 ↑↓

Freshwater discharge in estuaries has mixed effects on biodiversity (Chilton et al. 2021). Salinity changes driven by water discharge can promote life cycle events—such as reproduction—of aquatic species. They can also support opportunistic species that suppress the growth of dominant species (Shih et al. 2011). However, salinity changes can also cause osmotic stress and death of certain species (Park et al. 2014).

Biodiversity in Marine Systems

The following results show the effects of activities on biodiversity in marine systems.

There was one additional activity for which we did not find enough information in the literature to generate results:

- Habitat restoration

Marine: All Activities

	Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
Anchoring	↓						R:1 M:0 P:0 ↓				
Aquaculture	↑	R:0 M:1 P:0 ↑	R:0 M:1 P:0 ↔		R:0 M:1 P:0 ↔	R:0 M:2 P:0 ↑					R:2 M:0 P:0 ↔
Boating and shipping	↓		R:1 M:0 P:0 ↓			R:1 M:0 P:0 ↓	R:0 M:1 P:0 ↓				R:1 M:0 P:0 ↓
Dredging	↓								R:1 M:0 P:1 ↓		
Fishing	↓								R:0 M:2 P:0 ↓		
Offshore wind	↑↓								R:1 M:0 P:0 ↑↓		
Protected areas	↑					R:0 M:3 P:0 ↑			R:1 M:0 P:0 ↑↓		R:0 M:1 P:0 ↑

Marine: Anchoring

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↓						R:1 M:0 P:0 ↓				

While there is not much research that explicitly examines the effect of mooring on biodiversity in marine ecosystems, there is a general consensus that mooring physically disturbs communities of coral and seagrass, decreasing their abundance directly around the mooring and even creating bare patches on the sea floor (Boudouresque et al. 2009; Burgin and Hardiman 2011; Sagerman et al. 2020; Broad et al. 2020). One study noted a decrease in algal biodiversity in rhodolith beds around moorings (Broad et al. 2020).

Marine: Aquaculture

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↑	R:0 M:1 P:0 ↑	R:0 M:1 P:0 ↔		R:0 M:1 P:0 ↔	R:0 M:2 P:0 ↑					R:2 M:0 P:0 ↔

While marine aquaculture has positive effects on biodiversity in marine ecosystems—it has the potential to create habitats that enhance local biodiversity, such as kelp forests (Forbes et al. 2022), and has been associated with higher abundance and species richness of wild species (Barrett et al. 2018; Forbes et al. 2022; Theuerkauf et al. 2020) from providing additional food and nutrient sources (Ticina et al. 2020)—it can also disturb ecosystems (Claudet and Fraschetti 2010; Ticina et al. 2020). For example, escaped farmed fish may spread disease to wild fish populations; genetic interactions may negatively impact biodiversity as well (Ticina et al. 2020). However, properly managed marine aquaculture can reduce the impact on natural ecosystems (Ticina et al. 2020).

Marine: Boating and Shipping

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↓		R:1 M:0 P:0 ↓			R:1 M:0 P:0 ↓	R:0 M:1 P:0 ↓				R:1 M:0 P:0 ↓

Boating and shipping have negative impacts on biodiversity in marine ecosystems. For example, motor boats negatively affect fish and marine mammal populations through direct hits by propellers, boat noise that affects communication and behavior, and pollution from oil spills and exhaust emissions (Burgin and Hardiman 2011; Peltier et al. 2019; Whitfield and Becker 2014). In a case study of whale strandings, the predominant anthropogenic cause of large cetacean death off the coast of France (12.9%) was ship strikes (Peltier et al. 2019). Boats (and ballast water) also act as vectors transporting invasive nonnative aquatic species (Burgin and Hardiman 2011; Whitfield and Becker 2014). Boat traffic and mooring infrastructure can also negatively impact aquatic vegetation (Sagerman et al. 2020).

Marine: Dredging

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↓								R:1 M:0 P:1 ↓		

Dredging in marine systems has negative impacts on benthic species (classified as *noninsect invertebrates*). Species richness, species abundance, and biomass decline after dredging operations occur (Chen et al. 2020) and take 1.5 years or more to recover to predredging conditions (Shaftner 2010). However, evidence of the impacts of dredging on biodiversity remain limited, particularly for nonbenthic species.

Marine: Fishing

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↓								R:0 M:2 P:0 ↓		

Marine fishing had a negative impact on biodiversity (Hiddink et al. 2020; Sciberras et al. 2018). These two meta-analyses, drawing on similar data, report around 20% declines in benthic invertebrate richness resulting from bottom trawling.

Marine: Offshore Wind

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↑↓								R:1 M:0 P:0 ↑↓		

Research on the effects of offshore wind farms on biodiversity is quite limited. The one study included in our analysis indicated that offshore wind farms increase habitat for benthic communities by creating artificial reefs, but also lead to other forms of habitat loss for benthic species (Causon and Gill 2018). These heterogeneous effects on habitat are expected to have mixed impacts on biodiversity.

Marine: Protected Areas

Overall	Birds	Mammals	Reptiles	Amphibians	Fish	Plants	Insects	Non-Insect Invertebrates	Soil Microbes	All
↑					R:0 M:3 P:0 ↑			R:1 M:0 P:0 ↑↓		R:0 M:1 P:0 ↑

There is strong evidence across multiple meta-analyses that marine protected areas (MPAs) enhance fish diversity as compared to unprotected open-access areas (Sciberras et al. 2015; Topor et al. 2019; Côté et al. 2001; Stewart et al. 2008). The effect size varied across studies, with greater diversity in larger MPAs (Sciberras et al. 2015), but no studies found negative or mixed impacts on fish diversity. There appears to be limited research on the effect of MPAs on other taxa besides fish. For instance, Davies (2021) suggests that MPAs may have both positive and negative impacts on invertebrate species, although there is not enough evidence to substantiate that claim.

APPENDIX F: EFFECTS OF MANAGEMENT ACTIVITIES ON CARBON—RESULTS TABLES

Overview

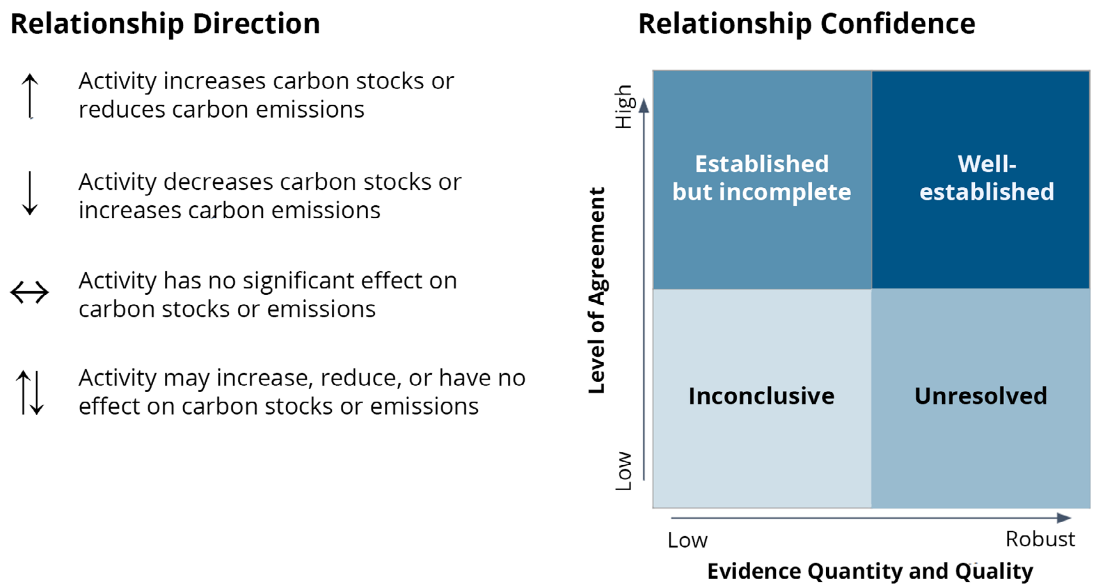
This appendix contains the summarized results for the effects of a variety of management activities on carbon storage and GHG emissions in land and water systems in the United States obtained using the methods described in this report.

Please keep in mind the following considerations when interpreting or using these results. The Limitations section in this report includes additional details and caveats.

- These results show the direction of the effect (i.e., positive or negative) of a management activity on carbon, but not the magnitude of the effect. Therefore, they should not be used to compare across activities in terms of which has a relatively greater effect. In addition, care should be taken not to assume the overall effect of an activity when the reported individual effects (within specific carbon pools) have different directions or when information is missing for certain carbon pools.
- When we did not find enough information to provide results for a relationship, it does not mean the activity does not have an effect on carbon, although it may indicate a gap in existing research. When an activity has mixed results, it could have positive, negative, or no effect. This may be due to variation based on other factors (which we include in the narrative summary when available), or the studies summarized in our results had conflicting findings.
- These results are based on broad syntheses and meta-analyses, and therefore obscure important local-scale factors that could change the direction of the effect. The results should not be used to predict the outcome of a management activity in any particular location without a thorough understanding of local factors.
- These results summarize studies that vary in terms of how they measure the effects of management activities over time. In some cases, results may vary substantially over different timeframes, and the included studies often do not cover a long enough period to see long-term results. The carbon results provide the timeframe of included studies.
- The results for a particular activity often group different intensities of that activity (e.g., low-, medium-, or high-intensity forest thinning). We describe differences in intensity in the narrative summary where possible, given information in the summarized literature.

Results for the effects of management activities on carbon are summarized in a separate section for each land or water system with arrows showing the direction and confidence level of each relationship. The direction of the arrows in the table represents the direction of the effect, and the color of the background shading represents the confidence level (Figure F1). Arrows provided by

Figure F1. Key for the direction and color of arrows in the results tables, reflecting the direction and confidence of the relationship



Note: The relationship confidence matrix is adapted from IPBES.

expert input during workshops were not assigned a confidence level and are in unshaded cells in the summary tables.

Each row in the table represents a different management activity, and each column represents a different carbon pool. Cells with arrows are ones for which the coded literature or expert input reported results for that activity and carbon pool; blank cells had no results reported in the coded literature or additional information from the expert workshop. A blank cell does not mean that the activity has no effect on that carbon pool.

Following the summary table for the land or water system, the detailed results for each relationship include information on the control condition to which the activity is compared in the literature and the timeframe represented by literature results. A narrative summary provides additional information about the relationship from the literature and input from experts.

Activities for which no synthesis or review papers were found are listed at the beginning of the results section for the land or water system.

Carbon in Working and Multiple Use Forests

This section contains results for the effects of management activities on carbon and GHG emissions in working and multiple use forests. We define working and multiple use forests as forests where timber harvest is permitted. These results were informed by a rapid literature review focused on syntheses and meta-analyses, and expert input obtained through discussion at a virtual workshop. More detailed methodology information is available in the Methods section of this report.

The next page of this document contains a summary table with arrows showing the effects of a variety of management activities on several forest carbon pools. The following pages include detailed results for each activity in the summary table, including a narrative summary of the relationship incorporating information from the literature and expert workshop, a description of the control condition to which the activity is being compared, the timeframe covered by the summarized results, and a list of references.

There were several additional management activities for which we did not find any relevant meta-analysis or review studies, which are not included in these results:

- Invasive species management
- Soil stabilization
- Riparian buffer

In addition to the general limitations of this approach described in the project background document, experts raised several issues relevant to working and multiple use forests:

- Several of the management activities included here (e.g., prescribed burn, thinning) are intended to reduce fuel loads, and therefore carbon stocks, in the short term in order to reduce the risk of future catastrophic fire. This long-term effect of avoided fire (and significant carbon loss) is not generally captured in field research or meta-analysis based on primary literature.
- Additional searches focused on biomass rather than carbon may help to fill some of the observed research gaps, and biomass is used as a proxy for forest carbon stocks.
- Effects of management activities on carbon in deeper soils (>30 cm) and coarse roots and stumps are current knowledge gaps that need more primary research.

Working and Multiple Use Forests: All Activities

Activity	Total	Belowground					Aboveground			
		Total	Soil	O Horizon	Roots	Microbes	Total	Live Trees	Understory	Debris/ Litter
Prescribed fire	↓ R:0 M:1 P:0		↔ R:0 M:2 P:0	↓ R:0 M:1 P:0					↓	↓
Thinning	↓ R:0 M:1 P:0		⇅ R:1 M:2 P:0				↓ R:0 M:1 P:0	⇅	↑ R:0 M:1 P:0	↔ R:0 M:1 P:0
Herbicide application			↔ R:0 M:2 P:0						↓	
Timber harvest	⇅ R:0 M:1 P:0		⇅ R:2 M:3 P:0					↓		
Reforestation			↔ R:0 M:1 P:0					↑		
Fertilization			⇅ R:2 M:4 P:0		↑ R:0 M:1 P:0	↓ R:0 M:1 P:0		↑ R:1 M:1 P:0		↔ R:0 M:1 P:0
Grazing			↔ R:0 M:1 P:1				↓ R:0 M:1 P:0			↔ R:0 M:1 P:0

Working and Multiple Use Forests: Prescribed Fire

Activity	Total	Belowground					Aboveground			
		Total	Soil	O Horizon	Roots	Microbes	Total	Live Trees	Understory	Debris/ Litter
Prescribed fire	↓ R:0 M:1 P:0		↔ R:0 M:2 P:0	↓ R:0 M:1 P:0					↓	↓

Control: Forests with no prescribed burning in recent past
Timeframe: Most observations were taken less than 20 years after prescribed fire for the total, soil, and O horizon carbon pools. A few observations for the soil and O horizon carbon pools extended out to 120 years after prescribed fire. The understory and debris/litter arrows represent the short-term (less than 1 year) direct effects of prescribed fire.

Prescribed fire substantially reduces carbon in the O horizon (established but incomplete) (James et al. 2018; Nave et al. 2011, 2022), but does not influence deeper soil carbon (well-established). Experts tended to agree; however, they noted that there is some new evidence that prescribed fire can create charcoal, which is an important long-term store of carbon in the soil (workshop 10/21/22). This results in a slightly negative effect on total forest carbon stock since the O horizon carbon is a relatively small component of the total carbon stock (established but incomplete) (James et al. 2018; Kalies et al. 2016). Differences in vegetation types and burn severity can result in different soil carbon responses to prescribed fire, but these effects are inconsistent and inconclusive (James et al. 2018). Responses to prescribed fire tend to be site-specific (workshop 10/21/22). It is important to note that prescribed fire is used to prevent larger, more catastrophic wildfires that would release more carbon (James et al. 2018). This effect is difficult to measure and is not well-represented in the primary literature.

Working and Multiple Use Forests: Thinning

Activity	Total	Belowground					Aboveground			
		Total	Soil	O Horizon	Roots	Microbes	Total	Live Trees	Understory	Debris/ Litter
Thinning	↓ R:0 M:1 P:0		⇅ R:1 M:2 P:0				↓ R:0 M:1 P:0	⇅	↑ R:0 M:1 P:0	↔ R:0 M:1 P:0

Control: Nonthinned forest
Timeframe: Most observations were collected less than 10 years after thinning for the aboveground biomass, understory, and debris/litter carbon pools. The soil carbon pool also had primarily observations from less than 10 years after thinning, and for some studies most observations were from less than 5 years after thinning. 80% of observations for the total carbon pool were from less than 20 years after thinning. The live tree arrow represents the short-term (less than 1 year) direct effect of thinning.

Thinning reduces total forest carbon stock (James et al. 2018; Kalies et al. 2016) (established but incomplete), primarily by directly decreasing aboveground biomass carbon (Zhou et al. 2013; James et al. 2018) (well established). Understory carbon is likely stimulated following thinning by increased light, water, and nutrient availability, but this does not offset the direct loss of aboveground biomass carbon (Zhou et al. 2013) (established but incomplete). Carbon in the debris/litter on the forest floor is not significantly impacted by thinning because of the balance between carbon additions (from litter and cutting residue) and carbon loss from accelerated decomposition from increased soil temperatures (Zhou et al. 2013) (established but incomplete). Experts emphasized that while thinning directly reduces aboveground carbon in the short term by removing live trees, it stimulates growth of the remaining trees and therefore would be expected to increase aboveground carbon accumulation over longer time scales (workshop 10/21/2022). Few empirical studies document effects for longer than 25 years, so these longer-term effects are not represented in current research (James et al. 2018). One meta-analysis did document enhanced growth in tree diameter at breast height following thinning, with higher-intensity thinning correlated with greater growth rates (Zhou et al. 2013). Evidence for the effect of thinning on soil carbon is mixed, with one study reporting increased soil greenhouse gas emissions following thinning (Yang et al. 2022), while others found no significant effect on soil carbon stocks (Zhou et al. 2013; Zhang et al. 2018; Mayer et al. 2020) (unresolved). The effects of thinning on soil carbon are thought to vary significantly with soil depth, but research to date has focused on shallow soils (<30 cm) and is missing impacts on deeper soils (workshop 10/21/2022). Intensity of thinning (how much aboveground biomass is removed) may correlate with total carbon loss (Zhou et al. 2013) (established but incomplete). Recovery likely occurs over decades following thinning, but more long-term research is needed to determine a specific timeframe (James et al. 2018; Zhou et al. 2013) (established but incomplete).

Working and Multiple Use Forests: Herbicide Application

Activity	Total	Belowground					Aboveground			
		Total	Soil	O Horizon	Roots	Microbes	Total	Live Trees	Understory	Debris/ Litter
Herbicide application			↔ R:0 M:2 P:0						↓	

Control: No herbicide application
Timeframe: Most observations were taken less than five years after herbicide application for the soil carbon pool. The understory arrow represents the short-term (less than one year) direct effect of herbicide application.

Only one meta-analysis or synthesis study examining the effects of herbicide use in forests on carbon stocks was found. Herbicides do not appear to affect soil carbon stocks (Nave et al. 2022) (inconclusive). Herbicides are expected to have direct negative effects on aboveground understory carbon, as they are used to eliminate undesirable vegetation; this effect was not represented in the literature summarized here.

Working and Multiple Use Forests: Timber Harvest

Activity	Total	Belowground					Aboveground			
		Total	Soil	O Horizon	Roots	Microbes	Total	Live Trees	Understory	Debris/ Litter
Timber harvest	⇅ R:0 M:1 P:0		⇅ R:2 M:3 P:0					↓		

Control: Unharvested forest
Timeframe: Soil carbon studies primarily included data from less than 20 years after harvest, but a few studies included longer-term field or modeled data (up to 110 years for field data, up to 500 years for modeled data). For the total carbon pool, 80% of data were from less than 20 years after harvest. The live trees arrow represents the short-term (less than 1 year) direct effect of timber harvest.

Evidence for the effect of timber harvest on total forest carbon is mixed, with clearcut harvest having a negative effect and non-clearcut methods having no effect (Kalies et al. 2016) (established but incomplete). The evidence for effects on soil carbon was also mixed, with some studies showing a negative effect (James et al. 2021; Mayer et al. 2020; Dean et al. 2017) and others no effect (Chen et al. 2020; Johnson and Curtis 2001); one study also showed a reduction in soil CO_2 emission following clearcutting (Chen et al. 2020) (unresolved). Removal of residue following harvest (biomass removal or whole-tree harvest) appears to have a more consistent negative effect on soil carbon stocks than bole-only harvest, but meta-analysis sample sizes for these practices are limited (James et al. 2021; Mayer et al. 2020). A large-scale field study using the North American Long-Term Soil Productivity dataset found no additional soil carbon losses from whole-tree removal relative to bole-only harvest unless the forest floor was also removed (James et al. 2021). The varying results for soil carbon may be due to the relatively short time frame of most studies and that most studies are conducted in secondary forests. While harvesting primary forest likely reduces soil carbon over very long timeframes, the effect in secondary forest may decrease with each successive harvest, making it difficult to detect in forests with many previous harvests (Dean et al. 2017). The effects of timber harvest on soil carbon are thought to vary significantly with soil depth, but research to date has focused on shallow soils (<30 cm) and is missing impacts on deeper soils (workshop 10/21/2022).

Experts highlighted the significant direct reduction in live tree carbon caused by timber harvest, as trees are removed from the forest (workshop 10/21/2022). While none of the evidence summarized specifically reported this effect, several mentioned that while timber harvest removes biomass from the forest, the biomass carbon may continue to be stored in wood products (Kalies et al. 2016; Mayer et al. 2020). Therefore, a life-cycle analysis of wood products would be needed to assess the wider impact on GHG emissions of harvesting and using timber from a particular forest.

Working and Multiple Use Forests: Reforestation

Activity	Total	Belowground					Aboveground			
		Total	Soil	O Horizon	Roots	Microbes	Total	Live Trees	Understory	Debris/ Litter
Reforestation			↔ R:0 M:1 P:0					↑		

Control: Reference natural ecosystems, including bare land, cropland, grassland, and forest
Timeframe: For the soil carbon pool, 80% of observations were taken less than 40 years after reforestation. The live trees arrow represents the long-term direct effect of reforestation.

Successful reforestation is expected to directly increase aboveground carbon through tree planting; however, reforestation failure caused by factors including herbivory and competing vegetation can negate this effect in individual cases (workshop 10/21/22). The literature found on reforestation only examined the effect on soil carbon. Reforestation in working and multiple use forests appears to have no consistent effect on soil carbon, with wide variation in effects likely resulting from site-specific factors such as climate, soil type, and land use history (Paula et al. 2022) (established but incomplete). Forest type may play a role, with some evidence that soil carbon is higher in conifer than broadleaf forests (Hüblová and Frouz 2021) (inconclusive). Time since restoration plays a key role in both soil carbon and live tree carbon stock measurements. Tree species used for reforestation plays a role in how carbon accumulates at the site, both in terms of how well the species is suited for the location where it is planted (and therefore its survival rate) and how much/how fast those trees accumulate carbon in both the soil and their own biomass. It is important to note that counterfactuals and land use history play a key role in how carbon is affected by reforestation (workshop 10/21/22).

Working and Multiple Use Forests: Fertilization

Activity	Total	Belowground					Aboveground			
		Total	Soil	O Horizon	Roots	Microbes	Total	Live Trees	Understory	Debris/ Litter
Fertilization			↑↓ R:2 M:4 P:0		↑ R:0 M:1 P:0	↓ R:0 M:1 P:0		↑ R:1 M:1 P:0		↔ R:0 M:1 P:0

Control: No fetilization
Timeframe: Papers varied in timeframes examined for fertilization studies. One paper contained studies that focused on short term effects, with roughly 90% of studies examining effects over 5 years or less. Other studies were more widespread, including measurements ranging from 1–45 years, 14–30 years, or 0–25 years after fertilization experiments.

Generally, papers tend to agree that nitrogen fertilizers have the capacity to increase soil carbon in nutrient-deficient forests, though how to determine which forests are nutrient-deficient is an open question (workshop 10/21/22). Whether the increase in carbon storage and/or sequestration is statistically significant varies (X. Lu et al. 2021; M. Lu et al. 2011; Nave et al. 2009, 2022; Hyvönen et al. 2008) (well established). Two reviews examined the effect of nitrogen fertilizer on tree carbon pools and found that fertilization had a positive effect on carbon stocks (Hyvönen et al. 2008; M. Lu et al. 2011) (established but incomplete); however, one review remarked that niotrogen-induced stimulation of aboveground plant production may not lead to an increase in soil carbon sequestration (M. Lu et al. 2011). Experts emphasize that adding fertilizer does not guarantee increases in live tree carbon and that results of this relationship may be either positive or neutral, depending on the context (workshop 10/21/22). The majority of results coded indicated either a positive or neutral relationship. Nitrogen availability influences carbon storage in forest soils through effects on plant growth, litter production, and soil carbon decomposition and stabilization (Nave et al. 2009). The relationship is mediated by fertilization regime (Nave et al. 2009; X. Lu et al. 2021), the form of nitrogen fertilizer used (X. Lu et al. 2021; Nave et al. 2022), length of experiment (X. Lu et al. 2021), soil type (Nave et al. 2009), tree species, stand age, and site fertility (Hyvönen et al. 2008). Inorganic nitrogen fertilization was shown to positively influence soil organic carbon, while other inorganic fertilizers and urea fertilization had no effect (Nave et al. 2022) (inconclusive). Fertilization may also increase soil respiration to a small extent, leading to GHG emissions (M. Lu et al. 2011) (inconclusive).

Working and Multiple Use Forests: Grazing

Activity	Total	Belowground					Aboveground			
		Total	Soil	O Horizon	Roots	Microbes	Total	Live Trees	Understory	Debris/ Litter
Grazing			↔ R:0 M:1 P:1				↓ R:0 M:1 P:0			↔ R:0 M:1 P:0

Control: Forests with no current livestock grazing and forests with no history of livestock grazing.
Timeframe: Most observations were taken less than 10 years after grazing began for the soil, debris/litter, and total aboveground carbon pools.

Grazing primarily affects forest carbon via negative effects on aboveground biomass carbon, which researchers suggest is due to consumption of understory vegetation (Li and Jiang 2021) (established but incomplete). No effect of grazing was evident on either debris/litter on the forest floor (established but incomplete) or soil carbon (well established) (Li and Jiang 2021; Fraterrigo et al. 2005); there may be a trade-off between increased litter and a higher decomposition rate via livestock trampling. Negative effects of grazing on forest carbon become evident one to five years after grazing begins (Li and Jiang 2021) (established but incomplete). No significant relationship between livestock density and effect size was observed, but data on livestock density was limited (Li and Jiang 2021) (inconclusive).

Carbon in Croplands

This section contains results for the effects of management activities on carbon and GHG emissions in croplands. These results were informed by a rapid literature review focused on syntheses and meta-analyses, and expert input obtained through discussion at a virtual workshop. More detailed methodology information is available in the Methods section of this report.

The next two pages of this document contain summary tables with arrows showing the effects of a variety of management activities on carbon pools and for specific GHGs. The following pages include detailed results for each activity in the summary table, including a narrative summary of the relationship incorporating information from the literature and expert workshop, a description of the control condition to which the activity is being compared, the timeframe covered by the summarized results, and a list of references.

There were several additional management activities for which we did not find any relevant meta-analysis or review studies, which are not included in these results:

- Prescribed fire
- Riparian buffer
- Extractive water use

In addition to the general limitations of this approach described in the project background document, experts raised several issues relevant to croplands:

- It is important to consider the changes that a management activity causes in both GHG emissions per area and GHG emissions per crop yield. While reducing emissions per yield is a step toward making food production less carbon-intensive, reductions in absolute emissions are needed to address climate change, and reducing per-yield emissions will not necessarily lead to a reduction in absolute emissions. Both of these metrics are included in results tables wherever possible.
- The effect of a particular agricultural management practice can vary not only by location, but from year to year in the same location. While these results show the general effect of an activity, it is important to consider local variability in responses and allow for adaptation of management practices to suit local conditions.
- Many research studies assume optimum implementation of practices, which is not always the case on the ground.
- Many research studies measure nitrous oxide emissions only at particular times during the year; these emissions should be measured throughout the year to get reliable results.

Carbon in Croplands: All Activities, Organized by Carbon Pool

Activity	Total per Crop Yield	Total	Belowground	
			Total	Soil
Improved fertilizer management	↑ R:0 M:1 P:0		⇅ R:0 M:1 P:0	↑ R:0 M:1 P:0
Herbicides	↑ R:0 M:1 P:0	↔ R:0 M:1 P:0		⇅ R:1 M:0 P:0
Cover crops		↑ R:0 M:1 P:0	⇅ R:1 M:2 P:0	↑ R:0 M:1 P:0
Crop selection and diversification	↔ R:0 M:1 P:0	↓ R:0 M:1 P:0	↑ R:0 M:1 P:0	↑ R:0 M:2 P:0
Fallow	↓ R:0 M:1 P:0	↔ R:0 M:1 P:0		↓ R:2 M:1 P:0
Drainage management				⇅ R:1 M:1 P:0
Reduced and no-tillage			↓ R:0 M:2 P:0	↓ R:0 M:2 P:0
Biochar	↑ R:0 M:1 P:0	↑ R:0 M:1 P:0	↑ R:0 M:2 P:0	↑ R:0 M:2 P:0
Land-use change to cropland		↓ R:1 M:2 P:0		↓
Land-use change from cropland		↔ R:0 M:1 P:0		↑ R:0 M:1 P:0
Reforestation				⇅ R:0 M:3 P:0
Constructed wetland		↑ R:1 M:0 P:0	↓ R:1 M:0 P:0	

Carbon in Croplands: All Activities, Organized by GHG

Because the cropland literature is focused on soil carbon stocks and fluxes and has detailed results about individual greenhouse gases, the following table has results organized by GHG.

Activity	Total GHG per Crop Yield	Total GHG	Belowground			
			N_2O	CO_2	CH_4	Soil Carbon Stock
Improved fertilizer management	↑ R:0 M:1 P:0		↑↓ R:0 M:1 P:0	↑↓ R:0 M:1 P:0		↑ R:0 M:1 P:0
Herbicides	↑ R:0 M:1 P:0	↔ R:0 M:1 P:0				↑↓ R:1 M:0 P:0
Cover crops		↑ R:0 M:1 P:0	↓ R:1 M:1 P:0	↑↓ R:1 M:1 P:0		↑ R:0 M:1 P:0
Crop selection and diversification	↔ R:0 M:1 P:0	↓ R:0 M:1 P:0	↑ R:0 M:1 P:0			↑ R:0 M:2 P:0
Fallow	↓ R:0 M:1 P:0	↔ R:0 M:1 P:0				↓ R:2 M:1 P:0
Drainage management						↑↓ R:1 M:1 P:0
Reduced and no-tillage			↓ R:0 M:2 P:0	↓ R:0 M:2 P:0	↓ R:0 M:1 P:0	↓ R:0 M:2 P:0
Biochar	↑ R:0 M:1 P:0	↑ R:0 M:1 P:0	↑ R:0 M:2 P:0	↑ R:0 M:2 P:0	↑ R:0 M:1 P:0	↑ R:0 M:2 P:0
Land-use change to cropland		↓ R:1 M:2 P:0				↓
Land-use change from cropland		↔ R:0 M:1 P:0				↑ R:0 M:1 P:0
Reforestation						↑↓ R:0 M:3 P:0
Constructed wetland		↑ R:1 M:0 P:0	↓ R:1 M:0 P:0	↓ R:1 M:0 P:0	↓ R:1 M:0 P:0	

Croplands: Fertilizer Management

Activity	Total GHG per Crop Yield	Total GHG	Belowground			
			N_2O	CO_2	CH_4	Soil Carbon Stock
Improved fertilizer management	↑ R:0 M:1 P:0		↑↓ R:0 M:1 P:0	↑↓ R:0 M:1 P:0		↑ R:0 M:1 P:0

Control: Cropland with conventional fertilizer management
Timeframe: More than half of included observations were measured during a one-year period or shorter; the longest-term observation occurred 25 years after the management practice was started.

While the use of fertilizers creates opportunities for greenhouse gas emissions, especially N_2O fluxes, an umbrella of improved fertilizer management practices, including changes to the type, rate, location, and timing of fertilizer application, can reduce emissions relative to conventional fertilizer use (workshop 10/24/22). A meta-analysis of meta-analyses evaluated the effect of several improved fertilizer management strategies on greenhouse gas fluxes and soil carbon stock (Young et al. 2021). Overall, the practices had a positive effect on soil carbon; specifically, using organic fertilizer or combined mineral-organic fertilizer rather than mineral fertilizer alone increased soil carbon, while using less mineral fertilizer had no significant effect on soil carbon (well-established). Organic fertilizer substantially increased CO_2 flux from the soil, while enhanced efficiency fertilizer (containing nitrification inhibitors) caused a slight reduction in CO_2 emissions (established but incomplete). Enhanced efficiency fertilizer, improved fertilizer placement, and reduced or optimized fertilizer rate all significantly reduced N_2O emissions, while optimized fertilizer timing and combined organic-mineral fertilizer had no effect on N_2O emissions; using organic fertilizer increased N_2O emissions (established but incomplete). Reductions in N_2O emissions were greatest in temperate climates and when the improved management practice was applied for a long duration. A more recent meta-analysis highlighted the importance of using nitrogen fertilizer at an optimum rate, which varies by crop type, to minimize the total greenhouse gas flux per crop yield (Guo et al. 2022) (established but incomplete). This meta-analysis also found evidence for reduced greenhouse gas flux per crop yield when fertilizer is applied in a split application rather than one-time application (established but incomplete).

Croplands: Herbicides

Activity	Total GHG per Crop Yield	Total GHG	Belowground			
			N_2O	CO_2	CH_4	Soil Carbon Stock
Herbicides	↑ R:0 M:1 P:0	↔ R:0 M:1 P:0				⇅ R:1 M:0 P:0

Control: Cropland with no herbicide application
Timeframe: Observations included in the meta-analysis were primarily taken during one growing season.

Few synthesis or review articles examining the effect of herbicide use in croplands on carbon were found, and the summarized literature was specific to rice paddies or focused on geographic areas outside of the US, so these results should be considered inconclusive. One global meta-analysis of the greenhouse gas effects of management activities in rice paddies found that herbicide application had no effect on total GHG emissions (including CH_4 and N_2O), but increased rice yield, therefore reducing the yield-weighted GHG emissions (Zhao et al. 2019). A narrative review focused on African croplands cited studies that had found evidence for increases and decreases in soil carbon following herbicide application (Raj and Syriac 2017).

Croplands: Cover Crops

Activity	Total GHG per Crop Yield	Total GHG	Belowground				
			N_2O	CO_2	CH_4	Soil Carbon Stock	
Cover crops		↑ R:0 M:1 P:0	↓ R:1 M:1 P:0	↑↓ R:1 M:1 P:0		↑ R:0 M:1 P:0	

Control: Cropland with no cover crops
Timeframe: Most observations are short-term (less than three years after cover cropping began).

Cover crops may increase or decrease GHG emissions from croplands via multiple mechanisms, including increased microbial growth and metabolism, decomposition of cover crop residues, and reduced need for nitrogen fertilizers (Muhammad et al. 2022). One meta-analysis found a slight reduction in total GHG emissions from cover crops, with a greater reduction from non-legume cover crops (established but incomplete) (Abdalla et al. 2019). Other studies that assessed the impact of cover crops on individual GHG emissions found mixed results. A meta-analysis of eight other meta-analyses found that cover crops slightly reduced N_2O emissions, but noted that limited data was available and that this finding was contrary to the general expectation of increased N_2O emission from cover crop residues (Young et al. 2021). Another meta-analysis that was not included in the previously mentioned meta-analysis found increases in N_2O emissions from cover crops, likely resulting from increased microbial activity (unresolved) (Daryanto et al. 2018). Several synthesis studies found evidence for increased CO_2 emissions from cover crops (Shackelford et al. 2019; Daryanto et al. 2018), while a narrative review found mixed results for CO_2 (unresolved) (Muhammad et al. 2022). The meta-analysis of meta-analyses also found an increase in soil carbon stocks following cover cropping (well-established) (Young et al. 2021). Studies found influences of climate, soil texture and bulk density, tillage system, and nitrogen fertilizer application on the relationship between cover crops and GHG emissions (Abdalla et al. 2019; Young et al. 2021).

Croplands: Crop Selection and Diversification

Activity	Total GHG per Crop Yield	Total GHG	Belowground			
			N_2O	CO_2	CH_4	Soil Carbon Stock
Crop selection and diversification	↔ R:0 M:1 P:0	↓ R:0 M:1 P:0	↑ R:0 M:1 P:0			↑ R:0 M:2 P:0

Control: Single-crop monoculture
Timeframe: For the two meta-analyses summarized that specified a timeframe, one included only observations from less than six years following crop diversification, and the other primarily included observations from one year or shorter following crop diversification.

A synthesis of meta-analyses plus two additional meta-analyses found that crop diversification, in particular adding more crop types to a rotation, increases soil carbon compared to a single-crop monoculture (Young et al. 2021; Liu et al. 2022; McDaniel et al. 2014) (well established). These analyses differ in their findings on other environmental variables' effects on this relationship, including climate and soil texture. The effect may depend on the type of monoculture crop to which additional crop types are added, with soybeans being the most responsive and corn the least (McDaniel et al. 2014).

However, analyses of the net GHG emissions effects of crop diversification had mixed results. A global meta-analysis found that this management change increased total GHG emissions (including N_2O, CH_4, and CO_2) (established but incomplete) (Sainju 2016). The strength of the effect decreased in longer experiments, so it is possible that this is a short-term response to adding crops rather than a long-term effect. The same study found that yield-standardized GHG emissions were not affected by adding more crops in rotation, as yields slightly increased along with GHG emissions (established but incomplete). However, a synthesis of meta-analyses found a slight reduction in N_2O emissions from adding more crops in rotation, so the effect on N_2O emissions specifically is uncertain (unresolved) (Young et al. 2021).

Croplands: Fallow

Activity	Total GHG per Crop Yield	Total GHG	Belowground			
			N_2O	CO_2	CH_4	Soil Carbon Stock
Fallow	↓ R:0 M:1 P:0	↔ R:0 M:1 P:0				↓ R:2 M:1 P:0

Control: Cropland with reduced fallow frequency or increased cropping intensity.
Timeframe: Observations of soil carbon stock changes were primarily from less than 10 years following the management change, though a few observations extended out to 80 years. Observations of GHG flux changes were from less than 6 years following the management change.

Leaving croplands fallow for part of the year is a common management strategy, especially in semiarid climates where it is used as a water conservation measure. Fallowed croplands have lower soil carbon than croplands where crops are grown continuously; a global meta-analysis, large-scale field study, and two narrative reviews show that soil carbon increases when fallow periods are reduced and cropping intensity (the number of crops grown on a given field in a year) increases (Shan et al. 2021; Rodgers et al. 2021; VandenBygaart et al. 2010; Campbell et al. 2005) (well-established). A global meta-analysis that assessed the relationship between cropping intensity, total GHG emissions (N_2O, CO_2, and CH_4), and GHG emissions per yield found no significant effect on total greenhouse gas emissions from increased cropping intensity, but a reduction in GHG emissions per yield resulting from increased yield under higher cropping intensity (Sainju 2016) (established but incomplete).

Croplands: Drainage Management

Activity	Total GHG per Crop Yield	Total GHG	Belowground			
			N_2O	CO_2	CH_4	Soil Carbon Stock
Drainage management						⇅ R:1 M:1 P:0

Control: Not specified in literature; assumed to be cropland without drainage management
Timeframe: Not specified

Limited evidence with inconsistent results was found for the effect of drainage management on carbon in croplands (inconclusive). A global synthesis of meta-analyses assessing agricultural management impacts on soil organic carbon included both wetting and drying of agricultural soils, but found no significant effect of these actions on soil carbon (Xu et al. 2020), while a narrative review pointed to increased losses of dissolved organic carbon from intensively drained agricultural fields (Kaushal et al. 2014).

Croplands: Reduced and No-Tillage

Activity	Total GHG per Crop Yield	Total GHG	Belowground			
			N_2O	CO_2	CH_4	Soil Carbon Stock
Reduced and no-tillage			↓ R:0 M:2 P:0	↓ R:0 M:2 P:0	↓ R:0 M:1 P:0	↓ R:0 M:2 P:0

Control: Cropland with conventional tillage
Timeframe: Many observations are from 1 year or less after no-tillage or reduced tillage began, but some observations extend up to 25–50 years.

Reducing the frequency of tillage, or eliminating tillage entirely, is a common component of conservation agriculture. A synthesis of meta-analyses found that reduced and no-tillage slightly increase soil organic carbon relative to conventional tillage (Young et al. 2021). However, many field studies only examine effects on shallow soils (0–10 cm); in deeper soils, carbon stocks may decline under reduced or no-tillage as carbon is no longer redistributed from shallow soils (workshop 10/24/22). A more recent meta-analysis that included deeper soils found significant reductions in soil carbon in soils between 10 and 60 cm deep under no-tillage, leading to an overall slight reduction in soil carbon (Cai et al. 2022) (unresolved). This effect diminished over time, such that no-tillage had no significant effect on soil carbon 14 years after implementation. Experts emphasized the uncertainty and likely small magnitude of soil carbon changes under no-tillage (workshop 10/24/22).

The effect of reduced and no-tillage on greenhouse gas emissions from croplands is also complex. The synthesis of meta-analyses found an increase in N_2O emissions under no-tillage, while reduced tillage had no significant effect on N_2O emissions (Young et al. 2021). Two more recent global meta-analyses saw consistent increases in N_2O emissions under no-tillage (Shakoor et al. 2022; Rietra et al. 2022). While continual no-tillage is expected to reduce N_2O emissions after it has been in place for several years, in practice it is often used for only a year at a time. The effect of no-tillage also depends on whether denitrification is limited by nitrogen or carbon in a specific location (workshop 10/24/22). Because of conflicting results in the literature and from expert input, this relationship is classified as *unresolved*. The synthesis of meta-analyses found a reduction in CO_2 emissions from reduced and no-tillage practices (Young et al. 2021). Two more recent global meta-analyses found diverging results for CO_2 and CH_4, with one study showing reduced emissions under no-tillage and the other increased emissions (unresolved) (Shakoor et al. 2022; Rietra et al. 2022).

Many additional environmental and agricultural factors appear to influence the relationship between tillage and greenhouse gas emissions—irrigation (versus rainfed crops), climate, soil texture and pH, crop type, nitrogen fertilizer application rate and timing, duration of no-tillage practice, and cropping system (monoculture versus rotation) all influenced the magnitude or direction of effect in at least one meta-analysis, and their effects often varied by specific greenhouse gas (Young et al. 2021; Shakoor et al. 2022; Rietra et al. 2022; Feng et al. 2018).

Croplands: Biochar

Activity	Total GHG per Crop Yield	Total GHG	Belowground			
			N_2O	CO_2	CH_4	Soil Carbon Stock
Biochar	↑ R:0 M:1 P:0	↑ R:0 M:1 P:0	↑ R:0 M:2 P:0	↑ R:0 M:2 P:0	↑ R:0 M:1 P:0	↑ R:0 M:2 P:0

Control: Cropland with no biochar application
Timeframe: Most observations are from less than 1 year after biochar application, and almost all are from less than 5 years after application; a few extend up to 10 years.

Applying biochar, or pyrolyzed biomass, to croplands is an emerging technique aimed at increasing crop yields, directly increasing soil carbon stocks, and reducing GHG emissions. A synthesis of meta-analyses on the topic plus an additional more recent meta-analysis (Young et al. 2021; Feng et al. 2022) both found substantial increases in soil carbon stocks after biochar application, although they note the need for additional longer-term research to assess the durability of this effect (established but incomplete).

Those same studies, plus three additional meta-analyses, also assessed changes in GHG emissions following biochar application. There was high potential for pseudoreplication among these studies; the total arrow direction is determined by the two most recent and comprehensive studies, which both found significant reductions in N_2O emissions after biochar application (established but incomplete) (Shakoor et al. 2022; Young et al. 2021). Additional meta-analyses also found reductions in N_2O emissions from biochar application (Zhang et al. 2020), while others saw no significant effect (Shakoor et al. 2021), or that the effect diminished with time as the biochar aged (Feng et al. 2022).

Results for other GHGs were more divergent, with some studies also showing reductions in CH_4 and CO_2 emissions (Shakoor et al. 2022), others showing increased CH_4 emissions and no effect on CO_2 emissions (Feng et al. 2022; Zhang et al. 2020), others showing no effect on either CH_4 or CO_2 emissions (unresolved) (Shakoor et al. 2021). Only one synthesis assessed the total global warming potential (all three GHGs) of biochar application and found a significant reduction in both total global warming potential, primarily due to reduced N_2O emission, and global warming potential per crop yield, since biochar also increased crop yields (established but incomplete) (Zhang et al. 2020). A variety of environmental and crop management factors was found to influence these relationships, with the direction of the relationship often changing as a result. These factors included irrigation, biochar feedstock, pyrolysis temperature, time since application, crop type, biochar and soil pH and carbon:nitrogen ratio, soil texture, and biochar application rate. More research (especially longer-term studies) is needed to establish the specific conditions under which this technique is effective.

Croplands: Land-Use Change to Cropland

Activity	Total GHG per Crop Yield	Total GHG	Belowground			
			N_2O	CO_2	CH_4	Soil Carbon Stock
Land-use change to cropland		↓ R:1 M:2 P:0				↓

Control: Natural land cover (forest or wetland)
Timeframe: Wide range both within and between studies, from less than 1 year to 200 years.

Several meta-analyses have examined the effects of agricultural-related land-use change, primarily conversion of natural land (primary and secondary forest, wetlands, and grasslands) to cropland, on GHG emissions. Studies tended to find increased emissions associated with conversion to cropland, although there was some variation based on the original habitat type (established but incomplete) For example, there was no significant effect from converting riparian wetlands to croplands because wetlands emit more CH_4 than croplands (Tan et al. 2020). There is potential to reduce CO_2 emissions when forest is converted to cropland because of lower carbon cycling in the lower-biomass crop system, but this is offset by increased N_2O and CH_4 emissions, resulting in an overall increase in GHG emissions (Han and Zhu 2020). A more general meta-analysis saw an overall increase in GHG emissions from converting natural land use to human land use (including croplands) (McDaniel et al. 2019). Conversion of natural land cover to croplands causes loss of soil carbon stock; however, research on this effect tends to be older and therefore may not be captured in the current search process (workshop 10/24/22).

Croplands: Land-Use Change from Cropland

Activity	Total GHG per Crop Yield	Total GHG	Belowground			
			N_2O	CO_2	CH_4	Soil Carbon Stock
Land-use change from cropland		↔ R:0 M:1 P:0				↑ R:0 M:1 P:0

Control: Cropland
Timeframe: Most observations were from less than 50 years after land-use change

Only one meta-analysis was found that assessed the effect of conversion from human land use (including croplands) to natural land use on total GHG emissions; it found no significant overall effect due to an increase in N_2O emissions after conversion, although CH_4 emissions were reduced slightly (McDaniel et al. 2019) (unresolved). Experts did not expect conversion to natural land use to increase N_2O emissions (workshop 10/24/22).

Several additional meta-analyses found positive effects of conversion from cropland to natural land cover on soil carbon (established but incomplete). One study looking at the change in soil carbon when cropland or grazed land was converted to natural land cover saw increased soil carbon (Parkhurst et al. 2021), and another that looked specifically at the transition from croplands to grasslands also saw a positive effect on soil carbon (Kämpf et al. 2016). Two additional studies saw a positive effect on soil organic carbon for conversion from cropland to forest (Xiang et al. 2018; Laganière et al. 2010). However, soil carbon in the post-conversion forests was still lower than reference (natural) forests (Parkhurst et al. 2021). The strongest effects were generally seen in the top 20 cm of soils (Parkhurst et al. 2021), and conversion to forests with broadleaf deciduous trees had a greater effect on soil carbon than coniferous trees (Xiang et al. 2018; Laganière et al. 2010).

Croplands: Reforestation

Activity	Total GHG per Crop Yield	Total GHG	Belowground			
			N_2O	CO_2	CH_4	Soil Carbon Stock
Reforestation						⇅ R:0 M:3 P:0

Control: Cropland or nonafforested agricultural soils
Timeframe: Most observations were from less than 40 years after reforestation

Several meta-analyses examining the effect of reforestation on soil carbon in previously agricultural land found either no effect or increased soil carbon after reforestation (Nave et al. 2013, 2021; Peng et al. 2022; Hou. 2019, 2020) (established but incomplete). These mixed results likely result from differences in how long after reforestation soil carbon changes were measured; several studies found that decades (20-plus to 35-plus years) are needed for reforestation to significantly increase soil carbon in agricultural lands (Nave et al. 2013; Hou et al. 2019) (well-established). Even if reforestation eventually increases soil carbon in former croplands, it is not clear whether those lands can ever attain soil carbon storage similar to that of forests without an agricultural land use legacy (Nave et al. 2021). Reforestation may have stronger effects on soil carbon on steeper slopes (likely caused by higher soil loss on slopes in agricultural use), and the type of trees used in reforestation may also influence soil carbon increase over time, with deciduous hardwood trees showing increased soil carbon sooner than other types of trees (Hou et al. 2019).

Croplands: Constructed Wetlands

Activity	Total GHG per Crop Yield	Total GHG	Belowground			
			N_2O	CO_2	CH_4	Soil Carbon Stock
Constructed wetlands		↑ R:1 M:0 P:0	↓ R:1 M:0 P:0	↓ R:1 M:0 P:0	↓ R:1 M:0 P:0	

Control: Studies compare GHG emissions among various types of constructed wetlands, but don't compare to croplands on which wetlands are constructed
Timeframe: Not specified

Syntheses found that report on the effects of constructed wetlands on GHGs are not specific to cropland areas and generally do not discuss net flux or compare emissions from constructed wetlands to those from alternative land use options. Therefore, the results gathered are of limited applicability to the question of how constructed wetlands affect GHGs in cropland areas. Multiple papers report on GHG emissions (CO_2, CH_4, and NO_2) from constructed wetlands (well-established) (Maucieri et al. 2017; Xu et al. 2019). While Maucieri et al. (2017) focus on GHG emissions, this synthesis includes limited reference to other studies that indicate that in many cases constructed wetlands are net carbon sinks (but not always). No studies found compare GHG emissions from constructed wetlands to other land use types, but one resource indicated that constructed wetlands emit up to 50% fewer GHGs than traditional wastewater treatment options (Maucieri et al. 2017) (inconclusive).

Factors seen to affect emissions from constructed wetlands include the type of wetland created (subsurface versus free water surface), carbon:nitrogen ratio of input wastewater (with carbon:nitrogen ratios of 5:1 emitting the least GHGs), temperature, presence of plants and plant species, age of the constructed wetland, wastewater quality, and feeding schemes (Maucieri et al. 2017; Xu et al. 2019).

Carbon in Grasslands

This section contains results for the effects of management activities on carbon and GHG emissions in grasslands. These results were informed by a rapid literature review focused on syntheses and meta-analyses, and expert input obtained through discussion at a virtual workshop. More detailed methodology information is available in the Methods section of this report.

The next page of this document contains a summary table with arrows showing the effects of a variety of management activities on carbon pools. The following pages include detailed results for each activity in the summary table, including a narrative summary of the relationship incorporating information from the literature and expert workshop, a description of the control condition to which the activity is being compared, the timeframe covered by the summarized results, and a list of references.

There were several additional management activities for which we did not find any relevant meta-analysis or review studies, which are not included in these results:

- Invasive species management
- Riparian buffer
- Herbicides

In addition to the general limitations of this approach described in the project background document, experts raised several issues relevant to grasslands:

- The term *grasslands* can be confusing, because it can include planted croplands and grazed pastures as well as perennial grasslands. Here, we focus on perennial grasslands that may or may not be grazed by livestock. Croplands are considered as a separate land system in this project. Rangelands is another related term that includes other grazed systems such as shrublands; only grasslands are considered here.
- Management of perennial grasslands is likely to have relatively small impacts on carbon compared with changes in how grassland is used, particularly if it is planted with crops. For example, continuous livestock grazing is generally expected to be better for carbon than using the same area as cropland. Land use conversions between grassland and cropland are included in the croplands summary.
- Local conditions play a large role in how grasslands respond to management and are not fully captured in this large-scale assessment. It is important to allow for nuance in management decisions at the local scale to accommodate these conditions.

Carbon in Grasslands: All Activities

Activity	Total	Belowground					Aboveground		
		Total	Soil	O Horizon	Roots	Microbial Biomass	Total	Live Biomass	Debris/ Litter
Continuous livestock grazing			↓ R:0 M:3 P:0	↑↓ R:0 M:1 P:0	↓ R:0 M:1 P:0	↓ R:0 M:1 P:0			↓ R:0 M:1 P:0
Improved livestock grazing			↑ R:0 M:2 P:0						
Livestock management (nitrogen inhibitor treatment)			↑ R:0 M:1 P:0						
Restoration			↑↓ R:1 M:2 P:0						
Prescribed fire			↑↓ R:0 M:1 P:0						
Fertilization			↑↓ R:0 M:4 P:0	↓ R:0 M:1 P:0	↑ R:0 M:1 P:0			↑ R:0 M:1 P:0	↑ R:0 M:1 P:0

Grasslands: Continuous Livestock Grazing

Activity	Total	Belowground					Aboveground		
		Total	Soil	O Horizon	Roots	Microbial Biomass	Total	Live Biomass	Debris/ Litter
Continuous livestock grazing			↓ R:0 M:3 P:0	↑↓ R:0 M:1 P:0	↓ R:0 M:1 P:0	↓ R:0 M:1 P:0			↓ R:0 M:1 P:0

Control: Grasslands with no livestock grazing
Timeframe: Most included observations were measured less than 10 years after livestock grazing began, but some were significantly longer (up to 146 years).

Most of the synthesis research on the effects of continuous livestock grazing on grassland carbon focused on soil carbon stocks, which are generally negatively affected by continuous livestock grazing, especially moderate to high intensity grazing (Zhou et al. 2017; Eze et al. 2018; Lai and Kumar 2020) (established but incomplete). Light-intensity grazing has a smaller effect on soil carbon, and one meta-analysis found mixed effects of continuous livestock grazing on O horizon soil carbon, with a slight positive effect of light grazing (Lai and Kumar 2020) (established but incomplete). Grazing effects on soil carbon are highly variable and context-dependent, with observed effects from precipitation, temperature, soil type, livestock type, grass type (C3 or C4), and grazing duration; these effects appear to interact with each other and were not consistent from study to study (McSherry et al. 2013; Zhou et al. 2017; Eze et al. 2018; Lai and Kumar 2020) (unresolved). Grazing can have different effects at different soil depths; most field research focuses on shallow soils (workshop 10/27/22). Several studies examining soil carbon fluxes under continuous livestock grazing found decreased CO_2 and NO_2 emissions and decreased CH_4 uptake by grazed soils, likely due to declines in biomass, soil water content, and changes in the microbial community (Tang et al. 2019, GuiYao et al. 2019) (established but incomplete).

Fewer studies looked at effects on other carbon pools, but there is some evidence for negative impacts of continuous livestock grazing on root, microbial biomass, and litter carbon (Zhou et al. 2017) (established but incomplete). Continuous livestock grazing is thought to reduce carbon stocks through a combination of direct consumption of aboveground plant production leading to reduced litterfall, reduced carbon allocation to roots in response to grazing, enhanced decomposition caused by trampling, and changes in the microbial community from livestock excrement (Zhou et al. 2017; Eze et al. 2018; Lai and Kumar 2020). The reduced (or possibly positive) effects of light grazing result from the lower intensity of these negative effects and the potential for compensatory growth in response to low-intensity grazing (Zhou et al. 2019). Heavy grazing also has potential to cause erosion and direct loss of carbon from the top layers of soil, especially in drier areas (workshop 10/27/22).

Experts emphasized that the relationship between livestock grazing and soil carbon is not straightforward, and that well-managed livestock grazing that mimics the wildlife grazing that grassland ecosystems are adapted to has potential to enhance soil carbon (workshop 10/27/22). Improved livestock grazing (including rotational grazing) is included as a separate management activity.

Grasslands: Improved Livestock Grazing

Activity	Total	Belowground					Aboveground		
		Total	Soil	O Horizon	Roots	Microbial Biomass	Total	Live Biomass	Debris/ Litter
Improved livestock grazing			↑ R:0 M:2 P:0						

Control: Grasslands with continuous livestock grazing
Timeframe: Almost all observations were taken less than 15 years after improved livestock grazing began

Two meta-analyses assessed the effect of improved livestock grazing strategies on soil carbon, as compared to continuous livestock grazing. One of these focused on rotational grazing, while the other used a broader definition of improved grazing, including lower stocking rates, rotational or short-duration grazing, and seasonal grazing. Both found positive impacts of improved livestock grazing on soil carbon when compared to continuous livestock grazing (Byrnes et al. 2018; Conant et al. 2017) (well-established). The positive effect on soil organic carbon increased with the study duration, suggesting that soil carbon continues to increase over time after improved livestock grazing is implemented (Conant et al. 2017). Most measurements were in shallow soils (<20 cm), and the effect on soil carbon declined with soil depth.

The authors emphasized that the positive effects of improved grazing practices are not likely to occur in every context, and that the observations included in the papers are from places where improved grazing practices made sense from a management perspective and were expected to be beneficial (Conant et al. 2017). Experts noted that rotational grazing appears to have a greater positive effect in wetter areas (workshop 10/27/22).

Grasslands: Livestock Management (Nitrogen Inhibitor Treatment)

Activity	Total	Belowground					Aboveground		
		Total	Soil	O Horizon	Roots	Microbial Biomass	Total	Live Biomass	Debris/ Litter
Livestock management (nitrogen inhibitor treatment)			↑ R:0 M:1 P:0						

Control: Grasslands with livestock without nitrogen inhibitor treatment
Timeframe: Most observations were taken less than 180 days after nitrogen inhibitor was applied

Livestock excreta can increase N_2O emissions from grasslands; a meta-analysis of the effect of nitrogen inhibitor treatment on N_2O emissions from livestock excreta found significant reductions in N_2O emissions from excreta patches when treated with dicyandiamide (Cai and Akiyama 2017) (established but incomplete). This effect was greater in the spring and fall than the summer, but did not vary based on urine nitrogen loading rates or rate of dicyandiamide application. See the sections on the effects of grazing for discussion of grazing at different intensities on grassland/rangeland carbon.

Grasslands: Restoration

Activity	Total	Belowground					Aboveground		
		Total	Soil	O Horizon	Roots	Microbial Biomass	Total	Live Biomass	Debris/ Litter
Restoration			↑↓ R:1 M:2 P:0						

Control: Grassland where restoration activity was not implemented (e.g., no compost amendment or no woody plant removal)
Timeframe: Varied by specific restoration activity. Studies of compost amendment and woody plant removal were mostly short-term (<5 years). Studies of silvopasture focused on grasslands with established oak trees (>80 years).

Evidence for the effect of grassland restoration on soil carbon is mixed, with no significant effect observed from woody plant removal (Ding et al. 2020) or compost application (Carey et al. 2020), but positive effects from restoring cultivated or mined grasslands (Derner and Schuman 2007) and silvopasture with oak trees in California (Carey et al. 2020) (unresolved). A field study in Oregon suggested that grassland restoration via topsoil removal has a short-term negative effect on soil carbon compared to other methods such as solarization (Pfeifer-Meister et al. 2012). Many of the studies found are geographically limited, and researchers pointed to a need for more and longer-term data collection to improve understanding. The majority of published research found was for grasslands in China (not summarized here).

Grasslands: Prescribed Fire

Activity	Total	Belowground					Aboveground		
		Total	Soil	O Horizon	Roots	Microbial Biomass	Total	Live Biomass	Debris/ Litter
Prescribed fire			⮃ R:0 M:1 P:0						

Control: Unburned grassland
Timeframe: Most observations were from less than 20 years following fire.

Evidence for the relationship between prescribed fire and carbon in grasslands could only be found in a single meta-analysis. This meta-analysis found that frequent fire in grasslands significantly reduced soil carbon at a depth of 0–5 cm and these burns had a neutral effect on soil respiration over time (Xu et al. 2022) (established but incomplete). For single burns, the analysis found a marginal increase in soil respiration (indicating a negative effect on GHGs) (Xu et al. 2022) (established but incomplete). It should be noted that this study examined both wildfire and prescribed burns, and that the grassland results did not distinguish between those two treatments and combined results for both.

Grasslands: Fertilization

Activity	Total	Belowground					Aboveground		
		Total	Soil	O Horizon	Roots	Microbial Biomass	Total	Live Biomass	Debris/ Litter
Prescribed fire			⇅ R:0 M:1 P:0						

Control: Grassland without fertilizer application
Timeframe: Most observations were from less than 20 years following fertilizer application; some extended up to 146 years

Evidence indicates that nitrogen fertilization in grasslands has a positive effect on plant-based carbon pools (live biomass and roots) both below- and aboveground (Sillen and Dielman 2012; Lu et al. 2011) (well established). Debris and litter was only examined in one study and fertilizer application was shown to increase carbon storage in that pool (Lu et al. 2011) (established but incomplete).

Nitrogen fertilizer's effect on soil carbon in some cases was positive (Contant et al. 2017; Eze et al. 2018), negative (Lu et al. 2011) or neutral (Lu et al. 2011; Sillen and Dieleman 2012; Li et al. 2019), indicating a mixed result overall (unresolved). One analysis found a slight reduction in O horizon carbon following fertilization (established but incomplete). One meta-analysis examined the effects of less traditional fertilizers—organic amendments such as biosolids, composts, and manures—on soil carbon and found applications of these amendments increased soil organic carbon (Gravuer et al. 2018) however authors note that at least some of the soil carbon increase is likely residual amendment material.

One meta-analysis observed that the positive effects for carbon storage of high nitrogen fertilizer addition declines over time, and that perhaps addition of fertilizer may in fact increase the risk of emissions of other more potent GHGs such as nitrous oxide (Eze et al. 2018). Factors mediating the relationship between carbon storage/sequestration and fertilizer addition in grasslands include study duration (Conant et al. 2017; Eze et al. 2018; Li et al. 2019), fertilizer application rate (Eze et al. 2017; Li et al. 2019), type of climate (Gravuer et al. 2018), form of fertilizer (Li et al. 2019), and depth of soil sample taken (Li et al. 2019).

Carbon in Freshwaters

This section contains results for the effects of management activities on carbon and GHG emissions in freshwaters. These results were informed by a rapid literature review focused on syntheses and meta-analyses, and expert input obtained through discussion at a virtual workshop. More detailed methodology information is available in the Methods section of this report.

The next page of this document contains a summary table with arrows showing the effects of a variety of management activities on carbon pools. The following pages include detailed results for each activity in the summary table, including a narrative summary of the relationship incorporating information from the literature and expert input, a description of the control condition to which the activity is being compared, the timeframe covered by the summarized results, and a list of references.

There were several additional management activities for which we did not find any relevant meta-analysis or review studies, which are not included in these results:

- Boating/shipping
- Dredging
- Filling
- Dikes and levees
- Piers/docks/jetties/boat ramps
- Gray infrastructure: pilings
- Mineral extraction
- Water discharge

Carbon in Freshwaters: All Activities

Activity	Total	Belowground		Aboveground		
		Total	Sediment	Total	Live Biomass	Water Column
Aquaculture			↑ R:1 M:0 P:0			↓ R:0 M:0 P:1
Draining & converting wetlands	↓ R:0 M:3 P:0		↑↓ R:0 M:1 P:1			
Dams & reservoirs	↓ R:1 M:0 P:0		↑ R:2 M:0 P:0			↓ R:3 M:0 P:1
Green infrastructure (freshwater wetlands)	↑ R:0 M:2 P:0		↑ R:1 M:0 P:0			
Green infrastructure (peatlands)	↑ R:0 M:2 P:0		↑↓ R:1 M:1 P:0			
Restoration (wetlands)	↑ R:0 M:1 P:0		↑↓ R:0 M:1 P:0			
Restoration (peatlands)	↑↓ R:0 M:1 P:0		↓ R:1 M:1 P:0			
Dam removal			↓ R:0 M:0 P:1			

Freshwaters: Aquaculture

Activity	Total	Belowground		Aboveground		
		Total	Sediment	Total	Live Biomass	Water Column
Aquaculture			↑ R:1 M:0 P:0			↓ R:0 M:0 P:1

Control: One study was a life-cycle assessment and therefore estimated emissions without a control, whereas the other study compared sediment carbon concentrations to average concentrations of other freshwater system types
Timeframe: One study examined emissions from the water column of aquaculture ponds over a 1-year period, while the other measured the carbon concentration of aquaculture pond sediments of ponds that ranged in age from 2–52 years

There was relatively little evidence to describe the effects of freshwater aquaculture on carbon storage. One review states that carbon burial occurs in the sediments of aquaculture ponds (inconclusive) (Boyd 2010), but these data come from a single database and data from many included sites are unpublished. Another study of global aquaculture reports aquatic N_2O emissions from freshwater aquaculture ponds (inconclusive) (MacLeod et al. 2020), however these results were generated using a life-cycle assessment methodology; while they report GHG emissions associated with aquaculture, the results have no control or comparison.

The carbon burial rate in aquaculture ponds was observed to be lower than that of large river impoundments and small, agriculturally eutrophic impoundments, but higher than that of inland seas and lakes. Burial rate was influenced by the input of external sediment and associated organic matter (Boyd 2010). Aquatic N_2O emissions in aquaculture ponds is a result of the microbial transformation of nitrogenous materials (e.g., fertilizers, uneaten fish food, excreted nitrogen), but rates of N_2O emissions can vary greatly depending on environmental conditions (e.g. dissolved oxygen concentration, pH, temperature) (MacLeod et al. 2020).

Freshwaters: Draining and Converting Wetlands

Activity	Total	Belowground		Aboveground		
		Total	Sediment	Total	Live Biomass	Water Column
Draining and converting wetlands	↓ R:0 M:3 P:0		↑↓ R:0 M:1 P:1			

Control: Either natural wetland control sites or before/after draining and conversion
Timeframe: Most studies do not report specific timeframes for measurement; one study reports including measurements taken between 1–60 months posttreatment

The activities *development* and *extractive water use* were combined for the freshwater system because all literature identified related to these activities discussed the draining of wetlands for the purpose of converting the land to an alternative use.

Draining wetlands generally has a negative effect on GHG emissions; however, land use postdrainage appears to determine the extent of that effect and, in very specific cases, drainage can result in fewer GHG emissions. Generally, when total flux of a wetland site is examined, drained wetlands release more CO_2, CH_4, and N_2O to the atmosphere than undrained wetlands (well-established) (Tan et al. 2019; Haddaway et al. 2014; Zhong et al. 2020; Maljanen 2010; Bridgham et al. 2006). However, in one of the more robust synthesis papers, findings point to no significant effect on GHG soil emissions postdrainage, which results in a mixed arrow for effects from soil (Haddaway et al. 2014).

Positive effects of drainage on GHGs are generally confined to reduced methane emissions from drained peatlands (well-established) (Abdalla et al. 2016; Zhong et al. 2020); however, one study indicated that when drained peatlands are transitioned to sites used for forestry, the forested areas can actually have lower GHG fluxes than the original peatlands (established but incomplete) (Maljanen 2010). Another study found that when natural riparian wetland was converted to pasture, net emissions rose (established but incomplete) (Tan et al. 2019).

Factors affecting GHG emissions from converted wetlands include water table depth, plant community composition of the wetland, soil pH (Abdalla et al. 2016), peat aeration and compaction, nutrient level (Zhong et al. 2020), time since drainage (Maljanen 2010), temperature (Abdalla et al. 2016; Zhong et al. 2020; Maljanen 2010), soil water content, soil nitrogen content, and bulk density (Tan et al. 2019).

Freshwaters: Dams and Reservoirs

Activity	Total	Belowground		Aboveground		
		Total	Sediment	Total	Live Biomass	Water Column
Dams and reservoirs	↓ R:1 M:0 P:0		↑ R:2 M:0 P:0			↓ R:3 M:0 P:1

Control: Emissions or sequestration in other freshwater systems
Timeframe: Many studies do not report specific timeframes, but most studies report reservoir age as related to emissions. Studies that did report age of reservoirs measured include reservoirs ranging from 1–73 years, 0–51-plus years, and 20-plus years.

Most research on the effect that dams have on carbon and GHG emissions focuses on the creation of reservoirs. It is understood that when land is flooded to create a reservoir, there is a release of methane and other GHGs resulting from decomposition of organic carbon that was stored in plants and soil in the flooded area (well established) (St. Louis et al. 2000; Deemer et al. 2016; Friedl and Wüest 2002; Wohl et al. 2017). However, there are also numerous sources that discuss the storage of carbon in reservoir sediments (well established) (Phyoe and Wang 2019; Friedl and Wüest 2002; Wohl et al. 2017). Sources agree that release of methane and other GHGs is high for a young reservoir and decreases as the reservoir ages (St. Louis et al. 2000; Phyoe and Wang 2019; Deemer et al. 2016), but these emissions can occur for up to 20 years (Deemer et al. 2016). No sources were found that examine total flux of reservoirs while accounting for both emissions and sequestration, and whether a reservoir becomes a net source or a net sink for GHGs depends on environmental conditions and likely needs to be studied further. However one source did discuss the total effect for carbon within the floodplain when dams are installed, indicating that total carbon would decrease (inconclusive) (Wohl et al. 2017).

Most studies do not provide a control when discussing emissions/storage in reservoirs; however, these systems are compared with other freshwater bodies such as rivers and lakes. Emissions from young reservoirs are higher than that of lakes (St. Louis et al. 2000; Deemer et al. 2016) and sequestration in sediments is also higher than that of rivers and lakes (Phyoe and Wang 2019).

Factors affecting emissions from reservoirs are noted as reservoir age (St. Louis et al. 2000; Phyoe and Wang 2019; Deemer et al. 2016) what type of habitat was flooded (St Louis et al. 2000), water temperature (St Louis et al. 2000; Phyoe and Wang 2019; Deemer et al. 2016), water retention time and frequency of reservoir drawdown (St. Louis et al. 2000, Phyoe and Wang 2019), and trophic status (Deemer et al. 2016).

Freshwaters: Green Infrastructure (Freshwater Wetlands)

Activity	Total	Belowground		Aboveground		
		Total	Sediment	Total	Live Biomass	Water Column
Green infrastructure (freshwater wetlands)	↑ R:0 M:2 P:0		↑ R:1 M:0 P:0			

Control: The activity is existence of wetland, so there is no control
Timeframe: Emissions/fluxes are measured from existing natural wetlands; there is no timeframe

All resources indicated that the existence of freshwater wetlands has a small but net positive effect on GHG emissions (well established) (Villa and Bernal 2018; Taillardat et al. 2020; Lu et al. 2017). This is seen both in terms of carbon stored in soil (Villa and Bernal 2018) as well as net ecosystem carbon (Taillardat et al. 2020; Lu et al. 2017). These syntheses characterize freshwater wetlands in different ways, calling them "permanent freshwater wetlands," "freshwater, tree-dominated wetlands," "freshwater marsh," "freshwater swamp marsh," and "freshwater shrub swamp." (Note that peatland results were coded separately.)

There is no doubt that wetlands store high levels of carbon, but their net effect on GHGs is less clear. While all sources agreed that these systems act as a carbon sink, they also caution that these systems emit relatively high levels of methane (Villa and Bernal 2018; Taillardat et al. 2020; Lu et al. 2017) and that, in certain cases, levels of methane emission may in fact turn freshwater wetlands into carbon sources rather than sinks (Lu et al. 2017).

Factors influencing carbon storage and emissions from freshwater wetlands include climate, type of biomass growing in the wetland, decomposition rate (Villa and Bernal 2018), and latitude (Lu et al. 2017).

It should be noted that all reviews included here report effects of existing (not built or restored) wetlands on carbon storage and sequestration.

Freshwaters: Green Infrastructure (Peatlands)

Activity	Total	Belowground		Aboveground		
		Total	Sediment	Total	Live Biomass	Water Column
Green infrastructure (peatlands)	↑ R:0 M:2 P:0		↑↓ R:1 M:1 P:0			

Control: The activity is existence of peatland, so there isn't a control
Timeframe: Emissions/fluxes are measured from existing natural peatlands; there is no timeframe to speak of

Results were mixed as to the effect of peatlands on GHG emissions. Multiple syntheses report on the extremely high carbon storage capacity of peatlands (well-established) (Villa and Bernal 2018; Taillardat et al. 2020; Lu et al. 2017), but also report on the potential of these systems to release large amounts of methane (well-established) (Villa and Bernal 2018; Taillardat et al. 2020; Lu et al. 2017; Abdalla et al. 2016). There are two reviews that document either the net ecosystem carbon budgets or net ecosystem productivity of peatlands and find that net effect of these ecosystems is positive (well-established) (Taillardat et al. 2020; Lu et al. 2017).

Factors influencing carbon storage and emissions from peatlands include the decomposition rate (Villa and Bernal 2018), climate, plant community composition (Villa and Bernal 2018; Abdalla et al. 2016), latitude (Lu et al. 2017), water table depth, and soil pH (Abdalla et al. 2016). Additionally, future climate change within the next 100 years is expected to increase the release of stored carbon from peatland areas and shift them from carbon sinks to sources (Loisel et al. 2021).

It should be noted that all reviews included here report effects of existing (not built or restored) peatlands on carbon storage and sequestration.

Freshwaters: Restoration (Wetlands)

Activity	Total	Belowground		Aboveground		
		Total	Sediment	Total	Live Biomass	Water Column
Restoration (wetlands)	↑ R:0 M:1 P:0		↑↓ R:0 M:1 P:0			

Control: Natural wetlands
Timeframe: Of the studies that report timescale, most appear to focus on measurements 10 years or fewer post-restoration; however, a small number of studies included take measurements beyond 10 years

Interpreting the effect of wetland restoration is very dependent on what the restored wetland habitat is being compared to. Almost all the syntheses found compare carbon variables in restored wetlands to intact or natural wetlands. Restored wetlands are typically observed to store less soil carbon than intact wetlands (well-established) (Yu et al. 2017; Xu et al. 2017; Moreno-Mateos 2012); however, the results for soil carbon are shown as mixed because in one wetland type (organic flat wetlands) the difference in soil carbon storage was not significant (Yu et al. 2017). Only one study examined net carbon flux of restored wetlands and found that at the decadal-to-century time scale, restored wetlands are a net carbon sink (established but incomplete) (Taillardat et al. 2020).

Recovery age is the major variable discussed in studies that compare soil carbon storage between restored and natural wetlands (Yu et al. 2017; Taillardat et al. 2020; Moreno Mateos 2012), with differences in soil carbon storage greatest between newly restored wetlands and natural wetlands. However, even 11–20 years post-restoration, the restored wetlands have significantly lower carbon storage (Yu et al. 2017). Other variables observed to affect this relationship are soil depth, whether the wetland was restored or created (Yu et al. 2017), wetland type (Yu et al. 2017; Xu et al. 2019), latitude, mean annual temperature and precipitation, and restoration approach (Xu et al. 2019).

Freshwaters: Restoration (Peatlands)

Activity	Total	Belowground		Aboveground		
		Total	Sediment	Total	Live Biomass	Water Column
Restoration (peatlands)	↑↓ R:0 M:1 P:0		↓ R:1 M:1 P:0			

Control: Natural wetlands
Timeframe: Most studies included do not report timescale; however, it appears at least some included studies took measurements beyond 10 years

Interpreting the effect of peatland restoration is very dependent on what the restored peatland habitat is being compared to. Multiple syntheses found compare carbon variables in restored peatlands to intact or natural peatlands. Syntheses often point out that soil methane emissions from peatlands are often lower in drained peatlands rather than in rewetted or intact peatlands (well-established) (Abdalla et al. 2016; Escobar et al. 2022). However, when the total GHG flux of restored peatland soils is examined, net GHG emissions of restored peatlands were seen to be less than that of drained peatlands (Escobar et al. 2022). A study documenting the net ecosystem carbon budget for restored peatlands also indicates that restored or rewetted peatlands can act as net carbon sinks or be carbon neutral (Taillardat et al. 2020).

Variables known to affect methane emissions from restored peatland soils include water table depth, plant community composition, soil pH, and mean annual air temperature (Abdalla et al. 2016). Variables affecting overall GHG emissions from restored peatlands include time since restoration (Taillardat et al. 2020), nutrient status, physical soil properties, and vegetation recovery (Escobar et al. 2022).

Freshwaters: Wildlife Management (Dam Removal)

Activity	Total	Belowground		Aboveground		
		Total	Sediment	Total	Live Biomass	Water Column
Restoration (peatlands)	↑↓ R:0 M:1 P:0		↓ R:1 M:1 P:0			

Control: No control (only result comes from a life-cycle assessment that estimates emissions without a comparison)
Timeframe: Not reported

Only one review was found that documents the GHG effects of dam removal on carbon storage in freshwater bodies. However, this was a review of dam life-cycle assessments, so the results reported have no comparators and the authors indicate that there has been relatively little research on the carbon effects of dam decommissioning. This review indicates that dam removal can result in carbon emissions from sediments resulting from decomposition of organic matter (unresolved) (Song et al. 2018), but these results come from a single primary source paper. That paper does report that sediment emissions after dam removal could be significant, greater even than emissions associated with dam construction and operation and maintenance.

Carbon in Coastal Systems

This section contains results for the effects of management activities on carbon and GHG emissions in coastal systems. These results were informed by a rapid literature review focused on syntheses and meta-analyses, and expert input obtained through individual calls. More detailed methodology information is available in the Methods section of this report.

The next page of this document contains a summary table with arrows showing the effects of a variety of management activities on several carbon pools. The following pages include detailed results for each activity in the summary table, including a narrative summary of the relationship incorporating information from the literature and experts, a description of the control condition to which the activity is being compared, the timeframe covered by the summarized results, and a list of references.

There were several additional management activities for which we did not find any relevant meta-analysis or review studies, which are not included in these results:

- Boating/shipping
- Filling
- Thin-layer sediment placement
- Dam removal
- Mining
- Oil and gas extraction
- Water discharge
- Gray infrastructure
- Green infrastructure (oyster reef, dune, living shoreline)

In addition to the general limitations of this approach described in the project background document, experts raised several issues relevant to coastal systems:

- Some activities, such as thin-layer sediment placement and living shorelines, are relatively new techniques and therefore have limited primary literature and no synthesis literature currently available. These are important research gaps that could be filled through new field data collection.
- Several activities, such as oil and gas extraction, are expected to have relevant primary literature, although in some cases it may be quite old, but not synthesis literature.
- Coastal system research is often very regional, with few people thinking about coastal wetlands at the national scale. This may be why there are few meta-analyses; larger-scale synthesis is another gap in the coastal systems literature. In addition, there are some regionally specific issues, such as oil and gas extraction causing subsidence and wetland loss in Louisiana.

Carbon in Coastal Systems: All Activities

Activity	Total	Belowground			Aboveground		
		Total	Sediment	Roots	Total	Live Biomass	Debris/ Litter
Habitat restoration	↑ R:0 M:2 P:0		↔ R:0 M:2 P:0			↑ R:0 M:1 P:0	
Fishing			⇅ R:1 M:0 P:0				
Aquaculture	↓ R:1 M:1 P:0						
River diversion			↑ R:0 M:0 P:1				
Anchoring			↓ R:0 M:0 P:1				
Avoided habitat loss (salt marsh)	↑ R:0 M:2 P:0		↑ R:0 M:2 P:0				
Avoided habitat loss (mangroves)	↑ R:0 M:1 P:0		↑ R:0 M:2 P:0			↑	
Avoided habitat loss (seagrass)			↑ R:0 M:2 P:0	↑ R:0 M:1 P:0			
Dredging			↑ R:0 M:0 P:1				
Development	↓ R:0 M:2 P:0						
Diking	⇅ R:0 M:1 P:0						

Coastal: Habitat Restoration

Activity	Total	Belowground			Aboveground		
		Total	Sediment	Roots	Total	Live Biomass	Debris/ Litter
Habitat restoration	↑ R:0 M:2 P:0		↔ R:0 M:2 P:0			↑ R:0 M:1 P:0	

Control: Of the studies that report descriptions of the control, there appears to be variation in what restored coastal habitats are compared to, including before/after measurements, comparisons to mudflats, cleared sites, and mature natural sites

Timeline: Most studies do not report timeframes; those that did reported measurement time ranges from 3–22 years and 2–50 years, with a majority of studies focused on shorter timeframes and with up to half of studies from less than 1 year after restoration

Evidence for the effect of habitat restoration on carbon showed increased carbon stocks in mangrove biomass after restoration (Sasmito et al. 2019) (established but incomplete) and in total carbon stocks in salt marsh, mangrove, and seagrass (O'Connor et al. 2020) (established but incomplete). There was no clear effect on soil carbon stocks in mangroves or coastal marshes (Sasmito et al. 2019; Xu et al. 2019); in fact, one meta-analysis showed a decline in soil carbon stock in tidal wetlands that had previously been in cultivation (Xu et al. 2019) (unresolved). The short time frame of most restoration studies may not be sufficient to detect recovery of soil carbon. Experts pointed out that the field of coastal wetland restoration is relatively new, so the body of literature on carbon responses to restoration does not yet capture the longer-term effects of restoration. Salinity of coastal wetlands is a key factor in their overall GHG flux because low salinity is correlated with high methane production. One meta-analysis that looked at coastal and freshwater wetland restoration found that coastal wetlands (mangrove and salt marsh) were the only types to have a positive effect on the overall carbon balance due to low CH_4 emission, but had a very small sample size for those wetland types (Taillardat et al. 2020). Recent verified carbon standards for tidal wetland restoration projects highlight the potential for coastal habitat restoration to have positive carbon effects, but also the need for context-specific planning and verification with field data due to uncertainties about variation in soil carbon sequestration rates in natural versus restored systems and methane emissions from fresh and brackish wetlands (Needelman et al. 2018).

Coastal: Fishing

Activity	Total	Belowground			Aboveground		
		Total	Sediment	Roots	Total	Live Biomass	Debris/ Litter
Fishing			↑↓ R:1 M:0 P:0				

Control: The single study included summarized papers that used varied controls including unfished sites (39% studies), before/after fishing (24% studies), and no control (13% studies)
Timeframe: Study times range from 1 month to 31 years

Evidence for the effect of fishing on carbon showed mixed effects on organic carbon storage in seabed sediments as a result of mobile demersal fishing. The review included data from 38 studies with a total of 49 observations, 16% of which were in the Northwest Atlantic, which could include US coastal waters. Of all studies (including those not in US waters) 61% of investigations found no significant effect, 29% found lower organic carbon in fished sites compared to unfished controls, and 10% found higher organic carbon in fished sites . The observations that reported no significant effect of demersal fishing on organic carbon were more likely to be undertaken on sand, lacked controls, and measured organic carbon in shallower sediment depths (inconclusive) (Epstein et al. 2022).

Coastal: Aquaculture

Activity	Total	Belowground			Aboveground		
		Total	Sediment	Roots	Total	Live Biomass	Debris/ Litter
Aquaculture	↓ R:1 M:1 P:0						

Control: Natural coastal wetlands
Timeframe: Not reported

One global meta-analysis and one comprehensive review agree that aquaculture operations in coastal systems have negative effects on the total carbon balance compared to coastal systems without aquaculture (Tan et al. 2020; Ahmed and Thompson 2019) (established but incomplete). This evidence covers two main types of aquaculture: creating aquaculture ponds within natural coastal wetlands, which become hotspots of methane emissions, and converting mangrove forests to shrimp farms, which releases stored carbon and reduces carbon sequestration. There may be potential for more ecologically friendly forms of aquaculture to avoid negative carbon impacts - for example, integrated shrimp-mangrove cultivation that involves restoring degraded mangrove areas (Ahmed et al. 2018), or farming algae for biofuel production that directly consumes waste carbon dioxide (Benson et al. 2014), but research is still underway and no evidence for these benefits was found.

Coastal: River Diversion

Activity	Total	Belowground			Aboveground		
		Total	Sediment	Roots	Total	Live Biomass	Debris/ Litter
River diversion			↑ R:0 M:0 P:1				

Control: No diversion scenario (modeled)
Timeframe: Modeled effects over 50 years: 2010–2060

No reviews or meta-analyses for the effects of river diversion on carbon in coastal systems were found, but one large-scale modeling study projected effects of a variety of Mississippi River diversions on soil carbon in Louisiana coastal marshes (Wang et al. 2017). They found significant potential for river diversions to increase marsh soil carbon, with enhanced soil carbon associated with increased river discharge up to about 1,400 m^3/s (inconclusive). Beyond that threshold, increased flows could reduce soil carbon, in part from conversion of brackish marshes to freshwater marshes, which have lower soil carbon density. The researchers emphasized that large diversions will likely be required to maintain Louisiana wetland soil carbon under sea level rise, but that effects are context-specific and more research to determine discharge thresholds in specific basins, with different vegetation types, and under future environmental conditions is needed.

Coastal: Anchoring

Activity	Total	Belowground			Aboveground		
		Total	Sediment	Roots	Total	Live Biomass	Debris/ Litter
Anchoring			↓ R:0 M:0 P:1				

Control: Sites with no anchoring
Timeframe: Measurements taken roughly 80 years since anchoring started (and has been continuous since)

No reviews or meta-analyses for the effects of anchoring or mooring on carbon in coastal habitats were found; however, one field study on Thomson Bay in Australia, a region with nearly two centuries of anchoring and mooring activity over seagrass habitat, was reviewed. The study looked at sedimentary organic carbon stocks in sediment cores from areas with mooring as well as undisturbed habitat. The study found that there was an average loss of 4.8 kg organic carbon per square meter over the course of 200 years in each moored sediment core as compared to undisturbed habitat. The authors concluded that the moorings led to destruction of seagrass meadows that resulted in both inability of seagrass to sequester carbon and eroded sediments normally stories underneath seagrass meadows (inconclusive) (Serrano et al. 2016). The authors indicated that the size and duration of scars may impact the amount of sediment that is eroded and the amount of carbon lost.

Coastal: Avoided Habitat Loss (Salt Marsh)

Activity	Total	Belowground			Aboveground		
		Total	Sediment	Roots	Total	Live Biomass	Debris/ Litter
Avoided habitat loss (salt marsh)	↑ R:0 M:2 P:0		↑ R:0 M:2 P:0				

Control: The activity is existence of marsh, so there is no control
Timeframe: Emissions/fluxes are measured from existing natural marshes; there is no timeframe specified

Total ecosystem carbon in salt marshes was measured in two reviews, and both concluded that the net effect of salt marsh habitats on carbon was positive (Taillardat et al. 2020; Lu et al. 2017) (well established). Other reviews examining soil carbon sequestration in salt marshes also found positive effects of these habitats on carbon (Chmura et al. 2003; Mcleod et al. 2011) (well established). Therefore, avoiding loss of salt marsh habitats has a positive impact on carbon.

Variables shown to influence carbon storage rates in salt marsh habitats include mean annual temperature and precipitation (Lu et al. 2017; Mcleod et al. 2011), hydroperiod, salinity, nutrient status, suspended sediment supply, sediment type, and amount of herbivory (Mcleod et al. 2011). Multiple reviews noted it is likely that, if sea level rise outpaces marsh accretion rates, then salt marshes could release stored carbon into the atmosphere (Chmura et al. 2003; Mcleod et al. 2011). Multiple reviews also noted that coastal marshes have low to negligible rates of CH_4 emissions (Taillardat et al. 2020; Lu et al. 2017); however, with human disturbance these methane emissions could potentially increase (Lu et al. 2017).

It should be noted that all reviews included report effects of existing (not built or restored) salt marshes on carbon storage and sequestration. There is a high possibility that restored or created salt marshes might have a different effect, at least in terms of magnitude if not direction. A review by Xu et al. (2019) found that soil organic carbon in restored wetlands was lower than that of natural wetlands, and cultivated wetland soil organic carbon was lower still. This same review indicated that restored wetlands with tidal hydrology had negative effects on soil organic carbon sequestration. Broome et al. (2002) report that it takes many years for a restored wetland to store a high amount of soil carbon.

Coastal: Avoided Habitat Loss (Mangroves)

Activity	Total	Belowground			Aboveground		
		Total	Sediment	Roots	Total	Live Biomass	Debris/ Litter
Avoided habitat loss (mangroves)	↑ R:0 M:1 P:0		↑ R:0 M:2 P:0			↑	

Control: The activity is existence of mangrove, so there is no control
Timeframe: Emissions/fluxes are measured from existing natural mangrove sites; there is no timeframe specified

One review reported the net ecosystem budget of mangrove systems, and indicated that these habitats are a net carbon sink (relationship is positive) (Taillardat et al. 2020) (established but incomplete). Two additional reviews summarized the carbon storage in mangrove soils, which was also positive (Chmura et al. 2003; Mcleod et al. 2011) (well established).

Therefore, avoiding loss of mangroves has a positive impact on carbon. Experts also noted that mangrove habitats have significant aboveground biomass carbon stocks as well (expert call 11/2/22).

Variables shown to influence carbon storage rates in mangrove habitats include hydroperiod, salinity, nutrient status, suspended sediment supply, sediment type, amount of herbivory (Mcleod et al. 2011). Multiple reviews noted that it is likely that, if sea level rise outpaces mangrove forest accretion rates, mangroves could eventually drown and release stored carbon into the atmosphere (Chmura et al. 2003; Mcleod et al. 2011).

It should be noted that all reviews report effects of existing (not built or restored) mangrove habitats on carbon storage and sequestration. However, primary literature from non-US sites seems to indicate that carbon storage and stocks of intact and restored mangrove sites are not substantially different (Hong Tinh 2020; DelVecchia et al. 2014). However, it has been noted that some restored tidal wetlands (including but not exclusive to mangroves) have had negative effects on soil organic carbon content (Xu et al. 2019).

Coastal: Avoided Habitat Loss (Seagrass)

Activity	Total	Belowground			Aboveground		
		Total	Sediment	Roots	Total	Live Biomass	Debris/ Litter
Avoided habitat loss (seagrass)			↑ R:0 M:2 P:0	↑ R:0 M:1 P:0			

Control: The activity is existence of seagrass, so there is no control
Timeframe: Emissions/fluxes are measured from existing natural seagrass sites; there is no timeframe specified

Only one review reported a summary of soil carbon sequestration rates in seagrass habitats, and found that these systems have a positive effect on carbon (Mcleod et al. 2011). Another synthesis focused on carbon stocks and found that seagrasses store significant amounts of carbon, primarily in sediments and to a lesser degree in root biomass (well-established). Therefore, avoiding loss of seagrass has a positive impact on carbon.

Variables known to affect carbon storage in seagrass habitats include meadow species composition, complexity of the canopy, whether the meadow is continuous, whether trophic webs are intact, exposure to hydrodynamic energy, turbidity, water depth, whether the meadow is intertidal or subtidal, nutrient availability, and the climatic region of the seagrass site (Mazarrasa et al. 2018).

It should be noted that information included here report effects of existing (not built or restored) seagrass habitats on carbon storage and sequestration. No information could be found on the difference in carbon storage and sequestration between restored and intact seagrass beds.

Coastal: Dredging

Activity	Total	Belowground			Aboveground		
		Total	Sediment	Roots	Total	Live Biomass	Debris/ Litter
Dredging			↑ R:0 M:0 P:1				

Control: Before dredging occurred
Timeframe: Directly after dredging

Limited evidence for the effect of dredging on carbon in coastal areas showed an increase in total carbon and total organic carbon in sediments in a before/after field experiment in an estuary in Singapore (inconclusive). The study found statistically significant increases in sediment carbon after dredging in silt and clay, and statistically significant decreases in sediment carbon after dredging in sand. The paper authors determined that higher rates of carbon are associated with resuspension of organic carbon from deeper layers of contaminated sediments from historic agriculture, aquaculture, land drainage, and flooding. As a result, it is unclear if these results would be replicated in contexts without the exposure of carbon found in deeper sediments (inconclusive) (Nayar et al. 2007).

Coastal: Development

Activity	Total	Belowground			Aboveground		
		Total	Sediment	Roots	Total	Live Biomass	Debris/ Litter
Development	↓ R:0 M:2 P:0						

Control: Natural coastal wetland
Timeframe: Most included studies were short-term (1 year or less); almost all were from 10 years or fewer after development

Two syntheses were found that discuss the effects of development of coastal systems to other land use on GHGs. One meta-analysis clearly indicated that development of coastal systems would have a negative effect on net emissions (Tan et al. 2019). When natural coastal wetlands were transitioned to croplands or aquaculture ponds, the comprehensive global warming potential of the sites increased by over 2,200% and 2,900%, respectively (Tan et al. 2019). Another global meta-analysis also found evidence for negative effects of development on total carbon stock, but did not see significant effects on total GHG fluxes (O'Connor et al. 2020) (established but incomplete).

Coastal: Diking

Activity	Total	Belowground			Aboveground		
		Total	Sediment	Roots	Total	Live Biomass	Debris/ Litter
Development	↓ R:0 M:2 P:0						

Control: Degraded coastal wetland
Timeframe: Half of included studies from less than one year after intervention

Only one meta-analysis was found that discusses the effects of altered hydrology, including diking, in coastal systems on carbon and GHGs. Altered hydrology had a positive impact on total carbon stock and no significant effect on GHG fluxes from coastal wetlands with altered hydrology compared to degraded wetlands (O'Connor et al. 2020) (unresolved). It is important to consider that this study groups diking with other hydrology alterations (including impoundment and altered flow), and treats it as a restoration method. Therefore, these results may not be relevant for situations where diking is used for purposes other than ecological restoration.

Carbon in Marine Systems

This section contains results for the effects of management activities on carbon and GHG emissions in marine systems. These results were informed by a rapid literature review focused on syntheses and meta-analyses, and expert input obtained through individual calls. More detailed methodology information is available in the Methods section of this report.

The next page of this document contains a summary table with arrows showing the effects of a variety of management activities on several carbon pools. The following pages include detailed results for each activity in the summary table, including a narrative summary of the relationship incorporating information from the literature and experts, a description of the control condition to which the activity is being compared, the timeframe covered by the summarized results, and a list of references.

There were several additional management activities for which we did not find any relevant meta-analysis or review studies, which are not included in these results:

- Offshore wind energy
- Fishing
- Anchoring
- Restoration
- Boating/shipping
- Dredging

In addition to the general limitations of this approach described in the project background document, experts raised several issues relevant to marine systems:

- Several of the activities for which no synthesis literature was found likely have relevant primary literature: anchoring, fishing, and dredging.
- There are several different methodologies for fishing that likely have different effects (e.g., trawling versus long-line).
- It is possible that there has not been any primary research on the carbon impacts of installing turbines for offshore wind energy.
- Some government agencies such as the National Oceanic and Atmospheric Administration, Bureau of Ocean Energy Management, and National Renewable Energy Laboratory may have information on certain activities, such as mining and oil and gas extraction.
- The community of researchers on marine and deep-ocean systems is relatively small, so it would be possible to get fairly comprehensive expert input on these with additional outreach.

Carbon in Marine Systems: All Activities

Activity	Total	Belowground		Aboveground		
		Total	Sediment	Total	Live Biomass	Water Column
Aquaculture			↑ R:1 M:1 P:0		↑ R:1 M:0 P:0	
Oil and gas extraction			↑↓ R:0 M:0 P:1			
Protection			↑ R:0 M:2 P:0			
Mining			↑↓ R:2 M:0 P:0			

Marine: Aquaculture

Activity	Total	Belowground		Aboveground		
		Total	Sediment	Total	Live Biomass	Water Column
Aquaculture			↑ R:1 M:1 P:0		↑ R:1 M:0 P:0	

Control: All studies are multisite comparisons that may measure change before/after treatment but do not outline control site conditions
Timeframe: Not reported for all included references

There are no global meta-analyses assessing the effect of aquaculture operations on carbon in marine systems. However, there are reviews or analyses of sources of carbon associated with marine aquaculture that can impact carbon fluxes in marine environments. Marine aquaculture for fish increases carbon in the sediment through depositions of organic matter from fish feed and excretion as evidenced by studies in Europe, Canada, and Hong Kong (Wu 1995; Kalantzi and Karakassis 2006). The evidence base for these findings is more than 15 years old and aquaculture technology has since evolved (inconclusive). Macroalgae mariculture, however, can be a sink for carbon and remove carbon from the environment. A study of macroalgae mariculture in all of China found it to be a significant source of carbon removal (Jiao et al. 2018); however, a global review has not yet been completed (inconclusive). It is important to note that offshore aquaculture in the US is still very rare.

Marine: Oil and Gas Extraction

Activity	Total	Belowground		Aboveground		
		Total	Sediment	Total	Live Biomass	Water Column
Oil and gas extraction			↑↓ R:0 M:0 P:1			

Control: Pre- and postdrilling surveys (though it is unclear if those survey sites had never previously been drilled)
Timeframe: Not reported

There are no global meta-analyses assessing the effect of oil and gas extraction activity on carbon in marine environments. However, one study of offshore drilling effects on marine sediment in southeastern Brazil (Dore et al. 2017) measured change in total organic carbon from oil and gas extraction activity. The study's results were inconclusive, noting that there was no conclusive pattern or change in marine sediment linked to drilling activities. The average change recorded was −0.39% with a ±0.62 confidence interval (inconclusive). Similar studies measuring marine sediment in areas with oil and gas exploration (including the Gulf of Mexico) focused on heavy metal concentrations. Many studies also pointed to the potential of decommissioned oil and gas pipelines as storage for sequestered carbon. The Bureau of Ocean Energy Management may have resources, including National Environmental Policy Act documents, that address the effects of oil and gas on carbon (expert call 11/3/22).

Marine: Protection

Activity	Total	Belowground		Aboveground		
		Total	Sediment	Total	Live Biomass	Water Column
Protection			↑ R:0 M:2 P:0			

Control: Untrawled seabeds (unclear if other disturbances to bottom habitat).
Timeframe: 20–40 years after Marine Protected Area implementation

There are two global meta-analyses assessing how protection through marine reserves or protected areas affects carbon in marine environments. One recent study (Jankowska et al. 2022) found that protection has positive carbon benefits by both facilitating carbon storage in the ocean area (14,745.67 ± 6,597.6 tC/ha) and avoiding carbon emissions from the protected seafloor (13.83 ± 6.36 t/ha per year). The study also included carbon removal benefits from macroalgae and wetlands protection that were not included in this results table as they were not in marine systems. This study is based off of carbon storage determinations from more than 11,000 data points and 685 sediment cores. Another study measured carbon sequestration, finding significantly higher rates of carbon sequestration in untrawled sediments than trawled (Jacquemont et al. 2022), though noting that the relative contribution of carbon sequestration from seabeds is less significant than other habitats such as mangroves. These are the first two studies published on this topic (established but incomplete).

Marine: Mining

Activity	Total	Belowground		Aboveground		
		Total	Sediment	Total	Live Biomass	Water Column
Mining			⮁ R:2 M:0 P:0			

Control: No controls, effects modeled based on data from previous sites and studies
Timeframe: Not specified

There are no global meta-analyses assessing how deep-sea mining to extract minerals affects carbon in marine environments, and likewise no published studies that measure the effect of these activities on carbon in sediment from mining activity. One publication (Orcutt et al. 2020) estimates the effect of mining on local carbon cycling in the deep ocean, citing that mining would result in resuspension of sediments but the effect would be trivial, because deep-sea sediments have low concentrations of organic matter that is not readily bioavailable and that would ultimately redeposit onto the seafloor. An additional publication (Levin et al. 2020) agreed, citing that mining activity could disrupt nonphotosynthetic carbon fixation associated with water, sediments, or nodules in the deep sea. Mining can also potentially enhance oxygen depletion, resulting in the release of GHGs or reducing the vertical transport of carbon via migrating fauna. The authors noted that similar effects are possible with trawling activity. They also noted that there is limited knowledge on deep-sea carbon cycling, restricting the understanding of mining impacts on carbon (inconclusive).

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