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Review

Environmental problem shifting from climate change mitigation: A mapping review

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Abstract

Climate change mitigation will trigger major changes in human activity, energy systems, and material use, potentially shifting pressure from climate change to other environmental problems. We provide a comprehensive overview of such "environmental problem shifting" (EPS). While there is considerable research on this issue, studies are scattered across research fields and use a wide range of terms with blurred conceptual boundaries, such as *trade-off, side effect*, and *spillover*. We identify 506 relevant studies on EPS of which 311 are empirical, 47 are conceptual–theoretical, and 148 are synthetic studies or reviews of a particular mitigation option. A systematic mapping of the empirical studies reveals 128 distinct shifts from 22 categories of mitigation options to 10 environmental impacts. A comparison with the recent IPCC report indicates that EPS literature does not cover all mitigation options. Moreover, some studies systematically overestimate EPS by not accounting for the environmental benefits of reduced climate change. We propose to conceptually clarify the different ways of estimating EPS by distinguishing between gross, net, and relative shifting. Finally, the ubiquity of EPS calls for policy design which ensures climate change mitigation that minimizes unsustainability across multiple environmental dimensions. To achieve this, policymakers can regulate mitigation options—for example, in their choice of technology or location—and implement complementary environmental policies.

Keywords: environmental policy, nexus, planetary boundaries, SDGs, sustainability

Introduction

Mitigation policies are intended to transform society in terms of activities, use of materials, and sources of energy. Transformation on this scale is likely to shift pressures from climate change to other environmental domains. For climate change mitigation policy to be sustainable in a broad environmental sense, it must anticipate the risk of environmental problem shifting (EPS). While this issue has been recognized in the case of certain climate change mitigation options, a broad and encompassing overview of EPS is lacking. This motivates the systematic mapping undertaken in this study.

EPS denotes efforts to address one environmental problem which create or worsen another. While the concept is relevant for environmental policy and strategies in general, we focus here on shifts caused by climate change mitigation. One example is bioenergy shifting pressure toward water stress due to biomass plantations requiring considerable irrigation.

Although the literature on climate policy is large, policy studies rarely account for the wider environmental impacts of climate change mitigation—instead, social and distributional impacts receive most attention. It is common in the natural sciences to examine how environmental problems are connected, for instance, as interactions between earth system processes (1). This has, however, not resulted in a comprehensive mapping of how biophysical interactions contribute or translate into EPS. Such a mapping requires the integration of biophysical interactions and socioeconomic systems. This has only been achieved for certain shifts, notably those that have received considerable attention in the literature. An example of such is the shift from renewable energy to biodiversity loss (2, 3). Some of these shifts—in particular those relating to land use change—have been used in integrated assessment models linked with global vegetation models, such as in the LPJml-ReMIND-MAgPIE model (4).

There are several reasons for the lack of a comprehensive overview of EPS. One relates to terminology—only a few studies have used this exact term. Generally, studies that examine EPS lack uniform terminology, partly because they come from different traditions and fields. Indeed, a wide diversity of terms can be found; *trade-off*, *spillover*, *ancillary effects*, *co-costs*, *interaction effects*, *unintended consequences,* and *adverse side effects*. Since these terms are often left undefined, their conceptual boundaries tend to be blurred, making it difficult to judge to what extent they differ or overlap. In addition, while a few studies put EPS center stage, most pay attention to it only as part of a broader analysis. By mapping the variety of terms onto our typology of policy effects, we delineate EPS and other terms for conceptual clarification. In turn,

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Table 1. Number of articles by journal.

Journal name	No.	Journal name	No.
Environmental Research Letters	33	*Biomass and Bioenergy*	8
Renewable & Sustainable Energy Reviews	21	*Energy Policy*	7
Journal of Cleaner Production	19	*Scientific Reports*	7
Global Change Biology	17	*International Journal of Greenhouse Gas Control*	7
Global Change Biology—Bioenergy	17	*Nature Climate Change*	7
Environmental Science and Technology	14	*Journal of Industrial Ecology*	6
Applied Energy	13	*Science*	6
Sustainability	13	*Journal of Environmental Management*	6
Science of The Total Environment	13	*Environmental Research*	5
Nature Communications	10	*PLoS ONE*	5
Energies	9	*Agriculture, Ecosystems and Environment*	5
PNAS	9	*Sustainable Production and Consumption*	5
Resources, Conservation and Recycling	8	120 other journals (four or less studies each)	198
Climatic Change	8		
Global Environmental Change	8		
Nature Sustainability	8	Total	492

this will help to improve the quality of future EPS assessments and ultimately the design of climate policy.

We review both theoretical–conceptual and empirical studies of EPS. The first type enables us to identify and compare the main concepts and frameworks proposed. The second type allows us to map the shifts from mitigation options to environmental problems.

Several earlier studies review particular types of EPS, although few use the term *environmental problem shifting* explicitly. An early review of *co-impacts* focused on monetary valuation methods and energy-based mitigation (5). A synthesis of economic, social, and environmental *coeffects* of mitigation examines the literature reviewed in IPCC WG3 AR5 and discusses methodical challenges of integrated modeling, particularly how to quantify and aggregate coeffects (6). Although not a systematic review (7) surveyed previous literature on concepts related to EPS and analyzed potential shifts from a hypothetical scenario in which solar energy becomes cheap. Other reviews are limited to specific subsets of shifts: related to certain sectors, such as agriculture and forestry (8) certain mitigation measures, such as bioenergy (9) or certain environmental impacts, such as biodiversity (10). A review of both positive and negative effects of mitigation on categories ranging from economic activity to conflict resilience provided limited detail on different environmental impacts (11).[1] In addition, there are multiple reviews of interactions between sustainable development goals (SDGs): they cover both interactions arising specifically from climate action (12) and interactions between SDGs in general (13, 14). These reviews adopt a broad socioeconomic perspective in line with the SDG framework but provide little detail on distinct environmental issues. The planetary boundary framework has also been used to examine interactions between earth system processes; one study surveys and estimates shifts from two interventions, namely diet change and bioenergy with carbon capture and storage (BECCS) (1), while another examines the impacts of carbon pricing on multiple boundaries (15). None of the above studies focus on the negative environmental impacts of climate change mitigation as we do in this study.

This mapping study aims to answer the following questions: what are the most studied shifts, i.e. from which mitigations options to which environmental impacts? Are certain shifts ignored or understudied? Which are the most frequently used terms in studies on EPS, and what is the clearest term to use? What factors underlie the occurrence and magnitude of shifts? Can EPS be assessed without accounting for the environmental effects of unmitigated climate change? How can policy and planning moderate or limit EPS?

The remainder of this article is organized as follows: The Results section cover the mapped publications and methods, a typology of policy effects to delineate EPS from alternative terms, terminology used, conceptual aspects, mitigation measures, environmental impacts, and categories of shifts identified. The Discussion section considers the findings and draws implications for research and policy design. The Conclusion section summarizes the key points. Finally, the Mapping method section describes the methods and mapping protocol employed.

Results

Publications and methods

Our final sample consists of 506 publications dealing with environmental problem shifting, of which 492 are journal articles and 14 are published in other formats such as book chapters and reports. The publications include 311 empirical studies of EPS caused by particular climate change mitigation options or policies, 47 conceptual or theoretical studies, and 148 reviews of subsets of impact categories or mitigation options. The large number of specialized reviews relative to primary research articles indicates that EPS spans many topics. These tend to be narrow in scope and limited to either a specific mitigation category, a particular environmental impact, a certain shift, or a specific national context. In line with the distribution of mitigation options among the empirical studies (presented in the Results subsection *Shifts from mitigation options to environmental impacts*), the most frequent themes in the reviews are biomass for bioenergy and biomaterial [32 reviews], carbon dioxide removal [32], and renewable energy technologies [16].

The studies reviewed have been published in 149 distinct journals. This indicates we are dealing with a diffuse subject, lacking a cohesive forum for discussion. Table 1 presents the journals with the most articles. Most of these are devoted to energy (six titles) or environment and sustainability in a broad sense [15]. Given the focus on mitigation, it is remarkable that only three journals specialize in climate change.

Figure 1 shows the literature reviewed by publication year. The first publication on EPS is a book chapter from 1989, while the first peer-reviewed study is from 2000. Since then, a gradually increasing number of publications on EPS have appeared.

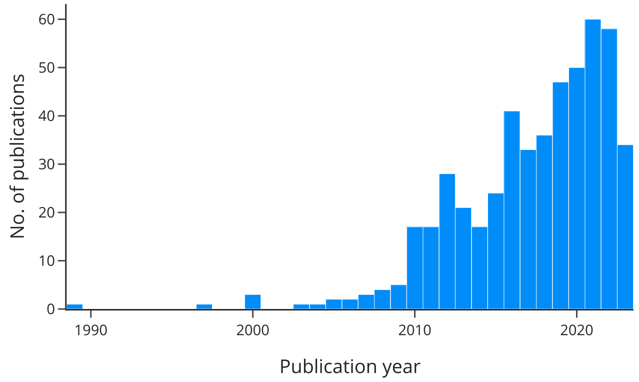

Fig. 1. Publications by year.

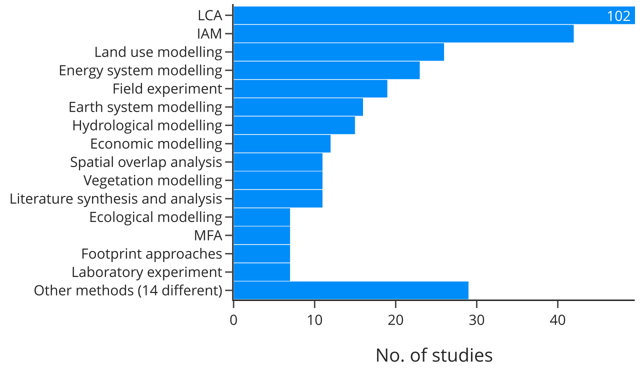

Fig. 2. Methods used in empirical studies. Notes: The horizontal axis is broken for readability. Studies can use more than one method. The category Other methods contains methods used less than six times. LCA, life-cycle assessment; IAM, integrated assessment modeling; and MFA, material flow analysis. Here, IAMs are defined as integrating biophysical and economic aspects, whereas Earth system models as integrating biophysical aspects only.

Figure 2 shows the methods used in the empirical studies. Life-cycle analysis (LCA) dominates [102 studies] and integrated assessment modeling (IAM) to a lesser extent [42]. Some IAMs are linked to other models to account for land use, vegetation cover, and hydrological processes, as in the case of the dynamic global vegetation model LPJmL or the agriculture and land use model MAgPIE (e.g. 16). Many of the IAM applications rely on established scenario frameworks, such as the Shared Socioeconomic Pathways, to project demographics, costs of technologies, and energy demand (see e.g. 17). This approach generates cost-effective paths of mitigation, based on a combination of measures.

Other common methods include land use models [26], energy system models [23], and field experiments [19]. A total of 14 other methods have been identified as appearing less frequently, while five studies could not be categorized.[2] The breadth of methods used to study EPS indicates that it is a subject lending itself to examination from many different perspectives and by a variety of disciplines.

A typology of policy effects

Environmental problem shifting is part of a broader literature on the effects of climate policy. Figure 3 presents a typology of policy effects, which shows how EPS is the only term that describes a certain subset of policy effects. The typology distinguishes between primary and secondary effects. Primary effects relate to the policy target, in our case climate change mitigation. Secondary effects are divided into three subtypes: indirect effects on the policy target, such as carbon leakage and rebound; socioeconomic effects like (un)employment; and nontarget environmental effects, such as on biodiversity. When the latter are negative, we speak of EPS. In general, all three subtypes of effects can be positive or negative. To be clear, this typology does not distinguish tertiary and *n*th-order feedback effects—these are implicit in the three subtypes. We use the typology to guide our mapping and separate EPS from alternative concepts used in the literature.

The definition of EPS given in the Introduction section mentioned efforts that address a problem at the expense of another. This encompasses both partial and complete shifting. Partial shifting occurs when a mitigation measure reduces or removes a limited amount of greenhouse gas emissions, as is most often the case in practice. Complete shifting becomes relevant, for instance, in scenario modeling, when renewable energy is scaled up to replace global use of fossil fuels (19).

EPS refers to problem-to-problem shifts; it does not apply to mere modification of stressors. To clarify, the distinction between the concepts of *stressor* (e.g. CO_2 emissions) and *impact* (e.g. global warming), as used in LCA, is relevant. EPS denotes a change from one environmental impact to another, not merely a change in stressor.[3] To illustrate, a mitigation measure that reduces atmospheric CO_2 emissions but increases N_2O emissions is not a case of EPS as both stressors are greenhouse gases, meaning the impact type does not change.

Terminology

Uses of the exact term *environmental problem shifting* in the literature reviewed are scarce. The first explicit mention is found in a book chapter by Weidner (20). Sometime later, it was used in a conceptual study of materials management, involving a distinction between forms of EPS (21). Climate change was first associated with EPS in a broader discussion of governance to address interactions between planetary boundaries (22). A study by van den Bergh et al. (7) was the first to focus on EPS from climate change mitigation, examining how a hypothetically large-scale expansion of solar photovoltaics could shift pressure to other environmental problems. Within the context of environmental law (23) described problem shifting as the result of gaps between departmentalized institutions each focused on distinct environmental issues. Finally, the LCA literature offers 10 studies that explicitly use the term environmental problem shifting.[4]

To clarify the difference between EPS and similar terms, we consider related terms used in the studies reviewed. Table 2 provides a count of their usage. The most frequent term is *trade-off*, which denotes having to sacrifice something to gain something else. Next, common terms, such as *cobenefit*, *side effect,* and *unintended consequence*, and less common terms, such as *cascade effect*, *spillover,* and *coimpact*, all denote secondary effects—often encompassing types of effects other than merely EPS (Figure 3), including positive ones. Other terms, such as *interaction effect*, *coupled effect*, and *linkage*, indicate that effects are connected without specifying a direction. This makes them difficult to apply in a policy context. *Displacement* refers to spatial shifts. *Environmental burden shifting* has a meaning similar to EPS in some cases, while in others it refers to shifts between life-cycle stages only (e.g. 26). The term *ancillary impact* frequently appears in monetary valuation studies. Another term, *environmental side effect*, indicates an effect of minor importance by suggesting a hierarchy between main and side effect. EPS, in contrast, indicates a shift from one environmental problem to

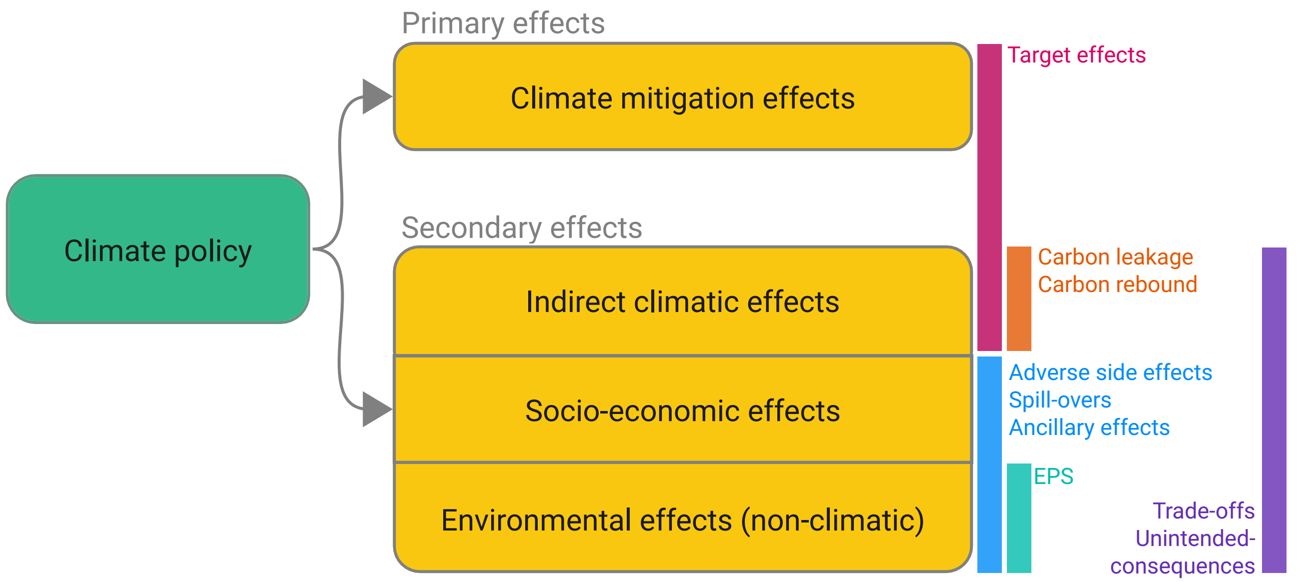

Fig. 3. Typology of policy effects. Notes: The vertical bars on the right signify which types of policy effects are denoted by the corresponding alternative terms. Cobenefits, ancillary effects and adverse side effects are categorized as defined in IPCC AR6 WG3 Glossary (Annex 1, 18).

another without claiming that the first problem is more important or different in magnitude that the second problem.

Conceptual aspects of EPS

Conceptual discussions of EPS are found in different fields of study: Earth system science and governance, environmental policy integration, industrial ecology, LCA, nexus studies, SDG interactions, and systems theory. These fields employ distinct concepts and frameworks to examine how the environment and the economy connect. Common examples are complex systems, systems integration, planetary boundaries, tele-coupling and metacoupling, integrated management, and socioecological systems approach. Various complexity issues—of which EPS is one—are central to these frameworks and include indirect effects, feedbacks, and interactions. There are also those methods that seek to account for EPS. Some do so by incorporating multiple environmental issues into integrated footprints, such as the ecological footprint. Others use performance criteria alongside each other, in a so-called footprint family, or the planetary boundaries.

The conceptual–theoretical literature reviewed [47 studies] proposes different forms of EPS. Here, we distinguish between type and form of EPS. *Type* describes the instances of EPS observed, e.g. from bioenergy to biodiversity loss. *Form* refers to the ways in which the shift occurs, including spatial shifts, temporal shifts, and shifts from one kind of environmental impact to another—or combinations hereof (23).[5] Temporal shifting is the postponement of impacts. Spatial shifting occurs when an environmental impact is relocated. The term *medial shifting* has also been proposed to denote a problem shift from one environmental medium to another, such as from air to soil (20). The literature also puts forward three other forms of EPS: shifts within and across material chains (21) shifts between life-cycle phases, such as electrification of cars intensifying the impact of vehicle production while lowering the impact in the use phase (28) and shifts in consumption, for instance, consumers changing to a meat-free diet while spending the savings on goods associated with other environmental pressures (21). These three studies, however, do not address problem shifting itself, but rather the underlying mechanisms of shifting. Other studies distinguish between biophysical and socio-economic mechanisms (1, 7). This categorization emphasizes the need for a multidisciplinary approach to assess shifts.

Table 2. Number of studies that mention various terms, by study type.

Alternative terms	Empirical studies [out of 311]	Conceptual–theoretical [47]	Reviews [148]	Total, all studies [506]
Trade-off	195	19	79	295
Cobenefit	25	9	36	70
Interact	24	13	16	53
Displacement	27	2	13	42
Unintended consequence	22	3	10	35
Side effect	19	0	12	31
Coupled effect	21	4	5	30
Problem shift	10	5	0	15
Feedback	6	2	6	14
Burden shift	10	0	1	11
By-product	7	0	4	11
Interlinkage	4	4	3	11
Spillover	3	5	2	10
Adverse side effect	5	0	4	9
Linkage	2	5	1	8
Cascade effect	4	1	3	8
Ancillary	0	3	1	4
Environmental side effect	2	0	1	3
Interdependent	1	1	1	3
Coimpact	0	1	1	2

The numbers account for slight variations in terms; e.g. *cascade effect* covers *cascading impacts*.

Various studies have attempted to characterize EPS and its variability along different dimensions. While some authors classify shifts by whether they are intended (5, 23), intent is difficult to assess in practice. A clearer distinction might be whether a shift is expected (assessed and evaluated) before a decision is made about a particular mitigation action or policy (29). Many studies characterize shifts based on their underlying mechanisms, but

Table 3. Number of studies on each mitigation option.

Mitigation options and subthemes		No. of studies
Bioenergy		75
First generation: food crops	28	
Second generation: energy crops, residuals	46	
Third generation: microalgae	5	
Biofuel for aviation	5	
Carbon dioxide removal (CDR)		61
Afforestation, reforestation & revegetation (ARR)	23	
Bioenergy with carbon capture and storage (BECCS)	19	
Direct air capture with CCS (DACCS)	8	
Enhanced weathering (EW)	5	
Biochar	4	
Soil carbon sequestration (SCS)	4	
Ocean iron fertilization (Ocean IF)	4	
Ocean alkalinity enhancement (Ocean AE)	2	
Solar, hydro & wind power		44
Solar: photovoltaics, concentrated solar power and solar thermal	15	
Hydro: dams, tidal power, and run-of-river facilities	15	
Wind: on-shore and off-shore turbines	24	
Low-carbon electricity systems		29
Carbon capture and storage (CCS)	23	
Carbon capture and use (CCU)	9	
CCS & CCU		30
Batteries for storage and transport	5	
Mineral and metal requirements	11	
Systems which include nuclear	12	
Electric vehicles		17
Carbon pricing		12
General mitigation		11
Other		27
Hydrogen energy carriers	10	
Diet change	6	
Biomaterials	5	
Agricultural management	4	
Waste-to-energy	1	

The frequency of subthemes does not necessarily match the numbers in the associated mitigation category, because one study can contain multiple subthemes while others lack a clear subtheme.

attributing these unambiguously and accurately can be difficult due to the potentially lengthy and complex chains of causality, which raise chicken-and-egg questions. For instance, the EPS associated with switching from vehicles with an internal combustion engine to electric vehicles could simultaneously be attributed to life-cycle phase shifts or technological innovations. A conceptual discussion by von Stechow et al. (6) suggests that EPS can occur across various levels: local, sectoral, economy-wide, and global. Reversibility, as suggested by Rodríguez et al. (30) in the context of changes in ecosystems services, can also be relevant to shifting. Epistemological distance and complexity are two other dimensions of importance (31). While originally used to characterize environmental problems unrelated to shifting, they may be relevant when analyzing shifts. For example, EPS from a perceptible problem, such as smog, to a less perceptible one like biodiversity loss, increases epistemological distance. Likewise, a shift from a global problem, such as climate change, to a local problem, such as ecotoxicity (e.g. due to herbicides used in biomass plantations), may be regarded as a shift that reduces complexity.

Mitigation options studied

Based on the empirical studies reviewed, the mitigation options are organized into 13 main categories, shown in Table 3. For brevity, five of these are collated into an *other* category because each cover 10 or fewer studies. From the 311 empirical studies, we exclude 16 in the following counts, tables, and figures, because while these focus on EPS, they do not find environmental impacts to be negative.[6] This ensures that all the results presented can be interpreted as a count of studies which find EPS rather than merely studies of it. That brings the total number of studies which find EPS to 295. Studies on mitigation related to energy production dominate, namely *bioenergy*; *solar, hydro & wind power*; and a broader category that we call *low-carbon electricity systems*. Together these make up more than half of the studies reviewed [148 of 295]. Next, carbon dioxide removal (*CDR*) [61] and *CCS & CCU* [30] come out as the most frequently studied mitigation options.[7]

Two of the categories warrant special explanation, while the rest are described in the Supplementary Material S2. *Low-carbon electricity systems* studies differ from the two categories *bioenergy* and *solar, hydro & wind power*. Whereas the two latter categories deal with specific low-carbon energy technologies, studies on *low-carbon electricity systems* consider comprehensive energy systems that combine energy generation technologies, energy infrastructure for transmission and storage, and add-ons, such as CCS and electrification of vehicle fleets. Two topics are frequently highlighted in these studies: batteries to store energy from intermittent sources and for use in transport; and materials, such as minerals and metals, required to allow the studied transition to a low-carbon energy system. Several studies discuss the environmental costs of extracting these materials, but disaggregating their findings was difficult as the shifts could not be attributed to distinct elements of the energy system. Nuclear energy was an element in some of the system models but was generally given limited attention. Finally, *general mitigation* studies investigate various broad policy mixes that include—besides energy systems—policies focusing on lifestyle change and agricultural practices. We used this category for studies with several mitigation measures and shifts that could not be disentangled.

Environmental impacts studied

The environmental impacts found in the empirical studies of EPS fall into 10 broad categories, as summarized in Table 4. The three impact categories most prone to shifts are *freshwater use*, *biodiversity loss & ecosystem functioning*, and *land use & degradation*.

The category *freshwater use* is almost exclusively related to quantity, such as water scarcity. Quality issues related to ecotoxicity and eutrophication are categorized separately, in line with LCA conventions. *Land use & degradation* encompasses environmental issues associated with the extent and intensity of land use by human activity.[8] We classify impacts such as ecosystem damage and habitat fragmentation as biodiversity issues, although these are often closely related with land use. *Biodiversity loss & ecosystem functioning* form a combined category, reflecting that they tend to go hand-in-hand.[9] This category contains a diverse list of impacts: species diversity, richness, or representation; threatened and endangered species; protected areas; habitat loss, diversity, and fragmentation; insect, animal, and plant mortality; and ecosystem quality damage such as streamflow regulation. Examples of impacts on the subcategory *marine environment* are deep sea acidification and changes to the marine biological pump. Most studies in the category *eutrophication & biogeochemical flows* described nitrogen or phosphorus leaching and run-off, but few specified the source of eutrophication. *Human toxicity* includes toxicants, ionizing radiation from

Table 4. Occurrence of environmental problems in the studies reviewed.

Environmental impact category and subthemes		No. of studies
Freshwater use		101
Quantity	97	
Quality	7	
Land use & degradation		85
Land use	82	
Land degradation	5	
Biodiversity loss & ecosystem functioning (incl. marine environment)		78
Terrestrial & freshwater	72	
Marine environment	7	
Eutrophication & biogeochemical flows		65
Nitrogen	15	
Phosphorus	4	
Human toxicity (incl. ionizing radiation)		52
Carcinogenic and noncarcinogenic toxicants	31	
Ozone layer depletion	6	
Ionizing radiation	8	
Air pollution		48
Conventional air pollutants (SO_x, NO_x, $PM_{2.5}$, and PM_{10})	35	
Ozone formation	5	
Mineral & metal depletion		38
Ecotoxicity		38
Freshwater	16	
Terrestrial	14	
Marine	8	
Acidification (mainly SO_2, NO_2, and NH_3)		31
Environmental impacts of mining (unspecified)		13

The frequency of subthemes does not necessarily match the numbers in the associated impact category, because one study can contain multiple subthemes while other studies lack a clear subtheme.

radioactive material, and ozone layer depletion. The category *air pollution* covers conventional air pollutants, such as sulphur oxides, nitrogen oxides, particulate matter formation, and ozone formation. *Mineral & metal depletion* is solely about depletion of resources and not the environmental impacts of associated extraction. *Ecotoxicity* includes both terrestrial and aquatic impacts, although these are rarely specified in the mapped studies. *Acidification* refers to deposition of acidifying substances to soil and surface waters. Note that ocean acidification is a separate issue categorized under biodiversity loss and ecosystem functioning. *Environmental impacts of increased mining* encompasses issues other than depletion. Studies in this category focus on the environmental damage from extracting and producing the minerals and metals required for certain low-carbon transition scenarios. The specific environmental impacts are not estimated and cannot be attributed to any of our other impact categories.

Shifts from mitigation options to environmental impacts

The panels in Figure 4 depict 128 distinct shifts from 22 mitigation options to environmental impacts. Figure 4A covers the nine aggregated mitigation categories through 73 shifts. From the figure, we see—by the thickness of colored lines—that the three of the four most mentioned shifts are all from *bioenergy* to *freshwater* [33 studies], to *land use* [30], and to *eutrophication* [26]. Next come shifts from *solar, hydro & wind power* to *biodiversity loss & ecosystem functioning* (30). The Figures 4B, C, and D depict disaggregated results for the three categories *CDR*, *solar, hydro and wind power*, and *other*. Again, we note that the number of studies cannot be interpreted directly as an indication of likelihood or magnitude.

The shifts in our mapping are neither absolute nor universal to all variants of a mitigation measure. Many of the findings reviewed are specific to a study's system boundaries, local features, or implementation of the mitigation activity. For instance, one study finds EPS from revegetation but limits its scope to savannas. Generally, shifts depend on the scale of mitigation and the ecological context, such as, soil, hydrological conditions, flora, and fauna.

Bioenergy dominates the literature on shifts to multiple impact categories, even when excluding bioenergy as a component of BECCS.[10] In line with being the most studied mitigation option, the four most commonly studied shifts are all from *bioenergy*, namely to *freshwater use* [33 of 101 shifts to freshwater], *land use* [30 of 85], *eutrophication* [26 of 65], and *air pollution* [13 of 48]. Shifts are found for all three subtypes of bioenergy, i.e. first-, second-, and third-generation bioenergy. There are several underlying mechanisms: feedstocks require land, irrigation, and fertilizer; biofuel combustion generates more air pollution in the form of particulate matter compared with certain fossil fuels; and the use of monocultural plantations provides little habitat for biodiversity. One study finds that given the expected bioenergy production in most IAMs, shifts to biodiversity loss are inevitable (38).

The shifts from the two categories *low-carbon electricity systems* and *general mitigation* reveal several common characteristics, as both categories tend to deal with mixed mitigation options or comprehensive energy system measures. Three examples illustrate the diversity of shifts in this category: hydro dams shift environmental problems to water scarcity due to increased evapotranspiration; bioenergy shifts to ecotoxicity due to herbicide use; CCS shifts to air pollution, ecotoxicity, and eutrophication due to the substantial use of material inputs (39). These examples aside, the two mitigation categories at hand mainly shift to four impact categories: *land use* [16 studies], *mineral and metal depletion* [15], *freshwater use* [14], and *environmental impacts of mining* [9]. Shifts to *land use* and *freshwater* are caused by the expansion of bioenergy cropland, solar power deployment, and hydropower. The two impact categories *mineral and metal depletion* and *environmental effects of mining* are both driven by the need for material inputs during a low-carbon energy transition. This includes installations such as solar photovoltaics as well as energy infrastructure such as transmission cables and energy storage. Another shift here relates to the sustainability issues of batteries, especially the environmental impacts of their recycling and other end-of-life treatment options.

CDR is the second most studied source of EPS, with the most common techniques being afforestation, reforestation & revegetation (ARR), BECCS, and direct air capture with CCS (DACCS), which we focus on here.[11] Figure 4b presents the results for CDR in disaggregated form. Most CDR studies focus on the shift toward *freshwater use* [25], *biodiversity loss* [20], and *land use* [19]. The shifts from ARR differ from those of BECCS because biomass is often produced as crop and ARR is not. Crops entail negative impacts on land use and biogeochemical flows, as they require arable land and fertilizer. Next, the shift from ARR to *freshwater use* is due to reduced stream flow and lower water tables caused by of irrigation (41). Biodiversity is also found to be at risk from ARR but only in certain biomes. Three studies find EPS only in the limited case that forest management is optimized toward carbon sequestration to a degree which comes at a cost to biodiversity. Moving from biological types of CDR to chemical CDR, the main shifts from DACCS are *land use*, *freshwater use*, and *mineral and metal depletion*. DACCS relies on energy to flow air over a sorbent that binds CO_2, but this process and the sorbent production are energy

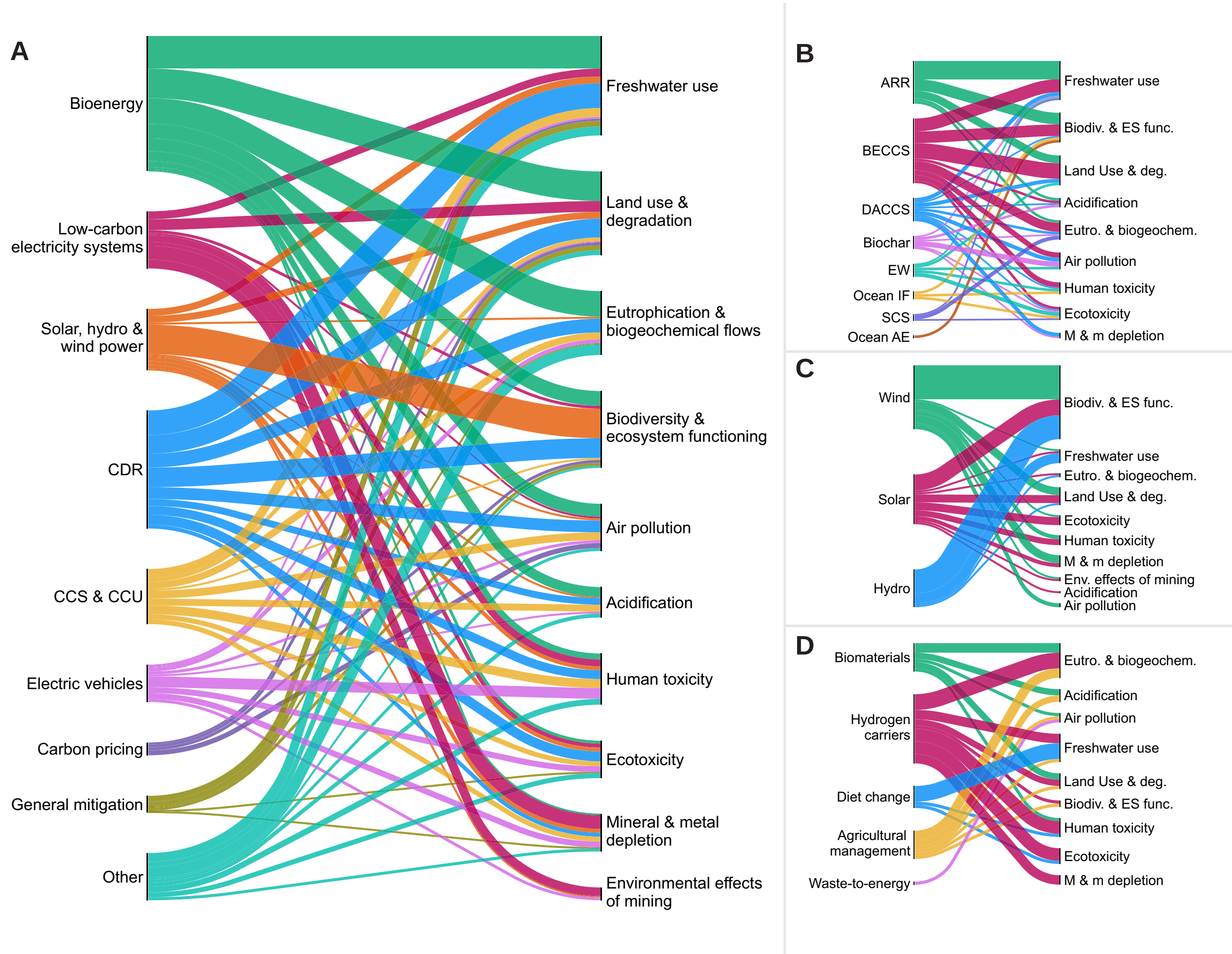

Fig. 4. Shifts from mitigation options to environmental problems. Notes: A) depicts the main categories of mitigation; B) is a disaggregation of CDR shifts; C) is a disaggregation of solar, hydro & wind power; and D) is a disaggregation of other. The width of a flow reflects the number of studies finding an environmental impact from a given mitigation option. Color blind-safe versions are provided in the Supplementary Material S3. Abbreviations are explained in Table 3.

intensive. Most of the shifting therefore arises indirectly from the upstream energy source, such as land use by solar photovoltaics (42). The impact on freshwater stems from the sequestration process (43), and to a lesser extent, from the use of aqueous sorbents (24).

Shifts from the category *solar, hydro and wind power* are mainly toward *biodiversity loss and ecosystem functioning* [30 of 62 shifts from this option]. Since solar power is land intensive it poses risks to biodiversity. Photovoltaics cause shifts to human toxicity due to leaching of toxic metals during use and in the material supply chain. Hydropower affects freshwater availability and ecosystem functioning in rivers and wetlands due to flow disturbances and artificial water level fluctuations. Wind power shifts pressures to wildlife conservation due to local disturbance of ecosystems, risk of collision with volant species, and cascading impacts through trophic levels. One global study diminishes the significance of shifts to biodiversity from solar and wind, finding that land use conflicts are limited, although they do occur in certain regions (44).

CCS & CCU are liable for impacts on all the categories of environmental impacts, notably *human toxicity*, *freshwater use*, and *acidification*. The main mechanism is the additional energy input required to compensate for the energy loss incurred by the capturing process—known as the energy penalty. The shifts from CCS to *human toxicity*, *ecotoxicity*, and *eutrophication* are consistent across different technologies and fuel options (45). The storage element of CCS also results in EPS: for subterranean storage, there are risks of land upwelling and groundwater contamination, and for ocean storage there are risks of acidification of both the seafloor and deep ocean water masses. In CCU, the process of converting captured CO_2 into feedstock is energy intensive, again driving shifts depending on the upstream energy production.

Shifts from *electric vehicles* are driven mostly by the electricity consumed in the use phase and the materials required to produce vehicles, notably their batteries. The exact shift and their magnitudes therefore depend on the materials needed for distinct battery types and the source of energy used for electricity generation. One study highlights that bioenergy-based electricity increases *air pollution* in the form of particulate matter formation. Three studies emphasize how battery production shifts impacts—through the production cycle and upstream mining—toward *human toxicity* and *ecotoxicity*.

Carbon pricing can generate different shifts. One pertains to cooking in low-income countries. When rising energy prices reduce access to clean cooking fuels, some families switch to stoves fired by wood, which pollute indoor air (46). Several studies find that carbon pricing shifts impacts to *land use* [3] and *freshwater use* [2], driven by the deforestation and irrigation associated with bioenergy expansion. Shifts to other impacts are disputed; two studies find that while carbon pricing causes some shifts, because of its systemic nature it also ameliorates many environmental problems (15, 47). Another study finds that although pricing results in land use changes with negative impacts on biodiversity, this is more than compensated by the biodiversity benefits of climate stabilization (48).

Discussion

EPS is the most precise term

The studies show a large variation in terms used to describe the phenomenon of EPS. Many of these have a rather general meaning without clearly distinguishing between the three secondary policy effect types (Figure 3). *Environmental problem shifting* is in our view a clear and accurate term, for several reasons: (i) It is specific to environmental effects beyond the policy target, i.e. climate change mitigation, and thereby distinct from other secondary effects in our typology of policy effects (Figure 3); (ii) it emphasizes direction and thus causality, in contrast to terms such as *trade-off* and *interaction effect*; (iii) it can encompass spatial, temporal, and problem-to-problem shifts, although we focus on the latter; (iv) it applies to shifts regardless of whether expected or unexpected, unlike terms such as *unintended consequences*; (v) though uncommon in the literature, the term has been used with consistent meaning.[12] One potential alternative is environmental *impact* shifting, however, *problem* is likely to appeal to a broader audience than the more abstract term *impact*.

Types of EPS mapped

Environmental problem shifting is characteristic of all the mitigation options reviewed, but the number of studies devoted to particular shifts varies considerably. We can divide the mitigation options most associated with shifting into two groups. First, are those related to low-carbon energy production including *bioenergy*, *solar, hydro and wind power* [148 studies]. The high number of studies on *bioenergy* [75] is partly explained by the frequent use of IAMs and energy system models. These use cost-minimization to project mitigation pathways, leading to high levels of bioenergy use because it is cost-effective relative to other low-carbon energy sources (50). A second group consists of mitigation options that involve carbon capture: BECCS, DACCS, CCS, and CCU [57 in total]. The common driver behind these shifts is the capturing process and its energy or feedstock requirements; direct air capture in DACCS requires direct energy use and when CCS is applied to electricity generation, it results in an energy loss, thereby requiring additional feedstock to maintain output levels. BECCS also causes shifts similar to bioenergy, due to the use of biomass plantations.

The environmental impacts most often mentioned in the empirical studies are *freshwater use*, *land use*, and *biodiversity loss & ecosystem functioning*. The relatively large presence of biomass-based mitigation might in part explain the high occurrence of these impacts—studies on *bioenergy* and BECCS account for 43 of 101 shifts to *freshwater* and 42 of 85 shifts to *land use*. Since the shifts to *freshwater* and *land use* in many cases depend on the use of land prior to mitigation, it is difficult to draw universal conclusions about how mitigation options affect these impact categories. The many mentions of shifts to *biodiversity loss & ecosystem functioning* might in part be explained by the long list of detailed impacts aggregated in this category (see the detailed description in Environmental impacts studied section).

Two of the mitigation options go beyond technology: *carbon pricing* and *diet change*. *Carbon pricing* [12 studies] is the only genuine policy among the mapped options; it causes shifting only indirectly by influencing the economic behavior of firms and individuals, in turn affecting, for instance, investment in energy systems and household vehicle choice. Our mapping indicates that carbon pricing contributes to four specific shifts: household *air pollution*, *land use*, *freshwater* use, and *biodiversity loss*. The last three are all driven by the use of land and water in bioenergy production and afforestation. Next, *diet change* [6] is the only mitigation option focused on consumer behavior. It has been found to shift impacts toward *freshwater use* if certain water-intensive products (e.g. cashew nuts) are used as substitutes for meat.

Mitigation options not mapped

While the mapped mitigation options cover all major options, a comparison with the full list of mitigation options in IPCC AR6 WG3 (Technical Summary, 51) reveals several options that lack attention in the literature on EPS (see Supplementary Material S4 for a full comparison). For example, we find no studies on EPS for any of the 14 mitigation options listed under the categories *Urban* and *Building*, such as “district heating”, “building envelope improvement”, and “changes in construction materials”.

Several other IPCC mitigation options are absent from our mapping. Some of these, however, are outcomes rather than mitigation options, e.g. “reduced food loss and food waste” and “reduced demand for energy and transport”. Such options entail less production or more efficiency, independent of whether the reductions come from behavioral change, innovation, or regulation. In turn, this lowers the need for multiple inputs, such as water, land, metals, and energy, and associated environmental impacts simultaneously. Other uncovered IPCC options relate to efficiency improvements in heating, appliances, material use, industrial processing, and fuels. One reason for the absence of studies on these options was that most of the screened studies on efficiency focus on energy input or emissions, and rarely on other environmental impacts. It should be noted however, that mitigation based on efficiency improvements might paradoxically increase demand because of cost reductions, while mitigation based on demand reduction of carbon-intensive goods might cause a consumption shift toward goods that are environmentally intense in other ways.

Nuclear and geothermal energy are also absent as separate mitigation options in our mapping, but they are, in fact, implicit in some of the mapped studies on low-carbon electricity systems.

The lack of studies on EPS for certain mitigation options does not necessarily imply that these options are invulnerable to shifts; that conclusion requires further evidence. Nonetheless, certain lacking mitigation options, such as reducing fossil fuel use or replacing vehicle use with public transport and bikes, may well be less susceptible to shifting, which would explain why they have been overlooked in the literature.

Moderating factors of EPS

Many factors moderate EPS, such as spatial context, implementation technique or national energy mix. Different options within a given mitigation category contribute to distinct shifts, as illustrated by the example of DACCS, which can make use of different sorbent technologies, each resulting in unique problem shifts.[13] To identify these factors it is, however, necessary to understand the underlying mechanisms of each shift—what drives the distinct environmental impacts of a mitigation option. We identify four mechanisms that are common across the mapped mitigation options: upstream energy production, upstream extraction of materials, land use change, and irrigation from biomass plantations. Energy-intensive mitigation options require significant upstream energy production, which results in shifting. Certain mitigation technologies, such as solar photovoltaics, wind turbines, batteries, and electric vehicles drive the upstream extraction of materials. Land use change—most frequently driven by bioenergy expansion—cause shifts to biodiversity loss and ecosystem functioning. Irrigation from biomass plantations, whether for bioenergy or BECCS, drives impacts to freshwater use.

Comparing estimates: gross and net EPS

A natural extension of this work would be to review the magnitudes of shifts by systematically appraising each study. Comparing shifts across studies tends to be complicated. Indeed, our mapping reveals that EPS takes three incomparable forms: *gross shifting* versus *net shifting* and *relative shifting*. Estimates of *gross shifting* are limited to describing the environmental impacts of a mitigation option without a baseline, which means it is unclear whether the shift may be outweighed by the positive environmental effects of mitigating climate change. A case in point is a study on biodiversity loss from wind farms, which lacks a comparison with biodiversity loss from current energy sources and ignores the environmental impacts associated with unmitigated climate change (57). In contrast, estimates of *net shifting* compare the environmental impacts of mitigation with a reference scenario without mitigation, thereby accounting for the avoided environmental impacts of climate change. These avoided impacts can originate from multiple sources. For instance, to understand EPS brought about by replacing coal-based energy with wind power, one has to account for the production of coal-based energy causing environmental damage during extraction, conversion, and combustion (e.g. toxicity and air pollution) as well as global warming causing environmental impacts (e.g. rising ocean temperatures are detrimental to marine life). As an example of net shifting, (58) estimate EPS from decarbonizing the power sector by comparing the environmental impacts of three different decarbonization scenarios with those of a baseline scenario without mitigation. They thus account for the environmental impacts of both electricity generation and global warming and find shifting to be negligible. Finally, estimates of *relative shifting* compare the relative environmental performance of mitigation options by measuring them in a common functional unit, such as emissions per kWh produced for energy technologies or per distance covered for different vehicle types. As a result, this method circumvents the need for absolute estimates of avoided impacts. One example of relative shifting is found in a study which compares DAC technologies by estimating their impacts (e.g. water depletion) per ton of CO_2 captured (42).

Comprehensive accounting of environmental impacts from climate change mitigation and comparison across similar studies are needed to arrive at accurate estimates of EPS.[14] This could also avoid overestimation of shifting (which gross EPS estimates are sensitive to) or even identify net positive effects (i.e. environmental cobenefits rather than EPS). The issue of incomplete accounting—as is the case with gross shifting—is part of a wider set of problems in the assessment of climate change mitigation (60). One of these problems occurs when cost–benefit estimations of mitigation omit the economic benefits of reduced impacts from climate change (61). Our mapping finds that this issue applies not only to economic assessments but also to environmental ones.

One might dispute whether gross shifting can be considered EPS, based on the argument that a measure cannot be understood as mitigation if the benefits of climate change mitigation—including avoided environmental damages—are not fully accounted for. We, nevertheless, still regard gross shifting as a relevant concept because it provides a logical starting point for examining mitigation options. Moreover, even when net EPS is zero, gross shifting is relevant if negative environmental impacts of mitigation occur locally, and benefits accrue globally. In addition, renewable energy deployment is generally considered mitigation, even when it adds to total energy use rather than displaces fossil fuels, as has been the case historically (62). The reason is that increasing energy use would otherwise have been met with higher-carbon sources. Gross shifting from renewable energy source and CDR, however, indicates that increasing energy use will translate into increasing negative environmental impacts, even if greenhouse gas emissions were to cease.

Policy implications

Our mapping indicates that environmental problem shifting, albeit widespread, can be addressed through policy. We draw three general insights from the studies reviewed. First, it is crucial to understand the type and extent of EPS when designing sustainable climate change mitigation policy. Second, policymakers can minimize EPS by regulating how and where mitigation options are implemented, thereby leveraging the moderating factors of EPS (63, 64). Examples include the choice of feedstock for bioenergy, which can minimize several shifts, and placing photovoltaics on rooftops or in agri-voltaic systems, which can prevent or limit shifts to land use and biodiversity loss. Third, complementary policies can prevent or compensate for shifting. Examples include two studies suggesting that EPS from carbon pricing can be anticipated through regulation of land use or biofuel production (15, 65). Design of complementary policy may require policy integration to avoid negative synergies, both horizontally between policy sectors and vertically across governance levels—from subnational to international (22, 66).

Completely eliminating EPS will not always be feasible. Policymakers will inevitably face trade-offs between environmental problems. Given that such problems are generally incommensurable and therefore cannot be compared easily, decisions are bound to be subjective. Still, robust estimates of the magnitude of shifts can assist decision-making and guide the design of sustainable climate change mitigation policies.

Conclusions

This paper mapped the literature on environmental problem shifting (EPS) in the context of climate change mitigation. We provided an overview based on a collection of 311 empirical studies of EPS, derived from screening a total of 10,997 articles. These appeared in a wide range of journals and pertain to a variety of research fields. The methods used to assess EPS varied as well, with LCA and IAM dominating.

We identified 21 terms that have been used to refer to EPS. To clarify their differences and to demarcate EPS, we presented a typology of secondary policy effects. Although the number of studies on EPS is steadily increasing, the use of the term *environmental problem shifting* is still uncommon, despite it being arguably the most accurate term to describe the shifting from one environmental problem (in our case climate change) to others. Alternative terms such as *trade-off* and *adverse side effect* reflect a broader set of policy effects.

The mapping of empirical literature revealed EPS to be characteristic of major mitigation options. We mapped 86 shifts from 13 categories of mitigation options to 10 environmental impact categories. The mitigation options most common in the EPS literature are *bioenergy* [75 studies] and *CDR* [61]. The most frequent environmental impacts are *freshwater use* [101] and *land use* [85]. A comparison of our mapping to a list of mitigation options in the latest IPCC report reveals that several options have not been studied in terms of EPS. Hence, further research is warranted to clarify if certain mitigation options are less prone to EPS, or if they are merely understudied.

The ubiquity of EPS indicates a need for sustainable climate policy which effectively ensures that mitigation does not aggravate other environmental problems unnecessarily. This mapping can support the improvement and selection of climate policy—it does not translate into an argument against climate change mitigation in general. Our discussion revealed how EPS can be minimized by regulating the implementation of mitigation (e.g. technology type, geographic placement) and through complementary environmental policies. The exact shifts of a mitigation option vary with the geographical context (e.g. prior land use or freshwater availability), specific implementation techniques (e.g. sorbent choice for DAC, irrigation practices for biomass plantations), and frequently, the upstream source of energy. It is important to disentangle these underlying mechanisms, as they can provide regulators with leverage points which can be exploited to minimize shifting. Complementary policies can also minimize shifting, for instance, by coupling a universal carbon price with dedicated biofuel regulation to prevent unsustainable use of bioenergy.

A systematic comparison of the magnitudes of EPS across studies has yet to be done. Our mapping has revealed that this task is complicated because estimates of EPS in the literature take many different forms, which rules out direct comparison. To estimate shifts accurately, it is important to consider the environmental impacts that would occur in the absence of mitigation, but not all studies do so. To distinguish between the distinct types of estimates found in our mapping, we introduced three terms: gross shifting, which captures the environmental impact of a mitigation option without using any baseline; net shifting, which compares the gross shifts to a reference scenario without mitigation, thereby accounting for the impacts avoided by mitigation—including damages from climate change and impacts from continued production and use of fossil fuels; and relative shifting, which circumvents the need for baselines by comparing the impacts of mitigation options relative to a common functional unit, such as kWh produced.

This distinction between EPS estimates is particularly important when environmental concerns are invoked to criticize mitigation proposals, be it from environmentalists or actors with vested interests in fossil fuels. For instance, if concerns about bird mortality are raised against wind power (i.e. gross shifting), the impact should ideally be compared with the impacts on birds from fossil fuel-based energy production and the impacts of unmitigated climate change (i.e. net shifting). This does not imply that gross EPS is irrelevant; on the contrary, it is necessary to understand issues of fairness that arise if EPS entails mitigating a global problem (e.g. climate change) by intensifying local environmental pressures (e.g. freshwater scarcity). In conclusion, identifying the category to which EPS estimates belong is crucial to clarify the evaluation of mitigation options and policies.

Mapping method

Our mapping of the literature followed the five typical stages of systematic evidence synthesis: initial scoping, evidence searching, evidence screening, information extraction, and synthesis (67). We omit the optional sixth step of appraisal of individual studies for internal and external validity since we offer a mapping rather than a review. We explain the core of our method here. Further details can be found in the Supplementary Material S5 while the literature sample is reported in the Supplementary data.[15]

The focus of the mapping is climate change mitigation, including policies, strategies, and technologies. Studies on solar radiation management were excluded, since we focus on measures that affect the atmospheric concentration of CO_2. We used a hybrid search strategy, combining results from the Scopus database with manual search, including literature mentioned in IPCC AR6. The Scopus search strategy was developed in an iterative process using topic modeling, a method of computational linguistic analysis. Based on an initial explorative search, we built a search query that requires the title, abstract or keywords of any document to mention at least one term from each of three groups of terms related to problem shifting, climate change, and greenhouse gas emission reductions. The query aimed to identify studies that investigate negative environmental impacts of climate change mitigation and to avoid studies that merely examine a range of environmental impacts of which climate change happens to be one. Figure 5 provides an overview of the search and screening procedure.

Initial results contained a large amount of irrelevant literature, which made screening by hand unfeasible. Several approaches were used to remove irrelevant studies and strike a balance between comprehensiveness and accuracy. First, we included only (i) articles and reviews in journals, (ii) in the English language, and (iii) published before May 2023. Second, we tested modifications to the search query and various filtering approaches. This involved manually screening samples of results and natural language processing using topic modeling.[16] The latter provided an overview of the results by clustering them into topics, which enabled us to identify irrelevant clusters of literature. While it found clusters about mitigation options and environmental impact categories, no clusters dealt with the links between them, i.e. the environmental problem shifts. The final search was performed in May 2023 and contained 10,997 results. Third, we applied multiple filters before manually screening the remaining articles. We double-coded several exclusions, both random samples and cases of doubt. We excluded journals if none of their Scopus subject areas included the following: Agricultural and Biological Science, Environmental Science, Economics, Earth and Planetary Science, Energy, and Multidisciplinary. We screened journal titles and removed those indicating limited relevance, for instance, those containing words such as *lubrication*, *refrigeration*, or *tourism*. Journals with only one article in the search results were excluded to avoid isolated studies. Articles with few citations were also excluded, namely if they were more than 5 years old and had one or no citations, and if they were more than 10 years old and had five or fewer citations. Lastly, we excluded articles containing clearly irrelevant terms in the title, abstract, or keywords of the remaining articles. These filters removed 6,642 studies in total.

This resulted in 4,832 studies when combined with literature from the manual search based on exploratory readings and snowballing [189] and the relevant literature from the search in IPCC AR6 reports [154]. These were screened according to whether they mentioned climate change, mitigation or emissions reduction, and another environmental problem or domain. Titles were screened first, then abstract and keywords, and full texts in cases of doubt. We excluded boundary cases if: (i) interventions were on a limited scale, such as a ban on plastic straws; (ii) mitigation only had a tangential role compared with other objectives of intervention, such as nature-based solutions in urban areas for both social and environmental benefits; and (iii) studies were focused on a small and highly technical aspect of a mitigation option, such as comparative performance of nickel-based catalysts

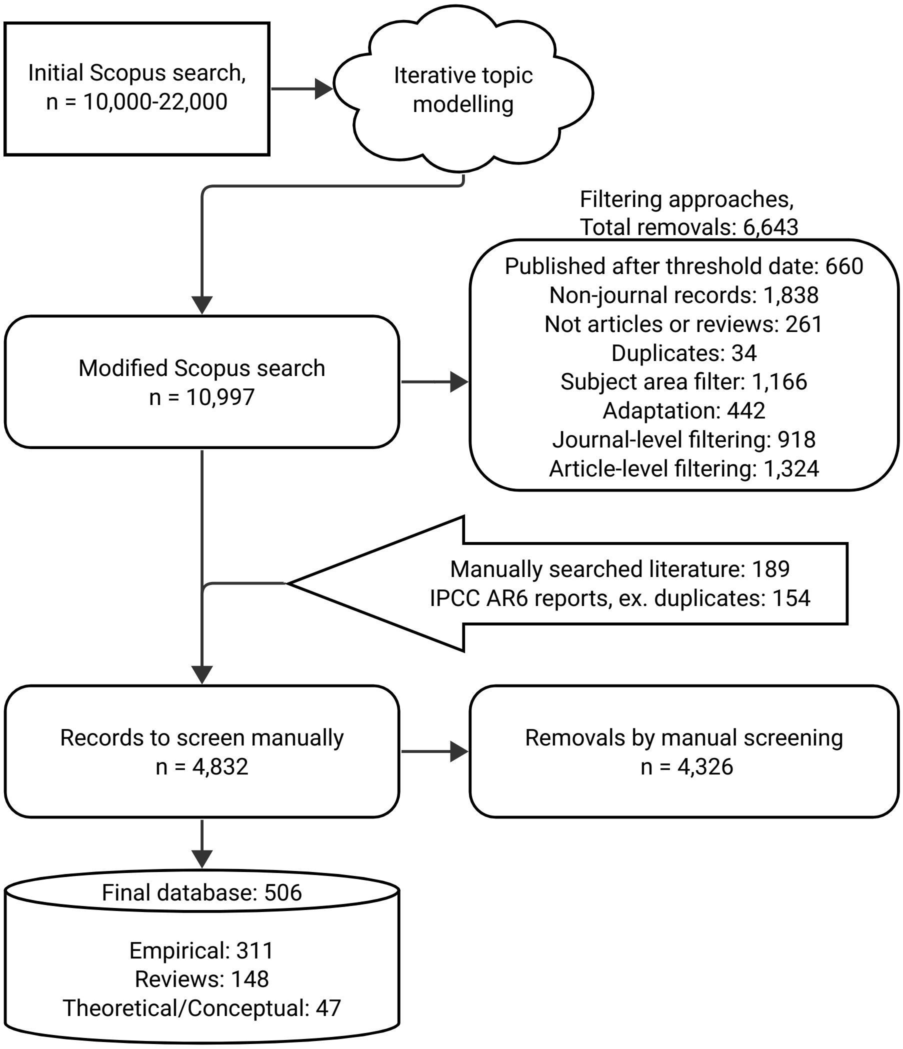

Fig. 5. Flow diagram of the mapping procedure. Note: An extended version and further details are provided in the Supplementary Material S5.

for CO_2 methanation processes used in carbon capture and use. This resulted in a final collection of 506 studies. Besides journal articles, it includes nine publications of other types, such as books and reports, originating from the manual search.

The information extraction included identifying the mitigation option(s), the environmental impacts of the shift, the method(s) and type of study. In studies with multiple mitigation options and impacts, we coded only those shifts that could clearly be identified or separated. The coding procedure started with simple extraction of relevant text snippets, then a coarse classification and finally an aggregation to reduce the number of categories.

For the synthesis of the empirical literature, we described the mitigation options and the empirical impact categories. We then counted connections between these to produce an overview of how EPS is represented in the literature reviewed. Reviews of specific mitigation options served, in some cases, to provide additional details on mitigation options and mechanisms underlying the respective environmental problem shifts.

Notes

[1] Deng et al. broaden cobenefits to include negative effects. This can be seen as confusing since the term *benefits* has a clear positive connotation while the negative counterpart is commonly denoted *costs*.

[2] Supplementary material S1 provides a figure which disaggregates "Other methods".

[3] LCA also uses recipient-specific impacts; for instance, a toxic spill can affect the health of inhabitants of a nearby town. This impact is likely to vary with distance to the emission source. Shifts from one recipient to another has been referred to as spatial or temporal (i.e. delay) problem shifting. Our mapping instead focuses on shifts from one type of environmental impact to another, without differentiating between recipients.

[4] This count includes uses in the title, abstract or keyword. See e.g. (24, 25). Many other LCA studies use the term in the full text.

[5] Shifting from one type of impact to another has also been referred to as *sectoral* shifting (27). In policy and the social sciences, however, sector tends to refer to an economic sector, such as agriculture or industry.

[6] Other notable studies to find environmental benefits rather than EPS focus on (REDD+) programs, i.e. Reducing Emissions from Deforestation and Forest Degradation (32), Soil carbon sequestration and biochar (33), and ecosystem restoration (34). For further examples, see the discussion in footnote 15.

[7] All abbreviations used are spelled out in Table 3.

[8] The LCA literature uses the term *land use* and *land use change*, which measures impacts on all major biomes. In contrast, the Planetary boundary framework refers to *land system change* and measures only forest cover. Here, the aggregated category *land use* includes

both definitions. Land use is by some considered both an environmental and a resource problem—the latter since it sustains many services including food production, forests, and freshwater (35).

[9] For a discussion of potential overlaps, see Mace et al. (36).

[10] The breadth of shifts from bioenergy is confirmed in a dedicated review by Jeswani et al. (37).

[11] Less common CDR subtypes are treated in a dedicated review by Fuss et al. (40).

[12] Problem shifting sound somewhat similar to *cost shifting*, a term proposed by Kapp (49) to denote that private producers maximise private profits by deliberately shifting costs of production, such as environmental damage, to society at large. In contrast, EPS is not limited to deliberate actions.

[13] Several specialized reviews examine the environmental impacts of certain subtypes of mitigation options, such as wind power (52), CCS (53), CDR (40, 54), diet change (55), and bioenergy and biomaterials (37, 56).

[14] Our review found only a few studies that directly challenge previous results in the literature. For example, three studies use scenario-based models to argue that shifting from wind and solar energy is negligible (39, 44, 59); two other studies contest the shifts from carbon pricing to air pollution and biodiversity loss (47, 48).

[15] Supplementary Material S5 includes the full search query, further details about manual search and IPCC literature, the filtering approaches, the Scopus classification of journal subject areas, a description of the topic modeling technique, and visual examples of the topic model results.

[16] Topic modeling is a natural language processing technique that employs machine learning to cluster documents. We used the model BERTopic to cluster studies based on TAK analysis and subsequently identify the central terms of each cluster (68).

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Supplementary Material

Supplementary material is available at *PNAS Nexus* online.

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Author Contributions

O.W.H: conceptualization, software use, data curation, data visualization, drafting, writing, and editing. J.B: conceptualization, review, editing, and supervision.

Data Availability

The data underlying this article are available on Zenodo at doi.org/10.5281/zenodo.8068521. The code underlying this article is available on GitHub at github.com/owoodhansen/epsreview.

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