How do Carbon Dioxide Removal strategies deliver on justice? Insights from a review of afforestation and reforestation research

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Abstract

While Carbon Dioxide Removal (CDR) and afforestation and reforestation (A/R) in particular have been advanced as mitigation actions which align with global sustainable development and wellbeing goals, however, justice remains under-represented in the policy and academic discourse on A/R impacts. In this paper, we review cases of A/R implementation across 37 different countries to understand their observed impacts. Our findings reveal that while justice is rarely a central objective in A/R implementation research, observed outcomes have profound justice implications. We find that in current, primarily market-based A/R activities, human individuals are likely to receive the most just outcomes and non-human entities the most unjust. We observe that implementing robust institutional mechanisms and adapting to the socio-ecological realities of specific contexts, A/R can deliver just outcomes. Ultimately, for A/R to truly enhance wellbeing, policy must ensure just outcomes for already-marginalised human and non-human communities and nature itself.

Introduction

Climate change mitigation policies require substantial reductions in emissions alongside Carbon Dioxide Removal (CDR) to bring cumulative global emissions into line with the 2015 Paris Agreement goal[1]. The Sixth Assessment Report of the Intergovernmental Panel on Climate Change identified CDR as crucial for balancing 'hard-to-abate' emissions[2]. Prominent CDR mechanisms span land- or nature-based options (e.g. afforestation and reforestation (A/R)) and technological options (e.g. direct air capture)[3].

While modelled pathways are able to deploy conventional and novel CDR for emissions reduction at a large scale, the real-world expansion of CDR is of questionable pace and impact. Technological CDR is at an early stage of development, and more established nature-based methods such as A/R require extensive (and slow) land use change[4]. Actors within the land sector face issues of poverty, power imbalance and injustice that undermine their abilities to enact these changes[5]. In principle, A/R strategies could create synergies with sustainable development, improvements in biodiversity and social and environmental wellbeing[6,7]. But A/R can also have drawbacks: beyond its potential for mitigation deterrence[8], it can have detrimental effects on food security, livelihoods, and biodiversity, among others[9–11]. A/R also creates additional competition for land, when the land sector already faces multiple demands for the provision of essential goods and services as well as climate change mitigation[12,13]. Finally, these methods face higher risks to durability from disturbances such as deforestation, agricultural expansion, pests and wildfires, which can release stored carbon back into the atmosphere[7].

Yet land-based CDR measures, often in the form of A/R, feature heavily in Nationally Determined Contributions (NDCs) for 2030 and beyond[6,13,14]. Much of the knowledge-base and emphasis on CDR comes from the Global North, while many of the burdens of actions and the consequential impacts are borne by the Global South[15]; an inversion of the net responsibility for emissions. This unequal distribution of burdens stems both from existing inequalities and from perceptions among policy-makers

that such effects are negative but unavoidable externalities of implementing climate action[16,17]. Many researchers, too, concentrate on technological and environmental challenges and impacts of CDR rather than social challenges[18]. As it stands, however, it is unclear whether A/R is making a net positive contribution to wellbeing, whether its impacts do represent barriers to implementation, or whether we are even in a position to properly assess these challenges.

We explore the implementation and impacts of afforestation and reforestation as strategies for CDR by reviewing case studies across 37 different countries. These case studies identify desired outcomes and observed consequences of A/R, which we use to further assess possible impacts on social and environmental justice. We seek to answer three broad questions: (i) Which impacts of A/R policies are prioritised and observed? (ii) through which recorded processes do the observed impacts of A/R occur? and (iii) do these processes and impacts have the potential to reduce or compound existing injustices? Together, these questions allow us to assess the extent to which justice implications of A/R are considered in the literature, properly understood, and pertinent to the implementation of land-based CDR.

Methods

We undertook a review of A/R case studies following the structure of a Rapid Evidence Assessment (REA). We used the Theory of Change (ToC) methodology to thematically assess case studies, observed impacts, and the contexts under which A/R was implemented. After thematically coding the results, we performed an abductive thematic analysis to identify the impacts of these processes on social and environmental justice. For this, we used the subjects and dimensions of justice described by Sikor et al., 2014[19] in their framework for evaluating justice claims within ecosystem governance. Through this methodology, we aimed to capture the implications of A/R as they have been recorded in different geographical regions, including implications for social and environmental justice.

Document Identification and Selection

A REA is used to swiftly and effectively gather the main findings from literature evidence by developing clear research questions and a replicable methodology of evidence selection[20]. The search used the Web of Science Core Collection database in January 2024 applying the process outlined in Fig. 1.

We explored case studies spanning the 10 years since the Paris Agreement, between 2015 and 2024, in the English language, which provided 628 papers in total. Given that the focus was on A/R in relation to climate mitigation and carbon dioxide removal, papers related to climate adaptation, conservation, and different types of forest management were eliminated, leaving 90 studies. We only included open-access peer-reviewed research articles to maximise the transparency and reproducibility of the results. The final screening process was related to the relevance of the studies to the research objectives: titles and abstracts were screened in order to eliminate non-relevant articles (i.e., those that did not consider impacts of A/R). Out of the 80 studies remaining, 51% (N = 40) used empirical analyses to study A/R impacts and 45% (N = 37) used modelled assessments. 4% (N = 3) of the cases used literature review

methodologies. These 80 research articles yielded 87 geographically distinct cases that were coded thematically.

Qualitative Thematic Coding

Qualitative thematic coding of the articles was completed using the software NVivo Version 14 and Microsoft Excel 2021, and developed using the Theory of Change framework[21]. ToC is widely used as a tool to determine the causal logic behind desired outcomes and to map the process by which inputs affect the realisation of these outcomes[22]. Here, we adopted the ToC approach by looking at existing conditions, inputs and activities, outputs, and impacts (as outcomes) through a backwards causal methodological flow, from desired outcomes to their preconditions[21].

Given that every case explored the impacts of A/R implementation on a study area, afforestation and reforestation was coded as having occurred in every case post the implementation. Hence, in the theoretical sense of the ToC, some forms of A/R (such as afforestation, mine reclamation, forest restoration) having occurred was thematically coded as the "output" for every case. This was considered as the starting point for the thematic assessment. The main outcomes for each case were then coded by pinpointing the specific impacts of A/R that the researchers focused on (the research foci). The conditions under which these impacts were observed (geophysical, environmental, technical, economic, social, and institutional) were recorded as "Contextual factors" while the processes through which A/R was implemented were considered as inputs or "A/R activities". The contextual factors were recorded as noted by the researchers and no additional information was used for the same. For example, if a particular case study focused on recording impacts of afforestation policy implementation on soil carbon stock in a deforested land, the *output* was considered as *afforestation*, and the *impact* or *outcome* was the *change in soil carbon stock*. Using the backwards methodological flow, the conditions under which afforestation was recorded, i.e. *deforested land*, was recorded under *environmental conditions*, while the actual afforestation policy was recorded as *inputs*. Simulated A/R and other environmental patterns in model-based papers were also considered as inputs, though not leading to A/R outputs in the real world. Coding these inputs and contextual conditions for each case allowed us to build the causal conditionality of the desired goal being achieved (or not achieved). A few research papers consider multiple case studies which were coded separately.

Assessment of Justice

Recording of any justice-related elements in the thematic assessment was complemented by an abductive analysis by all the authors to identify the implications that recorded processes of A/R have for justice. Abductive thematic analysis blends research evidence with conceptual frameworks, resulting in a theoretically informed understanding of the research data[23]. The conceptual basis for this assessment was the framework developed by Sikor et al., 2014[19] to understand and evaluate the subjective, contextual nature of social and environmental justice of environmental governance processes. This framework is used as a way to effectively evaluate implications for justice through subjective, post-hoc

categorisation of implications of A/R across dimensions and subjects of justice, and approaches[24]. This framework conceptualises justice as a function of three dimensions of justice experience by different subjects of justice in different forms. The dimensions of justice are defined as recognitional (relating to individual and collective identities), procedural (relating to inclusive decision-making), and distributional (relating to the distribution of burdens and benefits). Subjects of justice were considered as individuals (individual humans), communities (of humans), generations (in the future), social systems (such as economy, regulatory institutions), non-human individuals and communities, and nature as an entity in itself[19]. The way in which justice or injustice is experienced by the subjects is described as the 'forms of justice' which are defined, for this study as, equality-based (whereby everyone experiences the same impacts), needs-based (whereby the most vulnerable experience the greatest impacts), and merit -based (whereby those who either participate or claim ownership of resources experience the greatest impacts)[19,24,25]. Here, an effort was made to understand the implicit ideas of justice that underpin the process of A/R implementation, going beyond any explicit mentions in the studies.

Results

We found a wide range of conditions in which A/R was implemented, and a wide range of impacts, but clear biases in the open-access literature towards certain geographies and research questions. About 33% of the literature originated from China while 22% was from the European Union. Environmental impacts of A/R were the focus of most of the research studies. We also found a notable absence of explicit consideration of justice with regards to impacts of A/R. The results of the post-hoc assessment nevertheless show that there is strong potential for impacts on justice, suggesting that their absence from the literature signifies a research gap rather than a property of A/R implementation and its outcomes. Results are presented below firstly as an elaboration of the elements of Theory of Change and then as observed outcomes of A/R and their classified implications for dimensions and subjects of justice.

Contextual Conditions

While case studies spanned many different contexts and conditions, some general patterns and connections emerged (Fig. 2). Watersheds and wetlands were the most frequently-described geophysical settings (33%), followed by mountainous regions (27%) and arid and semi-arid regions (20%). Studies in watersheds tended to focus on the impact of A/R on water systems, studies in mountainous regions on impacts on regional climate and extreme events, and studies in arid and semi-arid regions on changes in soil and water dynamics. 33% of all cases studied were situated in China. A/R activities were most often given as responses to soil erosion and associated land degradation (33% of environmental conditions) or declining ecosystem quality as a result of degradation or high salinity (24%). Certain regions also exhibited a history of natural disasters (17%) such as floods, droughts, sandstorms, avalanches, and tornados, while others had a history of natural or anthropogenic deforestation (7%). Economic conditions were recorded via activities such as extensive, intensive or marginalised agriculture (39%) on the lands where A/R was implemented, and concurrent economic

activities such as agro-industries (18%), other industrialisation activities (21%), and commercial afforestation (13%).

Socio-cultural conditions (mentioned in 11% of cases) were strongly linked to economic conditions and covered population dynamics, rural-urban dynamics and poverty, lack of access to land, water and other resources and other socio-economic factors. The presence of historically and culturally significant forest plantations was also recorded under socio-cultural conditions. Finally, technical and institutional conditions were both mentioned in 11% of cases and covered species of tree used for A/R, land ownership and management structures in study areas.

A/R related activities

A/R activities (ToC inputs) were often similar across cases and hence we were able to categorise them into different input categories. Since almost half the cases used modelling to achieve their research objectives (N = 38), modelling study inputs were recorded separately (Fig. 3).

The inputs within cases following empirical and literature review methodologies (N = 49) could be categorised under different regulatory and policy mechanisms (Fig. 3). Miscellaneous activities such as natural regeneration and tree planting, but also agroforestry, urban afforestation, mine reclamation, conservation, and wetland restoration are recorded under ‘A/R activities’. Agricultural abandonment and migration from rural areas with the addition of developmental activities such as infrastructure development, were considered as inputs for some of the cases. Agricultural market reform through natural capital investments and interest-free loans, and private agricultural and forest land management through issuance of permits and certificates, were considered as regulatory inputs. Timber market and carbon forestry regulations were also recorded, in the context of carbon trading, managing the timber supply chain and other aspects of commercial plantations. Protected areas and natural reserves were expanded as a result of policy initiatives which in some cases also led to curtailing access to land for farming and grazing activities. These inputs were recorded by the researchers to have preceded the outcomes they observed. While not all of these measures mention the implementation of A/R explicitly, they are considered as extensions of the same.

Specific A/R related inputs are implemented in different combinations of contextual conditions. Figure 4 shows which conditions are observed and discussed when specific inputs are implemented in the study area. Predictive modelling of A/R impacts relies mainly on the knowledge about geophysical and environmental conditions in the study area (48%). Comparatively less focus is given to economic and technical conditions (16%). A combination of geophysical and environmental conditions recorded for more than half (59%) of the inputs under the 'A/R initiatives' while all other technical, economic, social and institutional conditions accounted for the other 41%. This is distinct from other regulatory initiatives, where socio-cultural, economic and institutional attributes feature heavily for agricultural market reform (68%), carbon trading and commercial forestry (67%), management of private land (54.5%), and rural exodus and developmental initiatives (45.5%). Interestingly, while most categories integrate diverse drivers, the expansion of protected areas remains a notable outlier by excluding social dimensions

entirely, focusing instead on institutional (31%), economic (23%) and technical metrics (23%). Agricultural market reforms are not recorded as being influenced by technical parameters, while plantations and monocultures have a low association with social and institutional contexts (19%). While all cases would have certain combinations of contextual conditions in which the impacts may be observed, this analysis gave an idea about the conditions that researchers focus on while they record particular A/R activities.

Highlighted Outcomes of A/R

While a broad range of A/R impacts were recorded, a strong focus was given to evaluating environmental impacts and assessing plantation techniques (76%). Conversely, only about 24% of cases focused on economic, social and institutional impacts of A/R implementation. Environmental impacts were recorded on soil chemical properties (17%), particularly as they related to carbon stocks, nitrogen and other nutrient dynamics, and soil salinity and moisture. Impacts on surface and ground water dynamics (16% of cases) included surface run-off, streamflow and ground water recharge. Impacts on regional climate and land surface temperature accounted for 13% of cases, with the remainder of environmental impacts being on biodiversity and ecosystem stability (8%), growth and longevity of tree species (6%), and particulate matter removal through A/R (2%). 14% of cases compared the effectiveness and relative advantages of different tree planting techniques including soil tilling and ploughing, the use of particular species, and suitability of chosen species to geophysical conditions. Social (11%), economic (9%) and institutional (3%) impacts were recorded on livelihoods, food security, and ecosystem service provision, as well as cost-effectiveness, viability and optimisation of timber supply chains.

Mapping distinct outcomes allowed us to trace their contextual conditions and inputs as seen in Fig. 5. Impacts on GHG removal, regional climate, properties of soil and water and cost-optimisation or effectiveness of A/R are mainly dealt with by modelling studies. Impacts on water cycle and assessments of A/R technique effectiveness were mainly in the context of geophysical and environmental conditions. Similarly, regulatory mechanisms for A/R implementation such as policies for management of private land, developmental initiatives, protected area expansion and agricultural reform tend to be strongly associated with impacts on soil properties, tree growth and longevity, biodiversity and socio-economic outcomes.

Figure 6 shows the outcomes of A/R as they have been described in the individual cases in the literature. Positive outcomes indicate a value addition representing beneficial gains while negative outcomes indicate losses and value reduction. In this section we consider only empirical and literature review cases (N = 49) to maintain the empirical causality of conditions and impacts of A/R.

Generally, recorded A/R outcomes are positive across impacts contained in the literature, including those to which most research attention has been paid (effects on soil properties, biodiversity and selection of appropriate A/R techniques). Assessments of soil post-A/R implementation overwhelmingly report an increase in carbon stock and improvement in soil quality, while rarer negative outcomes include

decreases in biogeochemical properties as a result of commercial forest plantation, and decrease in soil water content in humid regions. Biodiversity improvements mostly reflect increases in micro-arthropod and bacterial communities, contrasting with one isolated case of decrease in microbial diversity as a result of use of non-native exotic species of trees for commercial plantation. Positive outcomes from assessment of institutional mechanisms indicated successful supply and management of permits for private afforestation, and establishment of regulations for afforestation. The only empirical study focusing on impacts on regional climate observed a decrease in the number of avalanches experienced, hence improving the regional climatic conditions.

Other outcomes are more mixed. Impacts on water cycle are divided between cases in watersheds and catchment areas showing an increase in annual discharge, sediment control, and fish habitat quality, and cases in mostly arid and semi-arid regions showing depleted groundwater recharge. One positive outcome for financial viability of agroforestry and natural regeneration contrasted with a negative outcome for monoculture plantation. Positive socio-economic outcomes were linked to the successful adaptation of forest policies to incorporate and involve local agro-economic and socio-cultural conditions, while the negative outcomes are linked to failures of trans-national forestry programs such as REDD + in the Global South. It was through the assessments of the causal chains presented in the Fig. 5 that we understood that valence of these A/R outcomes was linked to the implementation activities as well as the contexts in which they took place.

Implications of A/R Outcomes on Justice

The main finding of this study concerning justice is that none of the 87 cases found sought to identify implications of A/R for social and environmental justice as a product of A/R or as a condition in which A/R is implemented. Our assessment of the cases through the lens of the framework of Sikor et al., 2014 that we undertook, showed that many justice implications have the potential to exist, however. These potential implications are outlined in Fig. 7. We found that justice implications are rarely uniform, have trade-offs between subjects and produce few 'win-win' outcomes.

Across categories, we found that positive and negative implications of the A/R cases could often affect the same groups, albeit with positive implications often being much easily identifiable than negative Fig. 7. In all categories, positive implications for nature were at least as clear as negative, and positive implications were more common if not ubiquitous across groups. Notable differences in the distributions of positive and negative implications occurred only in effects on biodiversity and other ecological consequences, and effects on socio-economic conditions. In the latter, nature, social systems and generations were the only groups vulnerable to negative effects, although these were smaller than the positive effects that could emerge for all groups. In the former, positive and negative implications affected almost entirely distinct groups; positive for nature and non-human entities and negative for individuals and communities, to the extent that changes in biodiversity could undermine established socio-economic systems.

Notable positive implications included those of effective A/R techniques (Fig. 7(b)) for distributional and procedural justice for future generations, social systems and individuals through carbon forestry initiatives. However, the use of monocultures or ecologically unsuitable species have the potential to produce unjust recognitional outcomes for nature and non-humans. The mechanism through which benefits are distributed also affects justice implications. For instance, agro-forestry initiatives tend to be cost effective and have the potential to improve recognitional justice, but market-based initiatives usually reflect the rights of landowners to compensation for forest transitions (Fig. 7(d)) and may neglect nature and non-human entities. In contrast, activities involving community awareness and participation have the potential to achieve high recognitional and procedural justice for nature, non-humans as well as human communities, while also ensuring just distributional outcomes for future generations as a result of improved tree growth and longevity (Fig. 7(e)).

While economic benefits can be unequally distributed, so can economic disbenefits. Restrictions on economic activities as a result of forestry initiatives may produce unjust recognitional and distributional implications for communities and individuals. This is also seen in the case of increase in soil carbon stock as a result of mine reclamation and restoration, producing just outcomes for nature and biodiversity through increased ecosystem stability, but potentially depriving some individuals and communities of place-based identities and immediate economic distributional benefits (Fig. 7(f)). In the context of the effectiveness of institutional mechanisms for A/R (Fig. 7(g)), the potential for procedural, recognitional, and distributional justice is high as a result of improved social and regulatory infrastructure being built for the improvement of nature and biodiversity, and the robustness of these systems may increase the benefits for future generations. Positive socio-economic outcomes through market reforms and well-adapted policies have the potential to create just recognitional and procedural outcomes for humans and non-human communities alike by recognising and empowering them as decision-makers. Improvement of regulatory systems within the forest supply chain as well as forest management have the potential for just distributional outcomes by fostering distinct, nature-inclusive cultural identities hence also impacting future generations. Negative social outcomes, on the other hand, have the potential for unjust recognitional outcomes through loss of livelihoods and identity during forest transitions. These outcomes could exacerbate existing socio-economic inequalities if left unaddressed.

Through a justice assessment of the processes and outcomes of A/R, we observed that while certain stakeholders have the potential to experience a reduction in their existing vulnerability (just implications), certain other vulnerabilities are compounded. This trade-off is especially apparent when probable just outcomes for individual humans are opposed to those for non-human entities. This trade-off could be minimised by conscious adaptation of forest transition policies to local environmental and social conditions (Fig. 7(i).

Discussion and Conclusion

We find widespread reporting of the impacts of A/R initiatives in the literature, but with clear gaps and biases. The literature is geographically aggregated, and focuses primarily on environmental impacts. Justice implications are almost entirely neglected, despite scope for these to be substantial. Below we discuss key aspects of these findings before identifying implications for future research.

Highest research priority for environmental impacts

The highest emergent priority for research on A/R impacts was environmental impacts. Even within this category, the study of impacts on soil and water far outweigh impacts on biodiversity and/or ecological stability. We posit that this could be a result of two conditions. Firstly, forest research has emerged as an environmental endeavour and research on socio-economic impacts of A/R has received much less priority, and social dimensions of forest research have received a secondary status[18,26,27]. Secondly, this may also reflect the attribution of value that researchers themselves give to these impacts in contrast to, in particular, socio-economic impacts[28]. This has been attributed to a general lack of intrinsic value afforded to human communities and non-human entities in A/R policies and in the subsequent evaluation of those policies[28].

Dominance of anthropocentric, market-based A/R activities

While the literature mostly focused on understanding the environmental impacts of A/R, the A/R activities themselves were market-based and anthropocentric. This includes activities such as carbon trading and commercial forestry, creation of plantations and monocultures, and forest transitions through financial compensation to landowners for management of private land. In this context, local, national and trans-national policies are devised and implemented with ecosystem services for forests valued via financial and market-based instruments. While this does represent a realistic mechanism for increasing forest cover and forest ecosystem services (Fig. 6), it may over-emphasise single outcomes such as carbon sequestration, and incentivise human communities to increase their material wealth in relation to these forests and forest services, creating the paradox of "*selling nature to save it*"[29], creating avenues more top-down forestry practices which have been the basis of historical marginalisation and injustices[30,31].

This paradox is apparent in the scope for just distributional outcomes for individuals and nature, but unjust recognitional outcomes, of market-based activities, the latter including loss of identity for humans and reduction in the intrinsic value of nature and biodiversity. Market incentives-based forestry not only create power structures based on financial incentivisation but also through governmental legitimisation of these structures, exacerbating the existing inequalities between and within humans and non-humans [32,33]. This also creates a potential for unjust distributional outcomes for future generations, as is evidenced in Fig. 7. At the same time, the dominance of the study of market-based systems means that the literature offers little guidance on which alternatives exist for A/R and what their implications are for justice and other outcomes.

Compounding vulnerabilities and future wellbeing

This study shows that research into the impacts of CDR is not actively invested in assessing its implications on justice. Studies focus on how CDR policies, specifically those that are technically and economically feasible, perform in relation to immediate environmental impacts. This shows that while CDR is feasible in current context, it does not indicate whether CDR is able deal with reducing existing social and environmental vulnerabilities.

From our justice assessment, it is apparent that most CDR policies have to deal with trade-offs for just impacts for some groups of stakeholders versus others, even when the outcomes that A/R produces are desirable. This leads us to believe that CDR, and A/R especially, in the form it currently exists is unable to produce just outcomes for all stakeholders and invariably produces net winners and losers. We posit that there are deeper structurally unjust elements that shape CDR outcomes but that CDR itself is unable to successfully address via the mechanisms that it is currently deployed. In particular, human relationships to the natural world are already deeply shaped by dominant social and financial systems that A/R can operate within. A neo-liberal approach to environmental, land-based and other forms of human activity, which prioritises material gains of a few, restricts the scope for A/R to generate just outcomes[34,35]. Considering a neo-liberal A/R initiative to pay for ecosystem services, financial compensation to individual landowners will have to be provided, however, land ownership is already fraught with systemic complexities, involving issues of historical and present-day socio-economic justice[36]. These payments, while creating material opportunities for land owners, may end up exacerbating these complex land conflicts. However, without a wider socio-cultural shift in governance at a much larger scale, it is not possible to alter these structural inequalities only through A/R and other CDR. More feasible, at least, is for CDR policies to acknowledge and account for the trade-offs they produce and to balance them through additional action[33]. This, among other reasons, also demonstrates the need for dedicated further research on the justice implications of A/R in different contextual conditions.

To support this necessary awareness of justice implications and mechanisms to improve them, we were able to pinpoint outcomes of A/R on which researchers focus, and the processes through which these outcomes occur in different environmental and socio-economic contexts. These processes produce desirable results in certain conditions, including just outcomes for many stakeholders. Nevertheless, there are several potential and several inevitable trade-offs between stakeholders when implications of CDR on justice are considered. Adapting polices to local environmental and socio-economic conditions should make it possible to reduce these trade-offs, and awareness of implications for social and environmental justice is a necessary precursor to this step towards truly successful climate change mitigation.

Declarations

Competing Interests

The authors declare no competing interests.

Ethical Approval

Ethical approval was not required as there were no human participants involved in this research.

Informed Consent

Informed consent was not required as there were no human participants involved in this research.

Author Contribution

MS conceptualised the paper and methodology with CB, EDG, and MR. All authors performed the formal analysis. MS wrote the original manuscript, prepared the visualisations. MS, CB, EGD, and MR reviewed and edited the manuscript. MR acquired the funding.

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Data Availability

The data supporting the findings in this study data supporting the findings of this study are available within the paper and its Supplementary Material 2 along with the along with the references to the original papers used for the review study in Supplementary Material 1. All additional data will be available upon request.

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Figures

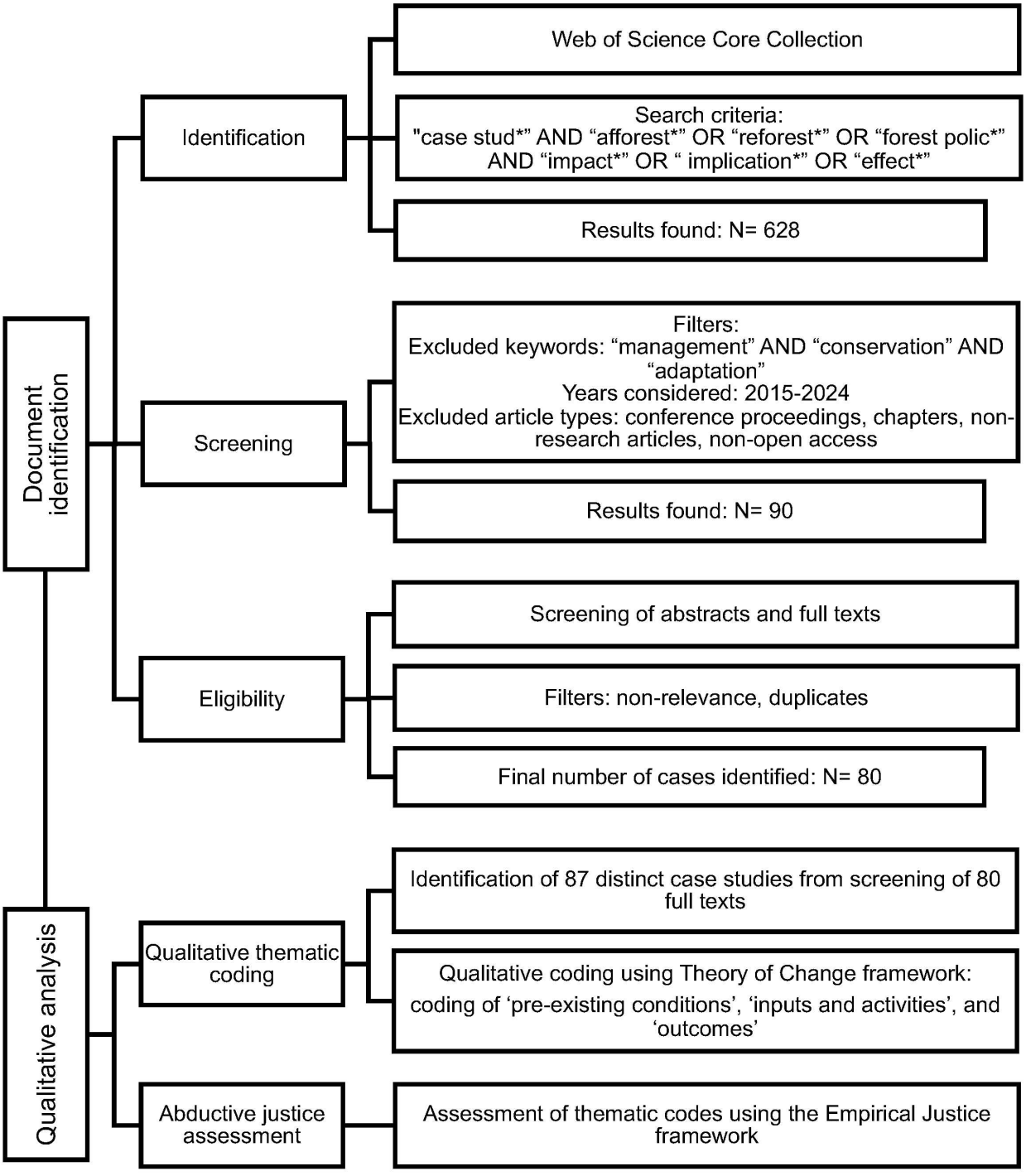
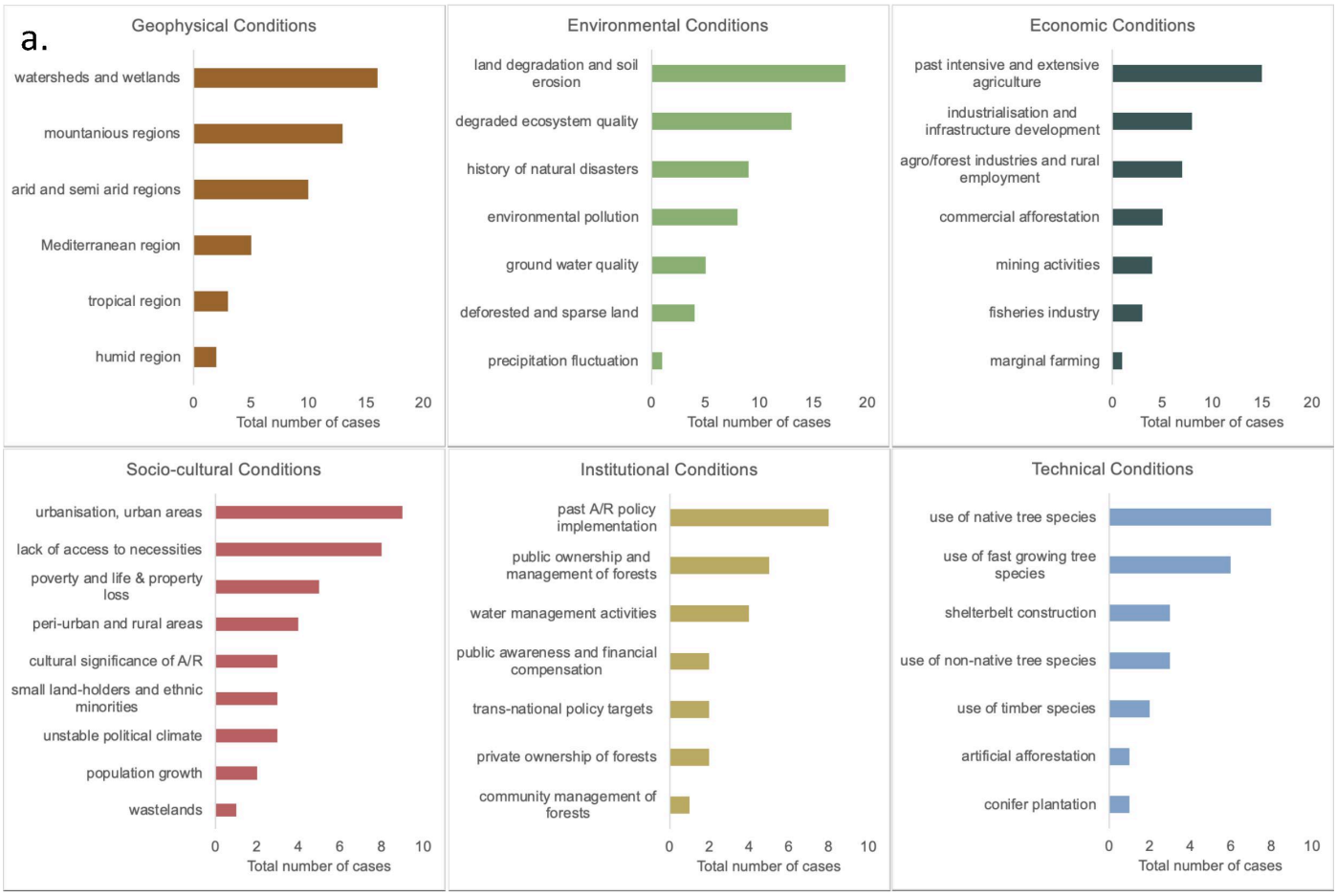


Figure 1

Flow chart of methodological process used for the review



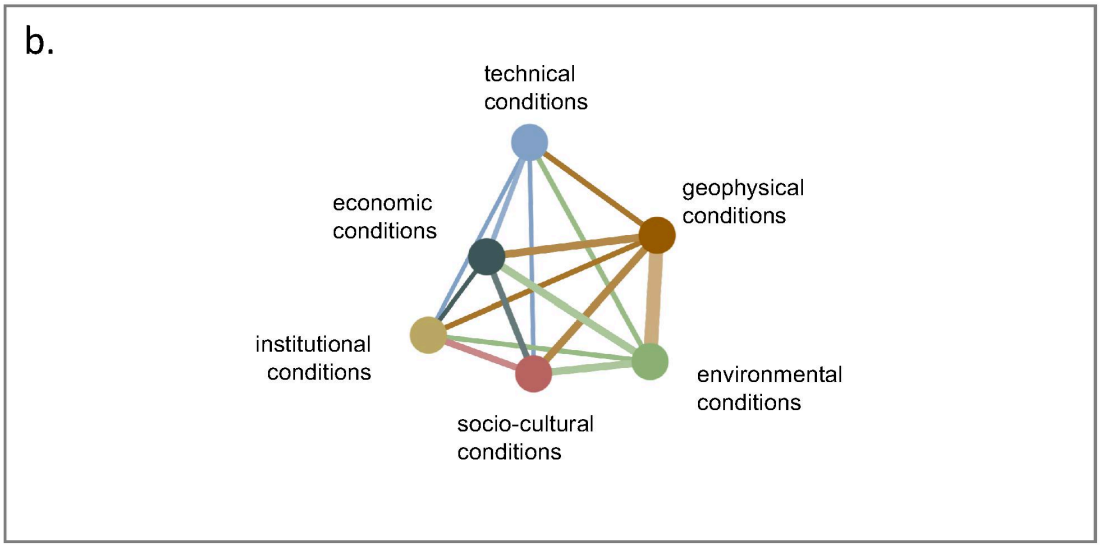


Figure 2

Contextual conditions described in the 87 reviewed cases as coded into 6 different categories: geophysical, environmental, technical, social, economic, and institutional.

Figure (a) shows the graphs with existing conditions in the case study areas before or as A/R was implemented. The x axis signifies the number of cases. Figure (b) shows the normalised co-occurrence

of these categories of conditions through a co-occurrence network graph. Each node (condition) is differentiated by a colour and is placed using the Force Atlas 2 algorithm in the Gephi Software Layouts. The layout signifies shared attributes and co-occurrence between the nodes. The thickness of the edges (connecting lines) refers to the normalised co-occurrence of these conditions within all the cases.

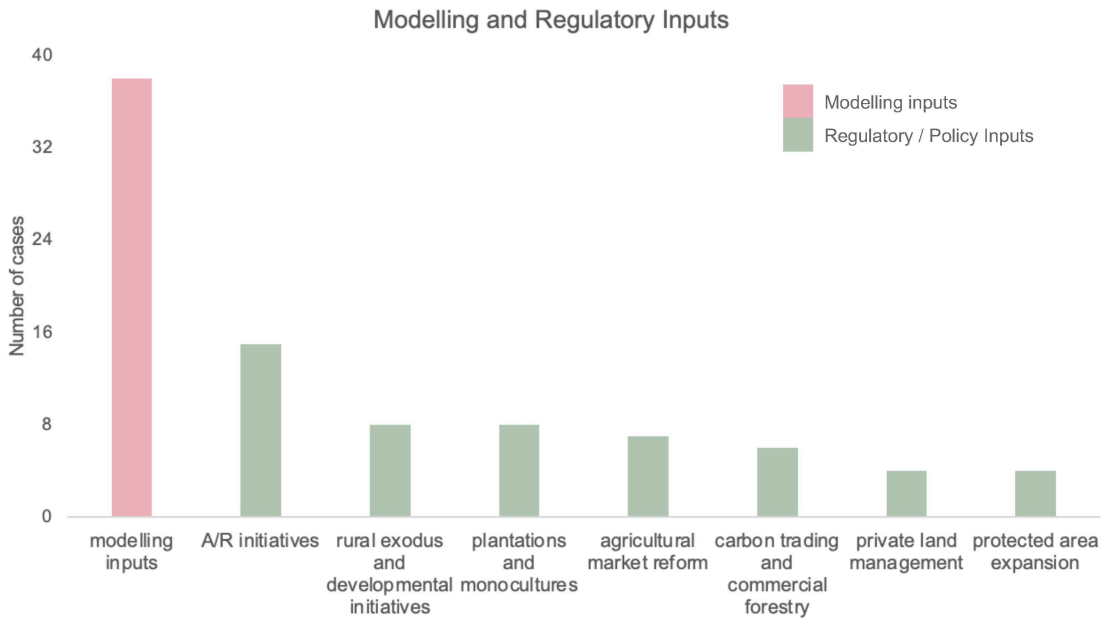


Figure 3

A/R activities as described in the cases, categorised according to study methodologies. The y-axis shows the number of cases attributed to each category of input.

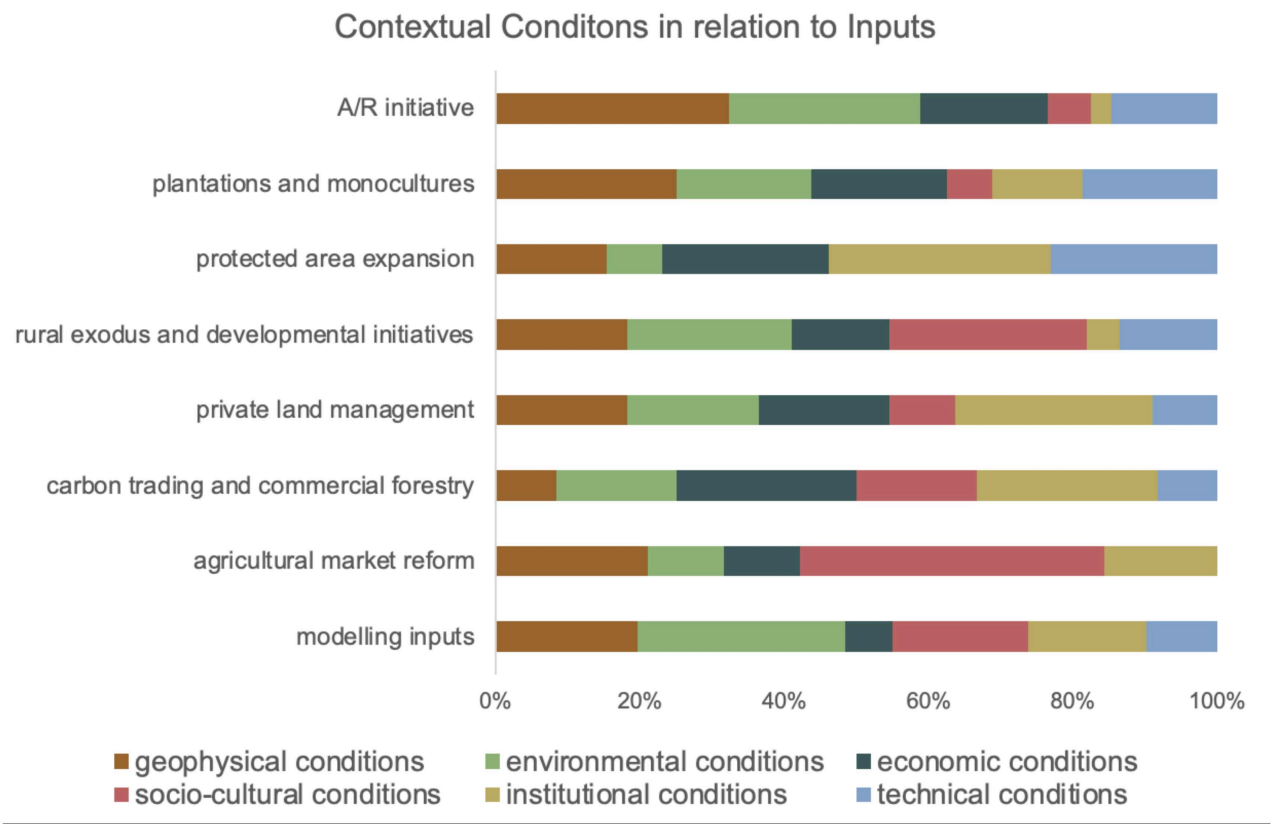


Figure 4

The combinations of contextual conditions and A/R inputs in the cases

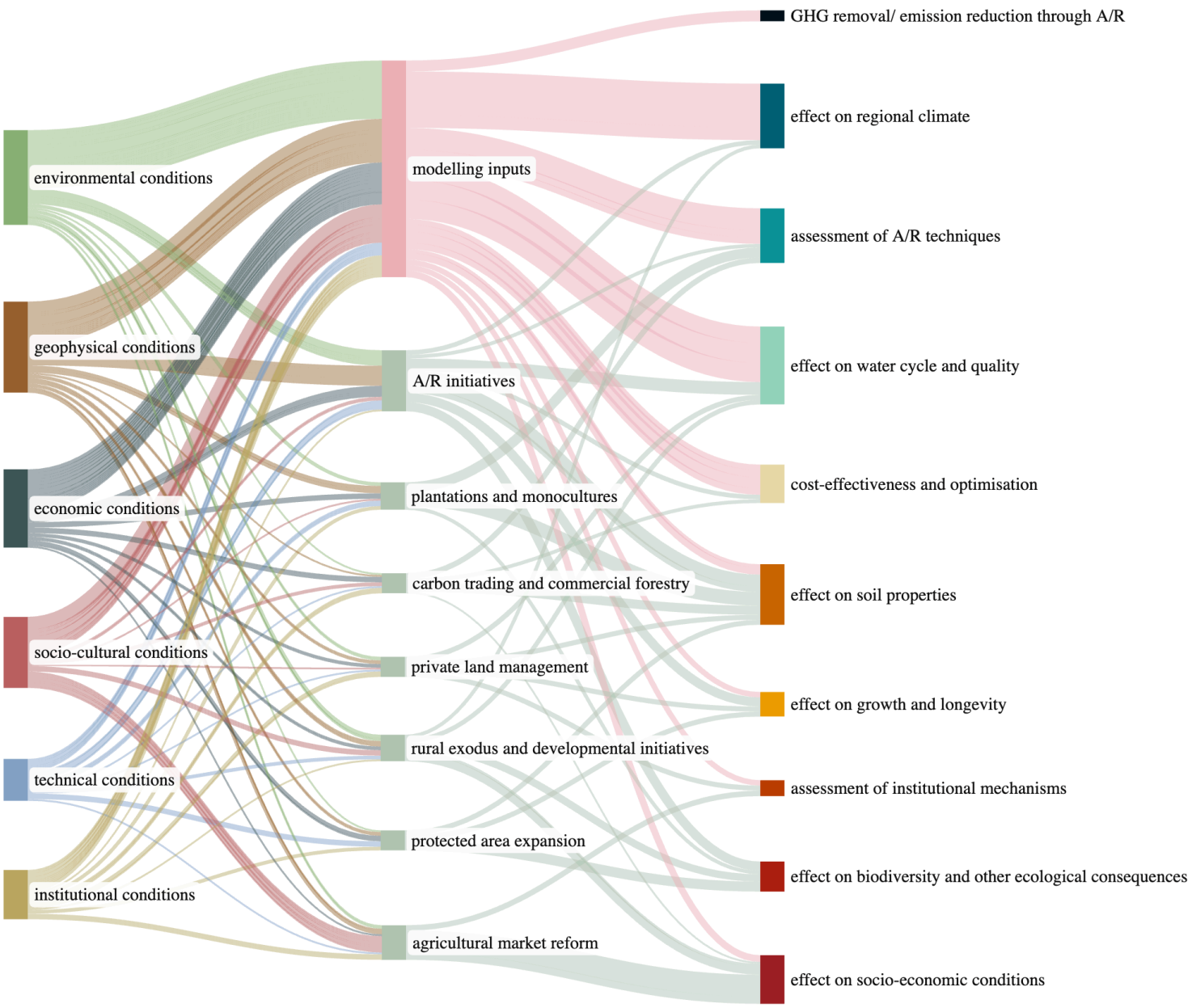


Figure 5

A graphical representation of the processes through which observed outcomes of A/R are realised. The 10 categories show the implementation and impacts of A/R which have served as foci for A/R research. The figure shows the causal pathways through which each outcome (research focus) is realised.

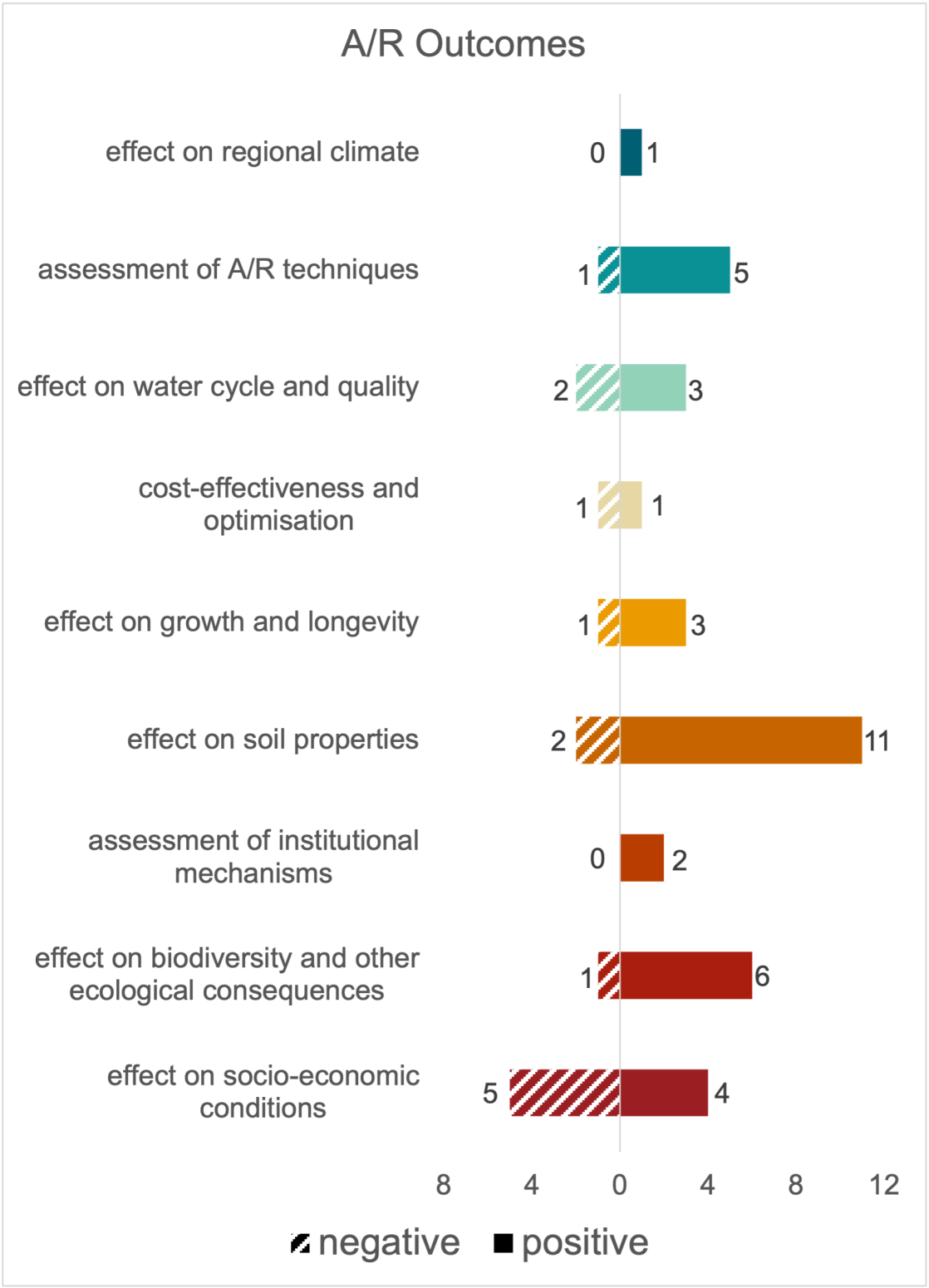


Figure 6

Outcomes discussed in 49 cases using empirical and literature review methodologies, categorised according to the research foci (y axis). The positive and negative outcomes are a value judgement of outcomes, as described in the cases, categorised thematically, and so the metric for "positive" and "negative" is qualitative and not quantitative.

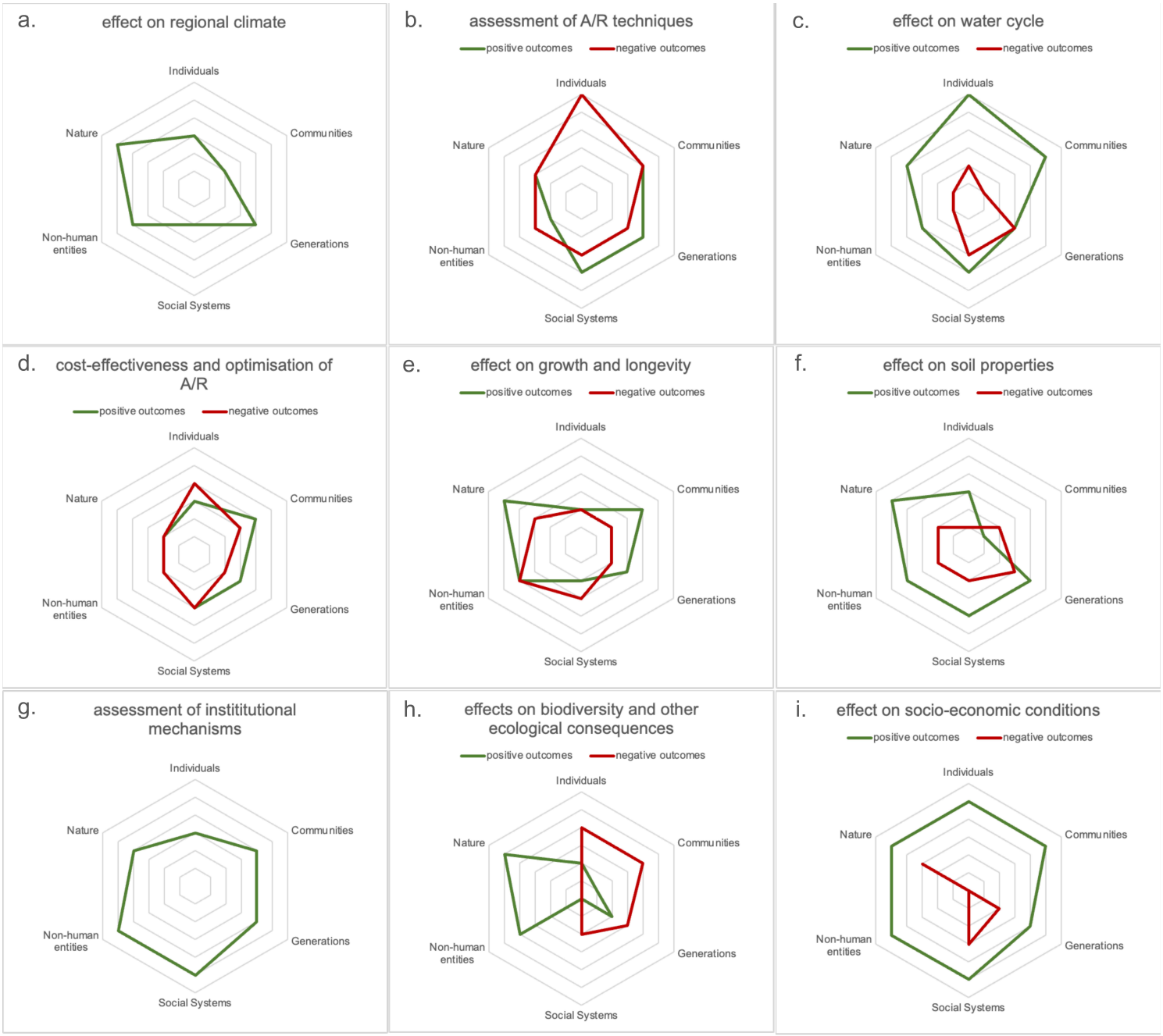


Figure 7

Justice implications of different A/R outcomes within research foci. The scale of the charts is based on the strength of justice implications. The outermost boundary signifies the most just implications while the centre signifies the most unjust implications for the subject concerned. These implications are based on the information provided in the original papers.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryMaterial1.docx

- SupplementaryMaterial2.pdf