Evaluating optimal solutions to environmental breakdown

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Abstract

The severity of environmental threats, especially climate change, biodiversity loss and pollution, are well established, as is the urgent need for them to be addressed. These threats act both in isolation as well as synergistically to contribute to overall 'environmental breakdown'. Debate exists around the most optimal governance and policy approaches to address these threats and, to date, little quantitative evidence exists to compare the different approaches. Using a modified Bayesian belief network model to assess the probability of environmental threats, we compare and contrast a range of proposed policy solutions to a selection of contemporary environmental problems that have been identified as having the potential to contribute to, or indeed may lead to environmental breakdown. Through interrogation of the models, we conclude that policies that prioritise economic growth at the expense of nature would be largely ineffective, whereas a more integrated approach, adopting comprehensive 'Green New Deal' policies combined with nature-based solutions would be the most effective approaches to preventing environmental breakdown, as they address societal and environmental issues simultaneously. We therefore recommend that decision makers take an integrated approach to decision making and policy development, accounting for social, economic and environmental drivers that ensure delivery of multiple benefits and real change.

Key Words Climate change; Biodiversity loss; Pollution; Nature-based solutions; Green New Deal; Economic growth

1. Introduction

Since the IPCC (2018) report on the importance of limiting climate change to 1.5 °C, there has been far greater public, political and scientific consensus on the urgent need to act on the causes of climate change (Zhenmin and Espinosa, 2019). Environmental problems in general have been increasingly in the spotlight in recent years, with further high-profile reports on biodiversity loss in 2019 (IPBES, 2019). It is increasingly clear that there is an urgent need to address these major environmental problems and this is coupled with evidence of a growing public appetite for the necessary actions (Cherry et al., 2018; Ostfield and Reiner, 2019). It is important to recognise that these environmental problems are not happening in isolation: they are interconnected and occurring simultaneously (Staudt et al., 2013; Mantyka-Pringle, 2015). This is leading to growing concerns that the interactions and synergies between them pose a significant risk of 'Environmental Breakdown' (Laybourn-Langton et al., 2019; Stafford and Jones, 2019a), which we define here as destabilisation of natural systems occurring at speeds unprecedented in human history (Laybourn-Langton et al., 2019).

In response to these challenges, a growing number of policy and management solutions to the environmental crisis have been proposed by many, including scientists, think tanks, government agencies, NGOs, journalists and activist groups (e.g. Cohen-Shacham et al., 2015; Griscom et al., 2016; Monbiot, 2017; Raworth, 2017; Laybourn-Langton et al., 2019; Stafford and Jones, 2019b; Sterner et al., 2019). Some are specific policy responses to threats such as climate change, others are more holistic in nature, intending to address multiple threats simultaneously. The solutions can also differ radically. For example, economic growth has been suggested by some as the dominant underlying cause of environmental destruction (Kalis et al., 2018; Sandberg et al., 2019). In spite of this, green growth policies actively promoting the development of green technology, which aim to both reduce carbon emissions *and* drive economic growth, are common in much contemporary political thinking (Fischer-Kowalski et al., 2011; Parrique et al., 2019; Sandberg et al., 2019), despite evidence that it is rarely feasible to decouple economic growth from environmental degradation (Parrique et al., 2019). Policies such as the Green New Deal intend to boost aspects of the economy specifically through investment in technology and infrastructure to reduce carbon emissions (e.g. renewable energy and energy efficiency through retrofitting buildings) (Congress Bill H.Res.109, 2019). However, many comprehensive Green New Deal scenarios proposed greatly expand on these basic principles, and do not emphasise continuing the overall growth of the economy (Elliot et al., 2019; Green New Deal for Europe, 2019). The UK proposals for a Green New Deal, previously submitted to the UK parliament, also suggest removing fossil fuel subsidies and increasing carbon taxes (Elliott et al., 2019), as did the election manifestos of the Green Party and Labour Party in the 2019 UK general election (Stafford et al. 2019).

In addition to policy solutions focused on reducing fossil fuel consumption and moving towards a low carbon economy, alternative policy approaches have focused on nature-based solutions to adapt to/ mitigate for the impacts of climate change and associated ecosystem degradation and biodiversity loss. While this is often discussed in the form of planting of trees, it also encompasses creation and restoration of habitats (e.g. saltmarshes, mudflats, peat bogs) and improved management of existing habitats, to capture carbon and protect wildlife (Griscom et al., 2017; Seddon et al., 2019; 2020).

To date, there has been no quantitative or semi-quantitative comparative analysis of the effectiveness of these different policy solutions for addressing environmental breakdown and of their impacts, nor on the interactions between approaches, or the effects of actions for one issue (e.g. climate change) on others (e.g. biodiversity loss). In this study, we separately, and comparatively, evaluate a selection of policy solutions to address three key environmental issues: climate change, biodiversity loss and pollution, recognised as the main planetary boundaries that have been breached (Steffan et al., 2015), and accepted as the main drivers of environmental breakdown (Laybourn-Langton et al., 2019). While it is widely acknowledged that environmental breakdown may lead to social disorder and reduction in economic growth (Stern, 2007; WEF, 2019), we have removed this added complexity and feedback from the model to focus on the aim of identifying policy approaches that prevent environmental breakdown from occurring. We do, however, consider the social and economic implications of different environmental policies in addition to their environmental contributions.

In this study, we use models developed from Bayesian belief networks by Stafford et al. (2015) to compare and contrast how different combinations of policy solutions address a range of environmental and socio-economic issues (Figure 1). In this format, we can evaluate their performance in limiting climate change, reducing biodiversity loss, reducing pollution and thereby addressing overall environmental breakdown, as well as examining their consequences for society. We base these evaluations mainly on developed countries but do also discuss the application of the results to the Global South, an area that is often under-researched. While we do not claim this to be a full quantitative evaluation or indeed an in-depth governance analysis of these policies (see Alexander et al., 2016 for an example of this approach), we suggest this approach provides a springboard for these discussions, as well as an enhanced conceptual awareness of the relationship between various solutions and the problems that they function to solve. Furthermore, this paper presents a semi-quantitative, or ranked, representation of different combinations of proposed policies, and thus provides some clarity of evidence for policymakers in deliberating on key decisions to tackle global environmental breakdown.

2. Methods

2.1 Overview

In this study we examine how a suite of policy measures (adopted either individually or in conjunction) can help mitigate environmental breakdown. We select a range of commonly proposed measures (e.g. Green New Deals, nature-based solutions) and examine some of the most comprehensive suites of policies related to these topics (e.g. the specific proposals within the UK proposal for a Green New Deal, as proposed by Elliott et al., 2019), compared to the core Green New Deal strategies (e.g. as proposed to the US congress (Congress Bill H.Res.109, 2019)). To address the performance of these policy measures in combatting environmental breakdown, we construct a directional network graph of policy, intermediate and societal outcome nodes (Figure 1; Table 1), which align, as best as possible, to the policies and outcomes considered in the strategies, as well as the overall environmental measure of 'Environmental Breakdown'. Weighting of edges between nodes is described as positive (the response node acts in the same direction as the source node: i.e. source node increases, response node increases as a response) or negative (response node acts in a different direction to the source node) and classified as strong, medium or weak. Evidence for these interactions is provided in the supplementary material. Where possible, we have referred to published literature to inform these edge parameters, but in other cases, where literature was not available, final parameters are based on agreement between the authors. Where literature sources were used to define the edges, we adopted a systematic approach to setting the strength of edge parameters. Strong connections were evidenced by higher numbers of studies, strong evidence within a study, agreement between studies and appropriateness of the study to the issue. The majority of edge links are geographically universal, although some will be more focussed on developed countries due to literature available, therefore the conclusions we draw focus mainly on developed countries. To assess uncertainty in the edge parameters, full sensitivity analysis was conducted using a randomised bootstrapping process (see below); hence, many parameters were assessed under both strong and medium, or medium and weak values within any given scenario. The graph is used as a basis for a Bayesian belief network, modified as per Stafford et al. (2015) to allow reciprocal interactions and prevent the necessity of parameterising complex interactions between multiple nodes independently. Removal of these traditional constraints of Bayesian belief networks essentially allow for evidence-based model building at this scale.

Policy nodes are changed (*a priori*) to address typical policy initiatives (summarised in Table 2), by changing prior values for these parameters to > 0.5 (likely to increase) or < 0.5 (likely to decrease) with all other prior parameters left at 0.5 (equal chance of increasing or decreasing). Responses to these policy changes are calculated through the Bayesian belief network. We have selected a range of policy options commonly proposed to address environmental problems, including: Green Growth (especially focusing on development of renewable energy), a full implementation of the European Green New Deal (the consideration of both of these encompasses a range of different strategies and proposals of 'green deals'), as well as full implementation of nature-based solutions, and typical political implementation plans for nature-based solutions, which often focus on only some aspects, such as tree-planting. In most of our scenarios, adjusting policy nodes will have effects on the intermediate and societal outcome nodes. The category of 'node' is largely to help understand the policies introduced, and mathematically all nodes operate in exactly the same manner. However, a selection of more specific policies (e.g. around food production) were considered in some of the scenarios by directly adjusting prior values of the intermediate nodes. Societal outcome nodes may affect each other but were not manipulated in the scenarios presented. Clearly, a larger suite of such nodes could be implemented, and additions such as poverty might be useful to further examine implementation of policy in the Global South. Those chosen here reflect the environmental parameters of concern, but also selected key policy drivers (e.g. Economic Growth) and measures of social justice in developed countries (e.g. Economic Inequality).

2.2 Belief network model

The belief network model used in this study was constructed using R (R Core Team, 2016) and a working version of the model, including full code and data files are provided as supplementary material. For each node in the network a 'prior' value between 0 and 1 is given to indicate the belief that a given node may increase or decrease [$P(X_i)$ and $P(X_d)$ respectively]. In this belief network, the sum of the probability of a species increasing and decreasing must equal 1.

Given these 'prior' parameters set by the policy initiatives, intermediate probabilities of each node *increasing* given node interactions are calculated using the following Bayesian equation:

$$P(X_i|Y)=[P(X_i|Y_i)*P(Y_i)+P(X_i|Y_d)*P(Y_d)], \quad [1]$$

where X is the node under consideration, and Y are the interacting nodes, subscripts i and d indicate increasing or decreasing respectively for the nodes. These values are calculated for each interacting node.

Where no knowledge of a change in node exists (i.e. the prior probability of change is 0.5) then this node is not included in the above equation, noting that such inclusion might occur in the second iteration of the model (see below for details).

At this point, no 'prior' information on node X is included in the calculation. To ensure any prior knowledge available is maintained in the network, the overall posterior probability for each species is calculated in two ways. The first ensures that additional information on node interactions add to the certainty provided by the prior, the second will ignore prior values, if information on node interactions provide more certain information than the prior:

(a) $Post(X_i)=P(X_i)+|1-P(X_i)|*[\sum 1-n(P(X_i)*(P(X_i|Y)-0.5))/n]$, [2]

And

(b) $Post(X_i)=[\sum 1-n(P(X_i|Y))]/n$, [3]

where n is the number of interactions with node X. The final value of $Post(X_i)$ is given by the value displaying the most certainty (i.e. furthest in magnitude from 0.5). The model is then repeated for a second iteration, but with updated prior probabilities such that:

$P(X_i)=Post(X_i)$, [4]

Technically, Bayesian belief networks measure the probability of a node, in this case, either increasing or decreasing. However, in this situation, it is difficult to distinguish between a probability of decrease and a magnitude of decrease – if a decrease is likely to be large, then it is typically more likely to occur than a small change, and the magnitude of changes were considered in the parameterisation of the edges of the network. While the distinction between probability and magnitude is clear in the scientific literature, this has often been developed from human behaviour studies (e.g. Young et al., 2014). For measurable phenomena, especially in natural systems, these distinctions would not apply. For example, you would be more certain of wind speed increasing, if you knew a storm was approaching. The parametrisation of the network therefore indicates high levels of certainty to large and certain changes. To account for this concept of interrelatedness of certainty and magnitude, as well as some lack of certainty in the parametrisation of the relationships between the nodes, we conduct a randomised, bootstrapped sensitivity analysis of the model. This involves randomly selecting 10 % of interactions in each iteration and adjusting them by a randomly determined amount of ± 0.1. This process was run 10,000 times and 95% confidence intervals of the output of each parameter are calculated by removing the highest and lowest 2.5% of values (as per methods in Crawley, 2012). These confidence intervals are applied to the actual values calculated in the model using the initial parameter set provided in the supplementary materials.

2.3 Implementing policy scenarios

We test a number of different policy combinations in their effectiveness in tackling environmental breakdown (detailed in Table 2), but adjusting the relevant 'priors' (or initial values in the model) in our network to the values indicated in Table 2; all other priors remaining at 0.5 (an equal probability of increasing or decreasing).

3. Results

1. Our results show there are a number of ways of tackling environmental breakdown, with scenarios 2, 3, and 4 (Comprehensive Green New Deal (excluding nature-based solutions), nature-based solutions, and a suite of measures proposed previously by some of the current authors respectively, (detailed in Table 2) providing significant declines in the probability of environmental breakdown (Figure 2). Of these scenarios, Nature-based Solutions (Scenario 3) produced the potentially biggest decrease in environmental breakdown (albeit with large confidence intervals), successfully tackling all three environmental issues. However, Scenario 3 encompasses increases in nature-based solutions including planting trees and habitat restoration, as well as improved management of natural systems, in a situation where economic growth is not forced to rise (economic growth node initially set at 0.5). Such an approach of limiting economic growth is not consistent with many national economic policies. Applying nature-based solutions in a weakened form (i.e. just planting rapid growth trees) while still pursuing economic growth results in the probability of reductions in environmental breakdown being greatly diminished over Scenario 3. This strategy (represented by Scenario 5) becomes the weakest of the strategies in terms of its effectiveness in reducing that risk of environmental breakdown, although it still results in a significant, yet small, benefit to the environment. Equally, the core Green New Deal principles (Scenario 1) did not demonstrate major environmental benefits, exhibiting a small increase in environmental breakdown and little change in warming, biodiversity and pollution. This scenario did, however, result in an overall increase in economic growth, whereas in the other examined scenarios (excluding scenario 5), changes to economic growth were found to be minor (although, as previously mentioned such growth may be temporary if environmental breakdown is to occur). Most scenarios involving new approaches to taxation and growth also resulted in a reduction of social inequity. Combining a nature-based solution approach to environmental management with other policy options (e.g. the full recent proposal for the UK Green New Deal as per Elliott et al. (2019) –

Scenario 6) produced more environmental benefits when compared with any other individual scenario. Again, in this case, societal challenges such as inequity also fell (Figure 2).

Approaches that involve localisation of resources, reduced intensive agriculture or increased nature-based solutions resulted in increases in land demand (especially seen in scenarios 3, 4, 5 and 6). However, it should be noted that the model is unable to account for the amount of available and appropriate land, therefore large increases in the land area required to deliver policy options of this type would need to be considered carefully. Finally, Nature-based solutions also demonstrated fewer 'societal' level changes (those affecting the behaviour of people), e.g. private transport and air travel are less affected by this solution than those involving green taxes or removal of fossil fuel subsidies, which perhaps does not align with recent calls for widespread individual and systemic behaviour change (CCC, 2019).

4. Discussion

Environmental issues affecting the planet are complex and entwined with each other, as well as with social and economic issues (Stern, 2007; Staudt et al., 2013; Mantyka-Pringle, 2015; Raworth, 2017; Laybourn-Langton et al., 2019). This study examines a selection of the multiple policy solutions proposed as potential mechanisms to address the current environmental crisis, from social and economic reform, through to enhancing natural solutions to capture carbon and boost biodiversity. We found that the optimal policy approach is likely to use both natural solutions, e.g. habitat restoration, along with wider societal reform, e.g. a significant reduction in the global dependence on fossil fuels, and changes to governments' economic policies. This approach largely mirrors the proposed policy initiatives presented in the UK proposals for Green New Deal plan (Elliott et al., 2019), and Decarbonisation and Economic Strategy Bill (2019) introduced to the UK parliament prior to the 2019 general election. It should be noted, however, that not all 'Green New Deals' contain all these measures. For example, the current resolution presented to the US Congress does not specifically mention taxes, fossil fuel subsidies or changes to economic growth strategies, although it should be noted that it does indicate a limited degree of nature-based solutions through changes to agricultural practices (Congress Bill H.Res.109, 2019). These ‘core’ Green New Deal strategies presented in the bill to Congress can be shown to be much less effective than comprehensive strategies, although it should be noted, that the sentiment of the Congress bill may be much stronger than the legal text accounts for (Klein, 2019; Chatzky, 2020).

We show that current political strategies that preferentially pursue economic growth are clearly counter to solving environmental issues. However, the most effective strategies we examined resulted in little overall change in economic growth, meaning that being ‘agnostic about economic growth’ as advocated in the concept of ‘doughnut economics’ is likely a good policy to adopt to protect the environment (Raworth, 2017). Agnosticism, rather than actively pursuing growth or degrowth strategies, is likely to be a sensible compromise, especially since there can be considerable differences in the environmental effects of economic growth, depending on the geographical, industrial and policy context (Raworth, 2017). However, it is clear that growth can fuel demand for resources, suggesting that promotion of excessive growth, green or otherwise, could be counter to solving environmental issues, especially in developed countries. Again, it should also be noted that economists have long agreed that environmental breakdown is likely to have major negative effects on economic growth in the long term (Stern, 2007; WEF, 2019).

Through the model, we found that strategies that pursued only the core aspects of Green New Deals which involve economic growth in certain areas (e.g. renewable energy and energy efficiency) alone did not result in environmental benefits, despite an increase in economic growth. This should raise concerns about some implementations or proposals labelled as ‘Green New Deals’ which tend to focus heavily on the economic agenda, and less on other methods such as progressive carbon taxation (Klein, 2019; Chatzky, 2020). In addition, the inclusion of nature-based solutions alongside ‘business as normal’ also failed to address environmental problems to the same degree as if economic growth was not a priority.

The lack of environmental benefits occurring alongside economic growth has been suggested by previous studies (e.g. Parrique et al., 2019; Sandberg et al., 2019). However, while core Green New Deal policies that increased economic growth did not reduce the probability of environmental breakdown, they also did not increase this probability. As such, this approach may be a viable option for Global South countries looking to economic growth as a mechanism for sustainable development, whilst still seeking to minimise, or at least mitigate against, any negative impact on the natural environment.

Natural climate solutions are found to be extremely beneficial in preventing environmental breakdown and are predicted to be the single most important factor in this model. While demand for land is an important consideration (for example in establishment of new areas of forest) and may have effects on available agricultural land, it is important to note that many natural climate solutions can be achieved through improved management of existing land, and through the construction of habitats in areas not suitable for farming (including coastal and marine habitats) (Griscom et al., 2017; Howard et al., 2017). Equally, while recent studies have suggested land demand and carbon output from organic agriculture is far higher than for non-organic agriculture (Smith et al., 2019), shifts in human consumption from meat to vegetable-based diets would reduce agricultural land demand considerably, while also having a direct impact on reducing greenhouse gas emissions (Poore and Nemecek, 2018).

The suite of changes suggested in the UK proposal for a Green New Deal (Elliott et al., 2019), or the suggestions previously expressed in an opinion article written by some of the authors of this paper (Stafford and Jones, 2019b) have multiple benefits, encompassing both environmental protection *and* societal benefit. While economic growth is limited, economic inequity across society falls, and personal wealth (the wealth of an ‘average’ person in society) increases a little, or at the very least, stays level. Therefore, due to the fall in inequity, personal wealth is likely to increase for those with below average wages, increasing overall social well-being and welfare across society.

The current study provides an initial framework for comparative assessment of the potential impact of different policy combinations on environmental, economic and social outcomes. Overall, the implications from this study addressing environmental breakdown are clear. First, we must urgently change the narrative around economic growth. While we do not need to focus on a strong 'degrowth' agenda, we must ensure that decarbonisation of the economy occurs rapidly and that future economic plans take environmental and social issues into account from the outset. Existing policies such as the UK proposal for a Green New Deal (Elliot et al., 2019), the Green New Deal for Europe (2019) or the concepts of Doughnut Economics (Raworth, 2017) provide strong frameworks for these changes to be implemented, especially alongside the removal of economic growth as a key policy objective goal. Secondly, these changes should be supplemented with investment in nature-based solutions, and changes to agricultural practices (e.g. meat production) and associated supportive policies may be needed in order to successfully manage land demand. Given the pressing dual issues of climate change and global biodiversity loss, the urgency of these actions should not be underestimated. This paper presents a starting point from which proposed actions and policies to address the environmental crisis currently facing the planet can be assessed and prioritised.

Author Contributions

Conceptualization, RS, PJSJ, CS, TG, EC, EMR: Methodology, RS, EMR, EC, JS: Software, RS: Validation, ARC, EMR, RS, JS: Formal Analysis, ARC, EMR, RS: Investigation, ARC, EMR, EMK, RS: Data Curation: ARC, EMR: Writing – Original Draft, RS, CS: Writing – Review & Editing, All Authors: Visualization, RS.

Declaration of Interests

The authors declare no competing interests

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Data and Software Availability

All data and software are provided as supplementary Information

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Table 1. Nodes in the network model. Codes correspond to those in Figure 1. Intermediate nodes could in some cases also act as policy nodes (e.g. active policies to reduce air transport), but can also be consequences of bigger changes, for example, in green taxation.

Name of Node	**Node Type**	**Examples**	**Code used in Figures**
Green Tax	Policy	Taxes on pollutants, such as fossil fuels	GreenTax
Fossil fuel subsidies	Policy	Government incentives to continue to extract oil, coal and gas	FosFuelSub
Core GND policies	Policy	Building or installing green infrastructure and products	CoreGND
Nature-based solutions	Policy	Reforesting, or marine solutions such as seagrass planting	NBS
Nature Education	Policy	Formal or informal education regarding nature and wildlife	NatEd
Renewable energy	Policy	Wind / wave / solar energy	RenewEn
Greenhouse gasses	Intermediate	Greenhouse gasses in the atmosphere (including CO_2 and methane)	GreenHGas
Personal Wealth	Intermediate	Income and savings of a typical individual	Wealth
Work	Intermediate	Time spent working	Work
Private Transport	Intermediate	Cars, vans etc	PriTrans
Public Transport	Intermediate	Busses, trains, trams	PubTrans
Walking or Cycling	Intermediate	As stated	Walk
Localisation	Intermediate	Localisation of economy, to include local power generation, food production etc	Local
Air transport	Intermediate	Personal / work travel and air freight	Air
Resource use	Intermediate	Use of resources, including fossil fuels, water and rare metals	Resource
Meat Consumption	Intermediate	Amount of meat consumed at a population level	Meat
Vegetable Consumption	Intermediate	Amount of vegetables consumed at a population level	Vegetables
Intensive agriculture	Intermediate	Intensive rearing of plants and animals involving fertiliser, pesticide etc	IntensAg
Organic agriculture	Intermediate	Less intensive agriculture using more traditional techniques	OrgAg
Industrial Fishing	Intermediate	Large boats, operating offshore for long periods of time	IndFish
Small-scale Fishing	Intermediate	Local fishing, close to land using small boats typically on day trips	SSFish
Land demand	Intermediate	Demand for land, for agriculture, houses etc	Land
Excessive Goods	Intermediate	Purchase of non-essential items	ExcessGoods
Inequity	Societal Outcome	Magnitude of difference between richest and poorest in society	Inequity
Economic Growth	Societal Outcome	National growth of economy – e.g. GDP	EcoGrowth
Warming	Societal Outcome	Climate change, global warming	Warming
Biodiversity	Societal Outcome	Number of species/ habitats etc	Biodiversity
Pollution	Societal Outcome	Pollutants in air, water, soil. Including plastic waste	Pollution
Environmental Breakdown	Societal Outcome	Sum of environmental pressures, potentially causing a tipping point in the natural environment	EnvBreak

Table 2. Key proposed scenarios to address one or more environmental issues alongside scenario of pursuing economic growth and combining policy solutions

Scenario Number	Name	Reference	Details	Model implementation
1	Core Green New Deal Policies	Congress Bill H.Res.109 (2019)	The renewable energy and efficiency strategy outlined in the US Green New Deal Bill to Congress. It includes plans to boost the economy and jobs through green infrastructure (house insulation, renewable energy). No changes to taxation or fossil fuel subsidies are included in this specific bill.	Adjust 'Core GND polices' node from 0.5 (no change) to 1 (high level increase)
2	Comprehensive GND policies (excluding nature-based solutions)	Elliott et al. (2019)	Comprehensive implementation of the Green New Deal concept. Core policies (as above), alongside increases in green tax, removal of fossil fuel subsidies, changes to intensive food production methods.	Adjust following nodes as indicated: Core GND policies = 1 Green tax = 0.75 Fossil fuel subsidies = 0 Intensive farming = 0.2 Industrial fishing = 0.2
3	Nature-based solutions	Griscom et al. (2017)	Conservation, restoration and improved land management measures (e.g. planting trees, avoiding fires, forest management).	Adjust Nature-based solution node to 1
4	Alternative socio-economic changes	Stafford and Jones (2019b)	Multi-point plan involving higher green taxes, improving public transport and cycling, increased localisation of processes, working less, valuing nature through enhanced education.	Adjust following nodes as indicated: Green taxes = 1 Public transport = 0.75 Walking and cycling = 1 Nature education = 1 Work = 0.35 Localisation = 0.75
5	Pursuing economic growth and partial implementation of nature-based solutions	UN (2019)	The actions with strongest international agreement from COP25. Twenty countries agreed to implement nature-based solutions, but frequently this thought of as 'tree planting' rather than a full range of restoration and change in management practices (Nature4Climate, 2019).	Adjust Economic growth node to 1. Adjust Nature-based solution node to 0.75
6	Combining solutions 2 and 3	Elliott et al. (2019); Decarbonisation and Economic Strategy Bill (2019)	Full implementation of these referenced proposals (Scenario 2 with the addition of nature-based solutions, Scenario 3)	Adjust following nodes as indicated: Core GND policies = 1 Green tax = 0.75 Fossil fuel subsidies = 0 Intensive farming = 0.2 Industrial fishing = 0.2 Nature-based solutions = 1

Figure 1. Overview of the network model used. Black arrows represent positive interactions between nodes (if the source node increases, it increases the probability of the target node increasing), red arrows represent negative interactions between nodes. The thickness of the line indicates the strength and likelihood of the interaction – thicker lines are stronger, more likely interactions. Grey nodes indicate key policy drivers, red nodes indicate intermediate nodes, some of which could also be policy drivers in a more direct sense than grey nodes. Yellow nodes are societal outcomes (including economic, social and environmental outcomes) and the single white node represents environmental breakdown. Details of what the nodes represent can be found in Table 1. (a) Full representation of the model, (b) the direct interactions from the policy nodes of the model, indicating how the key inputs would propagate through the network, (c) the factors directly affecting the output nodes of the model. A full indication of node by node interactions is given in Supplementary Material 1, and the full working model, including R code and data files for all scenarios is provided in Supplementary Material 2.

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Figure 2. Calculated mean (+/- 95% Confidence intervals from n=10000 bootstrap replicates) probability of increase in each category. Values > 0.5 mean likely increases, those < 0.5 mean likely decreases. Details of model inputs are given in Table 2 and presented here by scenario number.

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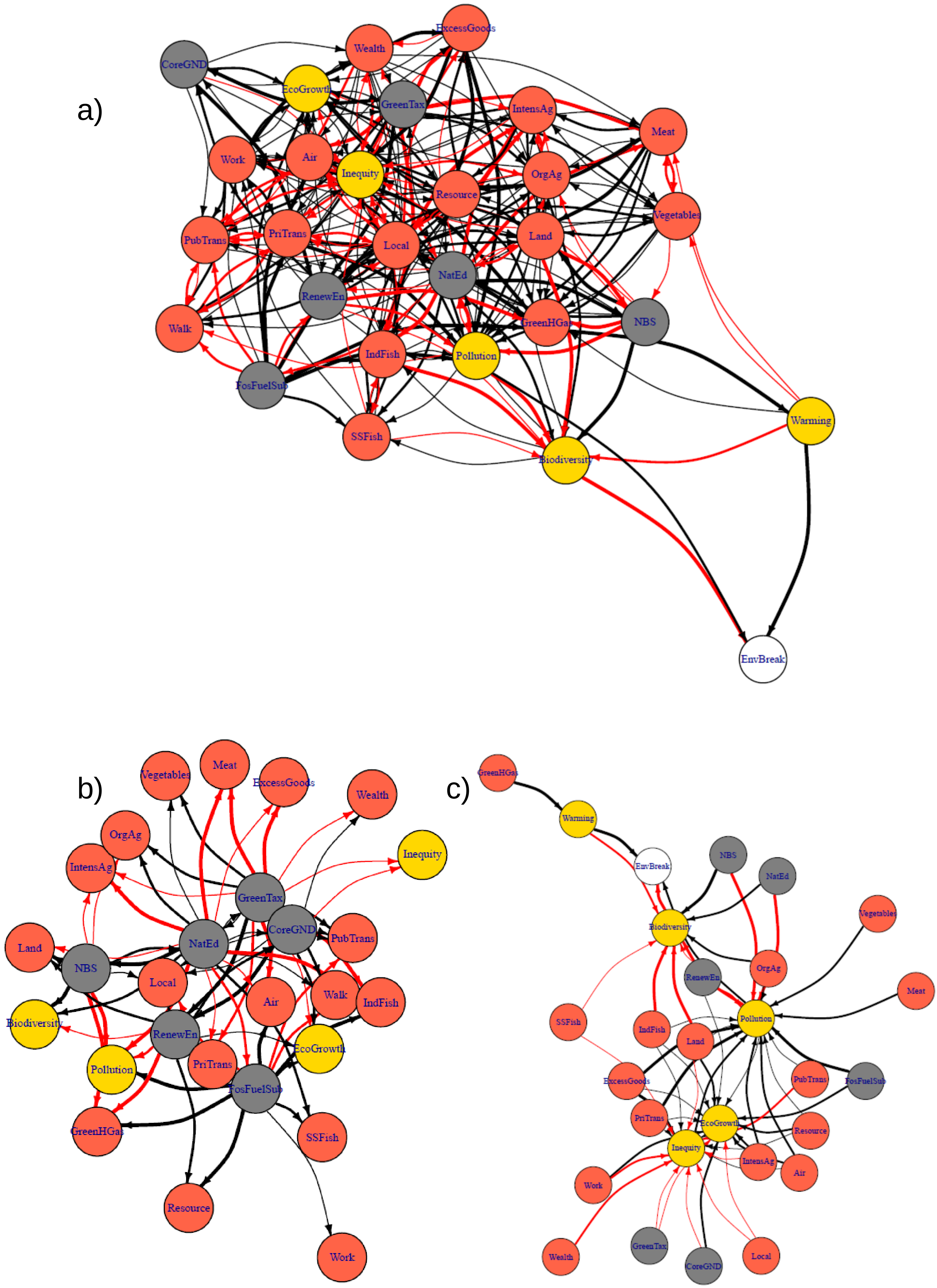
Supplemental Information

Supplemental Information 1 – details of references used to determine direction and weighting of edges in the models. Where no citation is given, values were agreed between a discussion of a sub-group of the authors (RS, EC, EMR, JS).

Supplementary material 2. R code and data files used to run the models and produce Figure 2.



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EcoGrowth
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ExcessGoods
GreenTax
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Air
Inequity
Resource
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PubTrans
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Land
NatEd
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GreenHGas
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FosFuelSub
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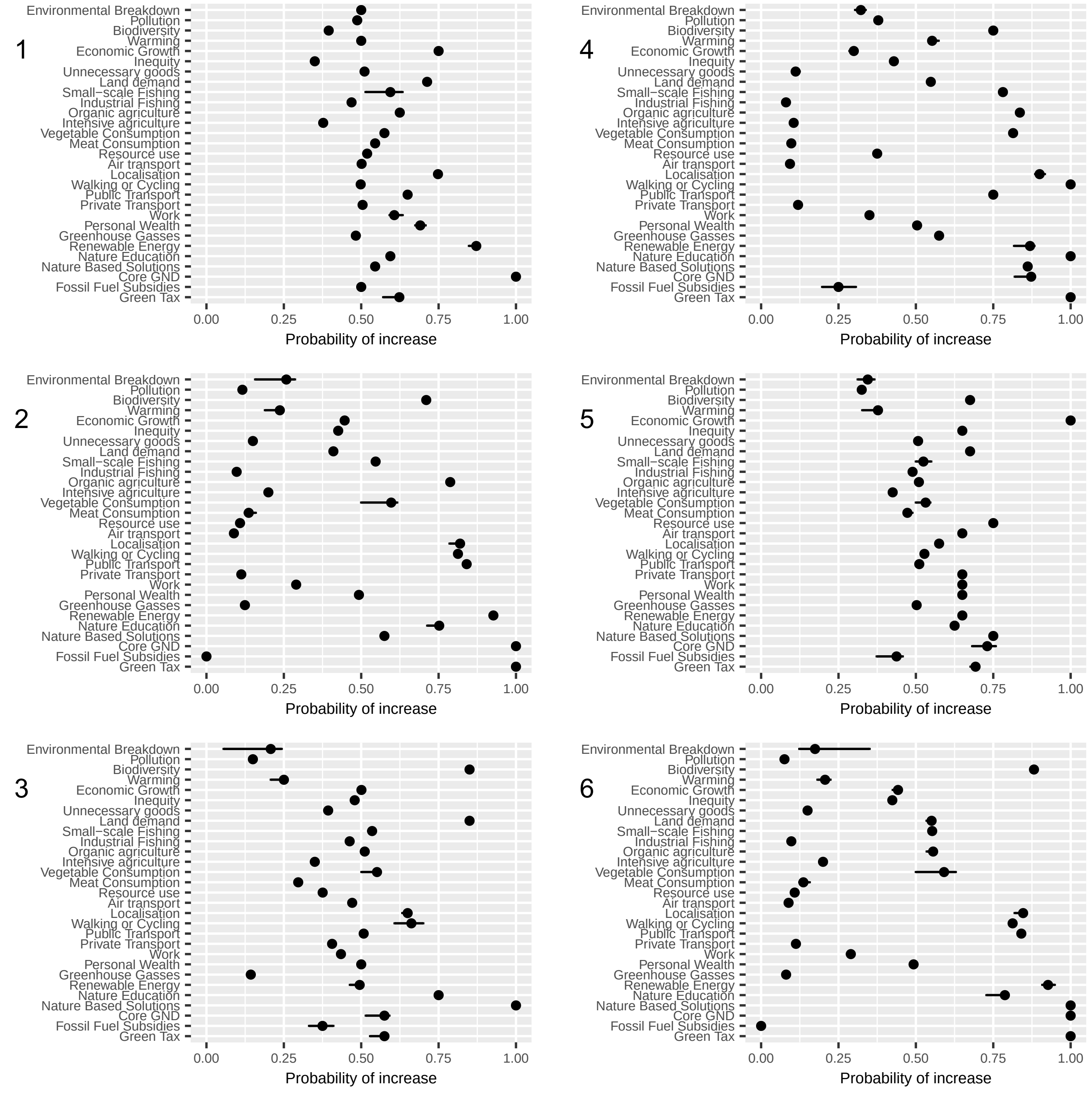
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4
5
6
Environmental Breakdown
Pollution
Biodiversity
Warming
Economic Growth
Inequity
Unnecessary goods
Land demand
Small−scale Fishing
Industrial Fishing
Organic agriculture
Intensive agriculture
Vegetable Consumption
Meat Consumption
Resource use
Air transport
Localisation
Walking or Cycling
Public Transport
Private Transport
Work
Personal Wealth
Greenhouse Gasses
Renewable Energy
Nature Education
Nature Based Solutions
Core GND
Fossil Fuel Subsidies
Green Tax
0.00
0.25
0.50
0.75
1.00
Probability of increase