Building resilience to climate-driven regime shifts

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ABSTRACT: There is increasing concern about potential climate-driven regime shifts – large abrupt shifts in social-ecological systems that could have large impacts on ecosystems services and human well-being. This paper aims to synthesize the potential pathways for building resilience to such regime shifts. Ten examples from the Regime Shift Database provided the cases for analysis. Causal loop diagrams were used to analyze feedback mechanisms at different scales and identify "leverage points" – places to intervene in the system in order to build resilience. Sixteen of these leverage points were identified, most of which relate to agricultural management. Most feedback mechanisms include at least one leverage point highlighting the potential for building resilience to climate-induced regime shifts. The most common leverage points identified in our analyses were vegetation cover, algae volume and atmospheric temperature. These leverage points were compared to mitigation strategies discussed by the IPCC. This comparison indicates that current climate change mitigation strategies do not alter most of the leverage points directly. This suggests that IPCC strategies should be broadened in order to reduce the risk of regime shifts, and the associated impacts on human well-being.

Key words: *regime shift, climate change, leverage point, mitigation strategies, ecosystem service*

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INTRODUCTION

Improved analysis of data, and more rigorous evaluation and comparisons among data from different sources have led to greater understanding of climate change in recent decades (IPCC 2007, Houghton et al. 2001). By the end of the 21st century, climate change impacts are expected to be the primary cause for biodiversity loss and changes in ecosystem services at a global scale (Millennium Ecosystem Assessment 2005, Thomas et al. 2004). The four most recognized impacts related to climate change are an increase in atmospheric temperature, precipitation, and extreme floods and droughts (Collier et al. 2002). These changes are likely to have substantial impacts on human well-being, through their impacts on ecosystem services. Ecosystem services can be defined as the benefits people obtain from ecosystems (Millennium Ecosystem Assessment 2005). These include *provisioning services* such as food, water, timber, and fiber; *regulating services* that affect climate, floods, disease, wastes, and water quality; *cultural services* that provide recreational, aesthetic, and spiritual benefits; and *supporting services* such as soil formation, photosynthesis, and nutrient cycling.

Research suggests that climate-induced changes in ecosystem services will not necessarily be gradual, but may be associated with abrupt, non-linear changes in social-ecological systems – or regime shifts (Mooney et al. 2009). For example, increased frequency in floods with flushing will increase P concentrations in water and alter provisioning services such as freshwater and fisheries in the clear water lake system, as it is likely to shift towards eutrophic lake regime. Scheffer (2009) defines regime shifts as "a relatively sharp change from one regime to a contrasting one, where a regime is a dynamic 'state' of a system with its characteristics stochastic fluctuations and/or cycles". Such abrupt changes are very difficult to manage in order to avoid the loss of ecosystem services. This is due to the complexity of identifying and manipulating the drivers of regime shifts at local, regional or global scales. This study identifies drivers as factors that externally alter the system by changing its dynamics through modifying the behaviour of feedback mechanisms (Dent et al. 2002). For instance, in the case of Arctic sea ice depletion greenhouse gases are the main external driver that affects the ice-albedo feedback mechanism.

A regime shift is usually preceded by a loss of resilience (Folke et al. 2004, Briske et al. 2008). Walker (2004) defines resilience as "the capacity of a system to absorb disturbance and re-organize while undergoing change so as to still retain essentially the same function, structure, identity and feedbacks". Resilience of a particular regime can be both desirable and undesirable depending on interests of stakeholder groups and the overall impact on human well being (Carpenter et al. 2001). In the case of a regime shift where ecosystem services are lost and decrease human well-being, the resilience of the new regime is undesirable and therefore tools are used for decreasing it and vice versa. This study focuses on building resilience of desirable regimes, and reducing the risk of undesirable climate-induced regime shifts.

Building resilience to climate-driven regime shifts is challenging as managers have limited options to directly reduce the drivers of climate change at local-regional scales. Nevertheless, it is possible for managers to intervene in other ways to reduce the risk of climate-induced regime shifts. One important way to build resilience to avoid undesirable climate-induced regime shifts is by understanding the mechanisms underlying regime shifts, their impacts on social-ecological systems, as well as their implications for human well-being. This can help managers anticipate regime shifts, avoid undesirable shifts, or facilitate beneficial shifts by better understanding the particular system dynamics and leverage points (Walker et al. 2006, Rocha 2010). Leverage points are key points or variables in the system where intervention can strengthen or weaken feedbacks. Two types of feedbacks can be distinguished in systems. Reinforcing feedbacks use their own momentum to drive a system increasingly in the direction it is already going, thereby amplifying growth or decline (Patterson et al. 2008). Balancing feedback loops are equilibrating mechanisms that maintain stability and act to resist change (Meadows 2008). Loss of resilience is typically associated with a weakening of the feedback mechanisms that maintain a particular regime, due to an external driver such as climate change. Identifying and manipulating leverage points in these feedbacks can help to counteract the effect of the driver, and build resilience even where the driver remains present.

The International Panel of Climate Change (IPCC) 4th report identified two main management strategies for systems altered by climate change: adaptation and mitigation. This study focuses on mitigation as the main strategy to build resilience to climate change, and analyzes the effects of the IPCC mitigation strategies on the drivers and leverage points of different regime shifts. The IPCC mitigation strategies mainly target reduction of CO_2 emissions in atmosphere (IPCC 2007, UNEP 2010). These strategies continue to evolve as the IPCC assesses the risks, feasibility, mitigation potential, costs and governance requirements of such controversial actions as geoengineering in its Fifth Assessment Report (Edenhofer 2010). However, such strategies will only gradually reduce the key drivers of climate change, and are often beyond the scope of local to regional scale managers. Many regime shifts may therefore be unavoidable in the near future even if the IPCC mitigation management strategies are implemented. Consequently it is necessary to identify alternative pathways and leverage points for reducing the risk of climate-induced regime shifts. By identifying and manipulating key leverage points resilience to undesirable regime shifts could be increased even if the drivers of climate change remain present.

This paper aims to synthesize the potential pathways for building resilience to climate change driven regime shifts by identifying leverage points that can strengthen the key feedback mechanism underlying desirable regimes. We then compare the leverage points to the mitigation strategies identified by the IPCC. The analyses presented in this paper are organized around four key research questions:

Q1: What aspects of climate change most affect the feedbacks that could trigger regime shifts?

Q2: What aspects of climate change most affect the direct drivers of regime shifts?

Q3: Which are the key feedbacks (leverage points) to bolster or weaken to reduce risks of regime shifts in a particular system?

Q4: What are the effects of mitigation strategies proposed by the IPCC on the risk of regime shifts?

METHODS

This study was conducted in three phases (Figure 1). Phase 1 consisted of data collection using the Regime Shift Database (RSDB) template. Five of the 10 regime shifts analyzed in this study were written up and published on the RSDB by the author of this study. The other five regime shifts had been previously written up and published by other students. The ten regime shifts were chosen as regime shifts specifically impacted by climate change.

Phase 2 involved the development of causal loop diagrams for each of the ten regime shifts, to identify the key feedback mechanisms and drivers of each regime shift. To analyze the effects of climate change, four key impacts related to climate change were introduced: i) increase of atmospheric temperature, ii) increased precipitation, iii) increased frequency of extreme floods and iv) increased frequency of extreme droughts. For each regime shift, the effects of these climate change impacts on drivers and feedback mechanisms were analyzed (see Appendix 1 to 10). These analyses were used to identify leverage points that could potentially build resilience to climate driven regime shifts.

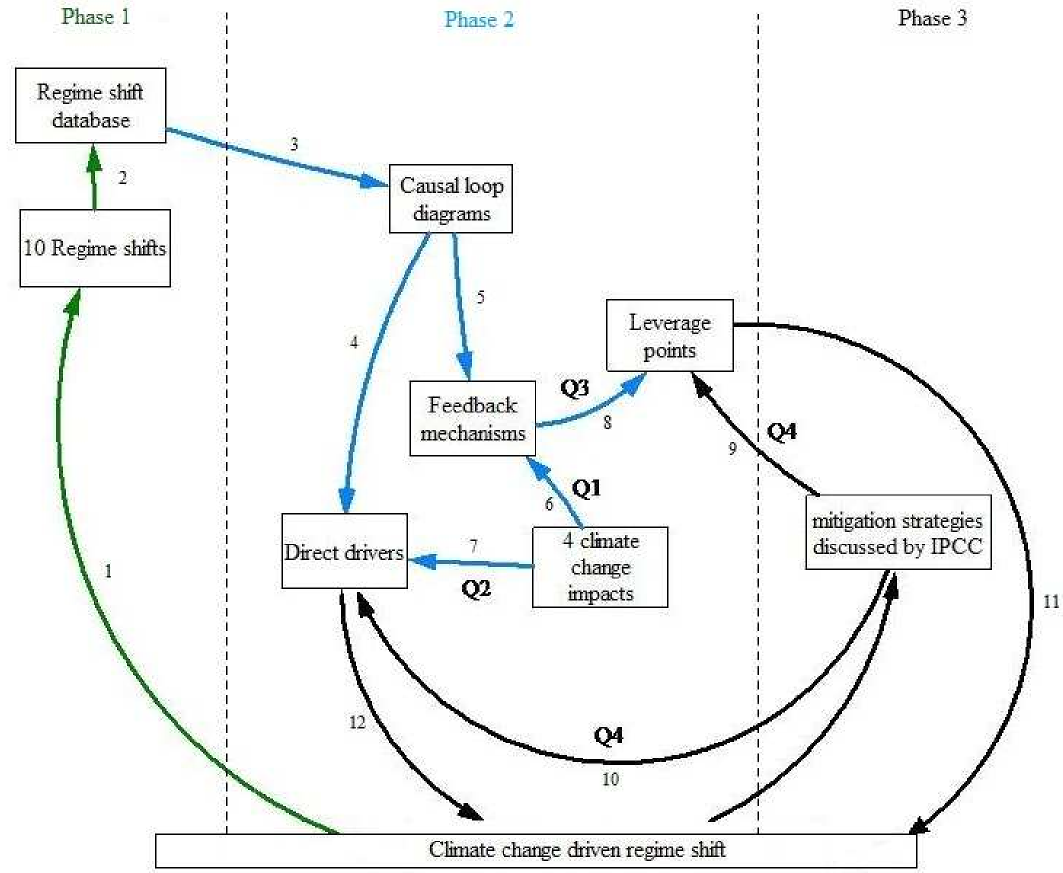

Figure 1. Conceptual model of this study. The numbers and arrows represent the order of the study process. Each colour for the links represent particular phase of the study.

The third phase of this study entailed the introduction of the IPCC mitigation strategies, and comparing them to the previously identified drivers and leverage points. The comparison enabled us to assess the effectiveness of current climate change mitigation strategies in averting regime shifts. These findings could confirm or oppose the necessity for alternative strategies for building resilience to climate change driven regime shifts.

Regime shift database

The data used in this analysis was taken from the RSDB. This Database includes a high quality synthesis of the literature of different types of regime shifts documented in social-ecological systems. Scientific databases such as Science Direct, ISI Web on Science and others were used to look for literature on different types of regime shifts. Each regime shift example includes the following types of data: i) causal loop diagram (CLD) and photographs illustrating both social and ecological dynamics of the regime shift; ii) definition of system boundaries and background of the regime shift; iii) description of the alternate regimes and feedback mechanisms that maintain each regime; iv) ecosystem services associated with each regime; v) external direct and indirect drivers that precipitate the regime shift; vi) management options to maintain a desirable regime or to restore a desirable regime.

This study includes data from 10 of the regime shift examples that are included in the RSDB. These ten regime shifts were chosen as they corresponded to the best documented and established cases in the literature linking to climate change. The ten regime shifts included in this study are given in Table 1.

Table 1. Regime Shifts analyzed in this study and description of their properties (RSDB 2011)

Regime shift name as used in figures	**Initial regime**	**Shifted regime**	**Key drivers**	**Ecosystem type**	**Key ecosystem service impacts**	**Evidence**	**Confidence**
Arctic sea ice	Arctic with summer sea ice	Arctic without summer sea ice	Green house gas emissions	Polar	*Provisioning services:* Wild animal and plant foods *Regulating services:* Climate regulation; Water regulation	Models Pale-observation Contemporary observations	Well established
Eutrophication	Clear water lakes	Eutrophic lakes	Fertilizers use	Fresh-water lakes & rivers	*Provisioning services:* Fisheries, Wild animal and plant foods, Freshwater *Regulating services:* Water purification, Pest & Disease regulation *Biodiversity*	Models Paleo-observation Contemporary observations Experiments	Well established
Hypoxia	Normoxia	Hypoxia	Fertilizers use, Erosion, sewage	Marine & coastal, Freshwater lakes & rivers	*Provisioning services:* Fisheries Wild animal and plant foods *Regulating services:* Water purification *Cultural services:* Recreation	Models Paleo-observation Contemporary observations	Well established
Greenland ice sheet	Greenland with permanent ice sheet	Greenland without permanent ice sheet	Greenhouse gas (CO_2) emissions	Marine & coastal, Polar	*Provisioning services:* Fisheries, Wild animal and plant foods *Regulating services* Climate regulation, Water regulation *Biodiversity*	Models Paleo-observation Contemporary observations	Well established
Monsoon	Monsoon with mean and regular precipitation	Monsoon with weak and irregular precipitation	CO_2 emissions	Moist savannas & woodlands, drylands and deserts	*Provisioning services:* Freshwater, Food Crops Livestock, Wild animal and plant foods, Timber, Other crops (eg cotton) *Regulating services:* Air quality regulation Climate regulation, Water regulation Regulation of soil erosion	Models Paleo-observation Contemporary observations	Contested

Thermohaline	Strong thermohaline circulation	Weak/ no thermohaline circulation	CO_2 emissions	Marine & coastal	*Provisioning services:* Food Crops, Livestock, Fisheries *Regulating services:* Climate regulation	Models Paleo-observation	Contested
Tundra-Boreal	Arctic tundra	Boreal forest	CO_2 emissions	Tundra	*Provisioning services:* Livestock, Wild animal and plant foods, Timber *Regulating services:* Climate regulation	Models Paleo-observation Contemporary observations Experiment	Well established
Coral bleaching	Coloured corals	Bleached corals	Sea surface temperature	Marine & coastal	*Provisioning services:* Fisheries, Wild animal and plant foods *Regulating services:* Water purification Regulation of soil erosion Natural hazard regulation	Models Paleo-observation Contemporary observations Experiment	Well established
Coral transitions	Coral dominated reefs	Algae dominated reefs	Sea surface temperature, Turbidity, Pollutants, Ocean accidification	Marine & coastal	*Provisioning services:* Fisheries, Wild animal and plant foods *Regulating services:* Water purification Regulation of soil erosion Pest & Disease regulation Natural hazard regulation	Models Paleo-observation Contemporary observations Experiment	Well established
Forest-Savanna	Forest	Savanna	Deforestation	Tropical Forests, Moist savannas & woodlands, Grassland	*Provisioning services:* Freshwater, Food Crops Livestock, Wild animal and plant foods, Timber, Woodfuel *Regulating services:* Climate regulation, Water regulation, Regulation of soil erosion Pest & Disease regulation Natural hazard regulation	Models Paleo-observation Contemporary observations	Contested

Construction of feedback mechanisms and causal loop diagrams (CLD)

To assess the "leverage points" in the system it was necessary to visualize the feedback mechanisms that exist in each system. To achieve this, CLD using Vensim PLE (Ventana Systems 2010) were developed to identify the links between the variables in the system and the climate change drivers. CLD is a technique to project the feedback structure of a system (Sterman 2000). CLD consist of variables connected by arrows denoting causal influence. Feedback loops, the basic structural units of the diagram, emerge by connecting these variables. CLD were constructed to represent the underlying mechanisms independently of the case specific context. Figure 2 gives an example of such CLD for Arctic sea ice depletion regime shift.

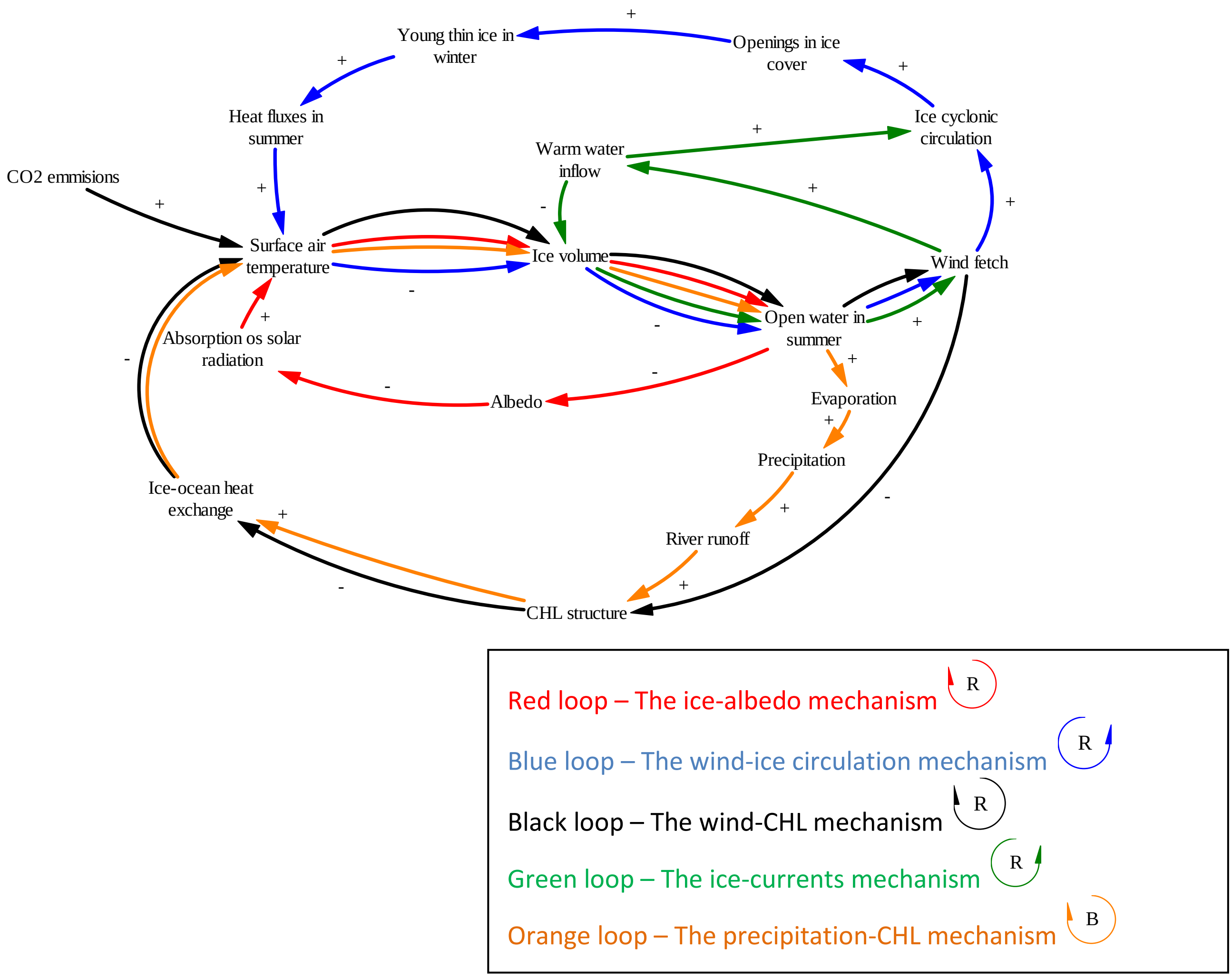

Figure 2. CLD for the Loss of Summer Arctic Sea Ice regime shift

In order to construct a CLD it is necessary to identify the key variables and feedback mechanisms that structure the system. This was done using the scientific literature. In the case of Arctic ice decrease such processes were identified as increasing atmospheric temperature, declining ice volume and increasing open water surface that were linked together to form part of one mechanism. The feedback loop is completed when a process is identified that links back to any of the previously identified variables. In the case of the Arctic sea ice example, it is the decrease in albedo and resulting increase in absorption of solar radiation that link back and add to the increasing atmospheric temperatures (see Figure 2).

To identify the feedback mechanisms and the level of detail for the system feedback mechanism representation, it is necessary to include all the variables at the chosen scale that are discussed in the literature as to having an effect on the particular system. The construction of a feedback mechanism begins with identifying key variables for each regime. This helps locate other variables that affect the main variable forming a feedback and looking if different key variables link through their feedback loops. This study did not include links between variables that are speculative.

Afterwards each mechanism is described in text to check if some of the variables do not overlap describing the same process and if the variable is linked to other variables in the system.

Recognizing the scale at which variables are identified is vital to focus on the main processes in the system. The borders of the system were determined by the number of feedback mechanisms that are directly linked with the main feedback mechanism. In the Arctic summer sea ice regime shift it was recognized that the processes are occurring on regional and global scale. Therefore in the mechanisms such variables were included that describe processes in these two scales – albedo decrease, openings in ice cover, ice cyclonic circulation, and ice-ocean heat exchange are some of the variables.

Random colours were used to illustrate the different feedback mechanisms. Each loop was named based on the main variables that described the feedback. In occasions when feedbacks at certain parts overlap and the main variables are already included in the name of other mechanism, then one of the main variables was included and the second was chosen from variables that could better describe the processes in the feedback.

Using these diagrams help to identify places in the system where climate change impacts affect the system. CLD’s are also essential to visualize the parts in system that should be altered to increase resilience of a particular system configuration. Nevertheless one should be aware that causal links do not describe the behaviour of variables, but only the structure of the system. This means that CLD’s describe what would happen if there were changes; therefore an increase in a cause does not necessarily represent an increase in a consequence. There are two reasons. First, a variable often has more than one input. The second and most important reason is that causal loop diagrams do not distinguish between stocks and flows (Sterman, 2000).

Approach used for the 4 core questions

The approach to address the first two questions involved the use of CLD to visualize the structure of the system. Each feedback mechanism for a particular system was studied in terms of its relation to any of the four identified impacts of climate change. For each driver and feedback mechanism that had been identified in a system, literature analysis was provided to identify the relation with climate change induced events (Appendix 1 to10). In this analysis scientific papers, assessments or books were used to find any suggested linkage between the drivers and the four events initiated by climate change. The feedback mechanisms or drivers that were recognized as being affected by climate change initiated events were summarized in tables (Appendix 11) using the six colours as grading criteria (Table 2).

Table 2. Grading criteria used for assessing the impact of climate change initiated events on feedback mechanisms or drivers in different systems.

Grading value	**Reasons to apply**
	if none of CC events *directly* or *indirectly* could be linked to having effect on any of the feedback mechanisms or drivers in a system
	if any of the four CC events *indirectly* alters a particular variable in a feedback mechanism or a driver that results in *increasing* risk of undesirable RS
	if any of the four CC events *directly* alters a particular variable in a feedback mechanism or a driver that results in increasing risk of undesirable RS
	if any of the four CC events *indirectly* alters a particular variable in a feedback mechanism or a driver that results in *decreasing* risk of undesirable RS
	if any of the four CC events *directly* alters a particular variable in a feedback mechanism or a driver that results in decreasing risk of undesirable RS
	Applied if the effect of CC event is still discussed for having positive (avoid undesirable regime shift) or negative (cause undesirable regime shift) impact on particular mechanism or driver

To address the third research question approach the CLD were used to identify the "leverage points" or parts in the system that are essential to build resilience of the desirable regime. Three criteria were used to identify leverage points. First, if a particular variable or parts of a mechanism when affected alter other parts of the same mechanism resulting in a decrease of resilience of the desirable regime. Second, if a particular variable or parts of mechanism when affected alter the main mechanism in a system. The influence it has on the main mechanism determines its importance and the vulnerability of the system. Third and most importantly, if there is a potential for a fundamental interaction to alter the variable or part of a mechanism to increase the resilience of the particular regime. If the identified variables or parts of mechanisms corresponded to these criteria, then they were considered to be a "leverage point".

For the fourth research question proposed actions from the IPCC assessment report Working Group III (IPCC, 2007) were introduced (Appendix 12). The expected outcome of these actions was summarized and compared to the leverage points. To evaluate the management options that are provided by this study and IPCC WG III the same grading scale as in the case of assessing the impact of climate change initiated events on feedback mechanisms was introduced, but applied under different conditions (Table 3).

Table 3. Grading criteria used for the IPCC suggested climate change mitigation strategies applied for managing climate change affected systems

Grading value	Reasons to apply
	- when the proposed strategy cannot be linked to any of the variables or feedback mechanisms presented in CLD. - if the effect of the strategy is unknown in order to increase or decrease the influence of certain variable or part of mechanism depending on the desirable system.
	- When the proposed strategy is *indirectly* linked to any of the variables or feedback mechanisms presented in CLD; - If the actions based on the proposed strategy is *indirectly* *decreasing* the resilience of a mechanism and leading to undesired regime shift in a particular system.
	- When the proposed strategy is *directly* linked to essential variables or feedback mechanisms presented in CLD; - When the strategy has essential effect on increasing or decreasing the influence of certain variable or part of mechanism depending on the desirable system; - when certain mitigation strategy or CC events has a *direct* impact on the main mechanism or key driver *decreasing* the resilience for the desirable system.
	- When the proposed strategy is *indirectly* linked to any of the variables or feedback mechanisms presented in CLD; - If the actions based on the proposed strategy is *indirectly* *increasing* the resilience of a mechanism and avoiding undesired regime shift in a particular system.
	- When the proposed strategy is *directly* linked to essential variables or feedback mechanisms presented in CLD; - When the strategy has essential effect on increasing or decreasing the influence of certain variable or part of mechanism depending on the desirable system; - when certain mitigation strategy or CC events has a *direct* impact on the main mechanism or key driver increasing the resilience for the desirable system.
	- Applied if the effect of the strategy is still discussed for having positive (avoid undesirable regime shift) or negative (cause undesirable regime shift) impact on particular mechanism or driver

The goal of the methodology was to render the essential parts of particular systems that are altered by Climate Change and assess the spatial scale and possible pathways where management strategies could be applied.

RESULTS

The findings of this study are presented in terms of each of the four research questions that guided the study.

Q1: What aspects of climate change most affect the feedbacks that could trigger regime shifts?

Temperature oscillations are affecting and decreasing resilience in 33 of 54 feedback mechanisms. Twelve of these occur in a direct manner. In comparison, precipitation increases the risk of a regime shift in 29 (directly 16 and indirectly 12) of the 54 feedback mechanisms. Floods and droughts have significantly less influence on feedback mechanisms by reducing their resilience and causing regime shifts. Only droughts cause direct risk of regime shifts (6 mechanisms of 55) as direct effect from flood occurrence has not been recognized. Indirectly floods increase the risk of regime shifts in 7 of the feedback mechanisms while in the case of droughts it is only 1 mechanism (see Appendix 11 Table A1).

The only direct or indirect increase in resilience associated with any of the four climate change impacts is linked with precipitation and droughts. Direct increase in resilience by droughts has been observed in 3 mechanisms that relate to the hypoxia regime shift. Indirectly this event increases resilience in 6 feedback mechanisms that are linked with thermohaline and eutrophication regime shifts. It was recognized that precipitation both directly and indirectly increases resilience to the desirable regime in 1 feedback mechanism (see Figure 3).

The most indirect decreases in resilience originate from temperature change (15 mechanisms affected).

When looking at the affected mechanisms where climate change impacts are decreasing the resilience it is altogether 40 occasions when mechanisms are directly altered by any one of the 4 events compared to the 35 occasions that they are altered indirectly. Therefore the direct effects on systems slightly dominate the decrease of its resilience. Only on 4 occasions are mechanisms directly altered by increasing their resilience and on 7 occasions indirectly.

The climate change initiated impact that affects feedback mechanisms the most is temperature change. Together temperature and precipitation oscillations results in 61 occasions when mechanisms are altered directly and indirectly therefore losing their resilience to the desirable regime. In the case of extreme droughts and floods this corresponds to 14 occasions.

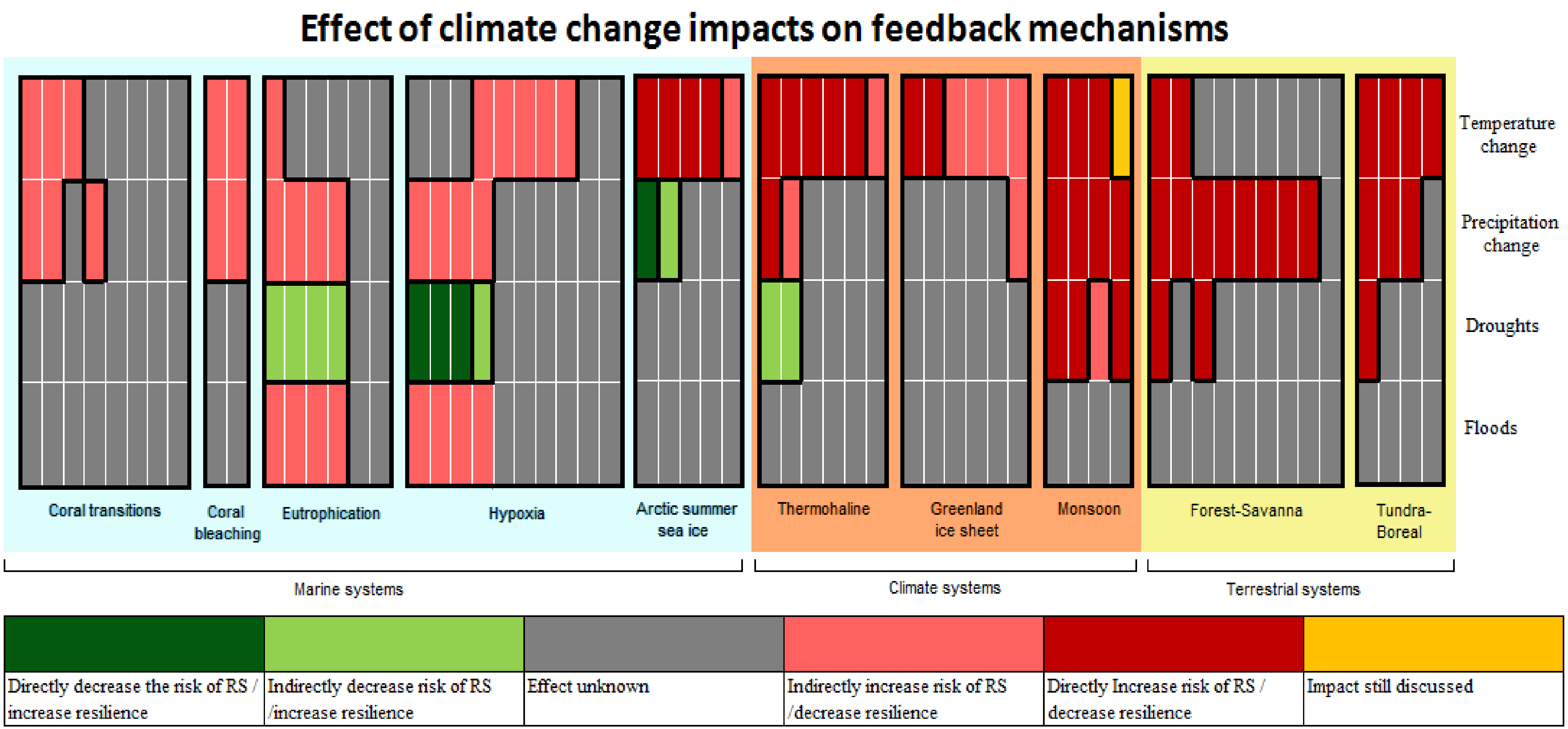

Figure 3. Effect of climate change impacts on feedback mechanisms arranged in clusters. Each cell represents a particular feedback mechanism affected by particular climate change impact. Number of rows represent the number of feedback mechanism in particular system. Each colour corresponds to particular effect to climate change impact.

Four different clusters of affected mechanisms can be identified. One is linked with mechanisms that are affected directly by different events resulting in increased risk of regime shifts. In this case there are only a few mechanisms that are also indirectly affected by increasing or decreasing the risk of regime shifts if they have already been affected directly.

A second cluster is mechanisms that are indirectly affected mostly by temperature resulting in increased risk of regime shifts. The unique pattern of this cluster is that these mechanisms have not been linked with direct effect by any of the four climate change impacts. There are only two occasions among these mechanisms where direct increase of resilience for the desirable regime has been recognized while influenced by the climate change impacts.

A third cluster of mechanisms are desirably or undesirably affected by precipitation, droughts and floods but not by temperature change.

The last is a small cluster of mechanisms that have not been affected by any of the four events.

Another four interesting patterns were identified while looking at these ten regime shifts when separating them into marine, climate and terrestrial systems (Figure 3). First, terrestrial regime shifts have been affected directly by precipitation more than the other impacts resulting in a decrease in resilience of the desirable regime. Second, marine systems are mostly affected indirectly and mostly by atmospheric temperature change. A third pattern that is worth noting is regarding droughts that have a positive effect on different marine system regimes, but a negative effect on terrestrial regimes. Fourth pattern – all feedback mechanisms of the three climate systems are directly or indirectly affected by atmospheric temperature oscillations thus increasing risk of regime shift.

Overall one can say from Figure 3 that the climate and terrestrial system regime shifts are at the greatest risk of occurring as most of their feedbacks mechanisms are directly affected by climate change impacts, thus increasing the risk or regime shifts. Tundra-Boreal regime shift mechanisms are the most vulnerable to climate change impacts and therefore are at greater risk of shifting. Climate system regime shifts can also be perceived as highly possible as most of their mechanisms are directly and indirectly affected by decreasing the resilience. Unlike terrestrial and climate systems, marine system regime shift feedbacks are mostly affected indirectly by the four climate change impacts.

After assessing all the regime shift examples one can see that climate change impacts in general have unknown effects on mechanisms in 129 of 216 occasions which is approximately 60% of all the occasions. The unknown effect for each climate change impact in percentage to the number of feedbacks was calculated and can be seen in Figure 4.

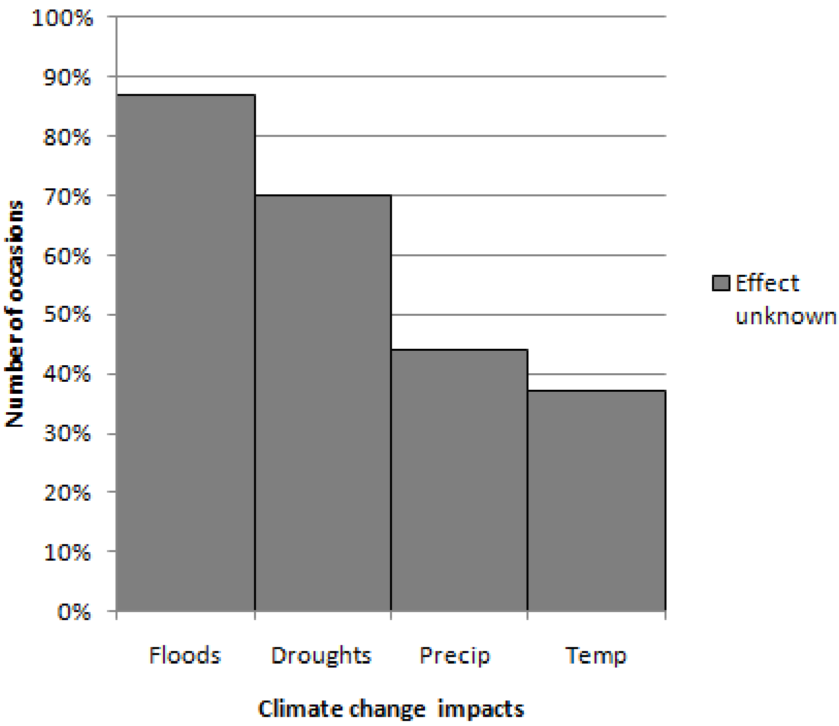

Figure 4. Percentage of unknown effect on feedbacks by climate change impacts

The unknown effect of droughts and floods relate to the majority of feedback mechanisms. This effect constitutes 87% of all the feedback mechanisms if linked with occurrence of floods, whereas for droughts this has been observed on 70% of the feedback mechanisms. Both oscillations in precipitation and temperature has unknown effect on less than half of the feedbacks – 44% and 37% respectively.

Q2: What aspects of climate change most affect the direct drivers of regime shifts?

Direct drivers of each regime shift were identified using the CLD. Then the effect of all four climate change impacts on these drivers was assessed to determine their vulnerability.

Floods and temperature change directly have the most negative effect on drivers therefore increasing the risk of regime shifts. Respectively this applies to 8 of the 22 drivers for floods and 6 of 22 drivers for temperature change that in percentage coincide to 37% in case for floods and 27% for temperature change (see Figure 5). When changing emphasis to overall negative effect (both direct and indirect increase risk of RS) on drivers the pattern changes as temperature in this case affects 68% of the drivers while for floods and droughts it is 41% (Figure 5). Therefore when looking at the overall pattern of negative effects on drivers it is the extreme events that have the least negative effect.

Overall the effect of climate change impacts on drivers is negative as the processes causing direct or indirect increase in RS almost equal (43 against 44 occasions) the positive or neutral impacts The effect of the climate change impacts on drivers by direct or indirectly increasing the risk of regime shifts is greater from the slow changes (temperature and precipitation) that affect drivers on 26 occasions while extreme event impact has been identified on 18 occasions (see Appendix 11 Table A2).

Droughts and floods together are directly increasing the risk of loss in resilience affecting drivers on 10 of 44 occasions. In the case of slow events in mean temperature and precipitation oscillations 11 occasions have been found.

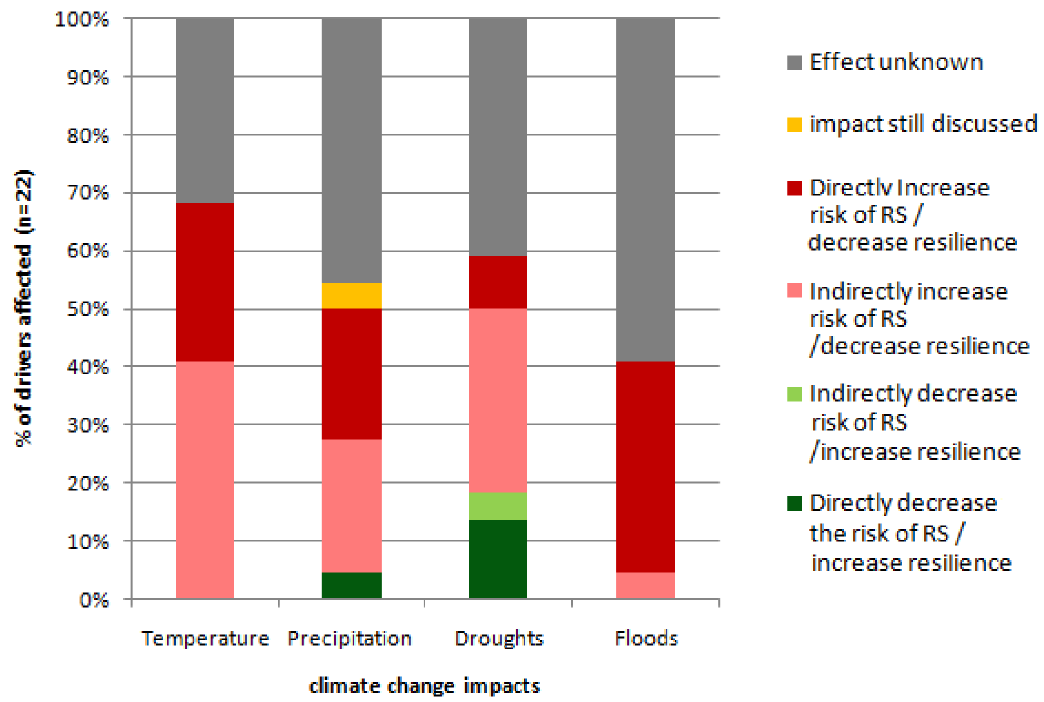

Figure 5. Effect of climate change impacts on direct drivers.

The drivers that are related to agriculture are the most affected by the climate change driven impacts. Majority of the effects by these events on the eight drivers (fertilizers use, erosion, flushing, deforestation, food production, sediments, water turbidity and sewage) are directly or indirectly increasing the risk of regime shift (see table 4).

Table 4. The drivers most affected by climate change impacts that initiate decrease in resilience for the desirable regime.

Driver	Occasions of direct effect from the 4 climate change impacts	Occasions of indirect effect from the 4 climate change impacts
Food production	3	0
Erosion	2	2
Fertilizers use	2	1
Sediments	2	1
Sewage	2	0
Flushing	1	3
Water turbidity	0	4
Deforestation	0	1

The two drivers identified not to be affected by climate change impacts were CO2 emissions and low tide frequency.

Only one indirect effect on drivers is identified that would decrease the risk of RS and maintain resilience of the desirable regime. Nevertheless there are 4 occasions where direct effect by precipitation and droughts on particular drivers result in increased resilience.

Given that the most affected drivers and mechanisms from the 10 RS have been identified this allows recognition of the most vulnerable system to the four climate change impacts. Figure 6 projects all ten RS that are included in this study by projecting the percentage of drivers and feedbacks affected by any of the climate change impacts.

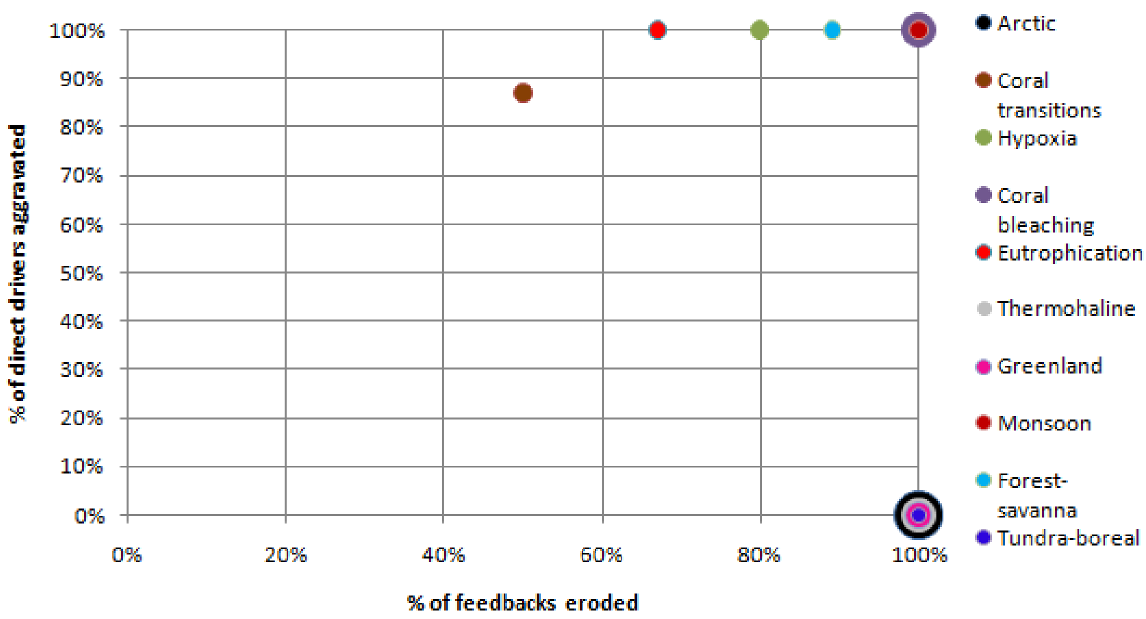

Figure 6. Regime shifts most vulnerable to climate change impacts.

The two most affected RS are Coral bleaching and Monsoon where all of the identified drivers and feedbacks are affected by climate change impacts. Altogether there are 6 RS including the two most affected RS that have all of their feedbacks affected by climate change impacts. However, the drivers for four of those RS – Arctic, Thermohaline, Greenland and Tundra-boreal maintain unaffected. The least affected RS among all of these is coral transitions although 87% of drivers and 50% of the feedbacks are affected (Figure 6).

Q3: Which are the key feedbacks (leverage points) to bolster or weaken to reduce risks of climate change induced regime shifts in a particular system?

Leverage points of each regime shift were identified using the CLD and the three criteria points described earlier. Then the effect of all four climate change impacts on these leverage points was assessed to determine their vulnerability.

Altogether 44 from the 54 recognized feedback mechanisms include at least one of the leverage points (see Appendix 11 Table A3). Overall there are 16 leverage points identified that are essential and realistically manageable in all the analyzed systems. Figure 7 shows the number of leverage points that were found in feedback mechanisms. Five feedback mechanisms were recognized among all the feedbacks that include the most key variables to manage. These mechanisms are the vegetation-surface albedo mechanism that includes five key variables, the dust-precipitation mechanism in the monsoon shift (4 variables), solar radiation-sea surface temperature in the monsoon shift, the dissolved oxygen-algae mechanism in the hypoxia shift, and phosphorus-DO mechanism in eutrophication that all include 3 key variables to manage.

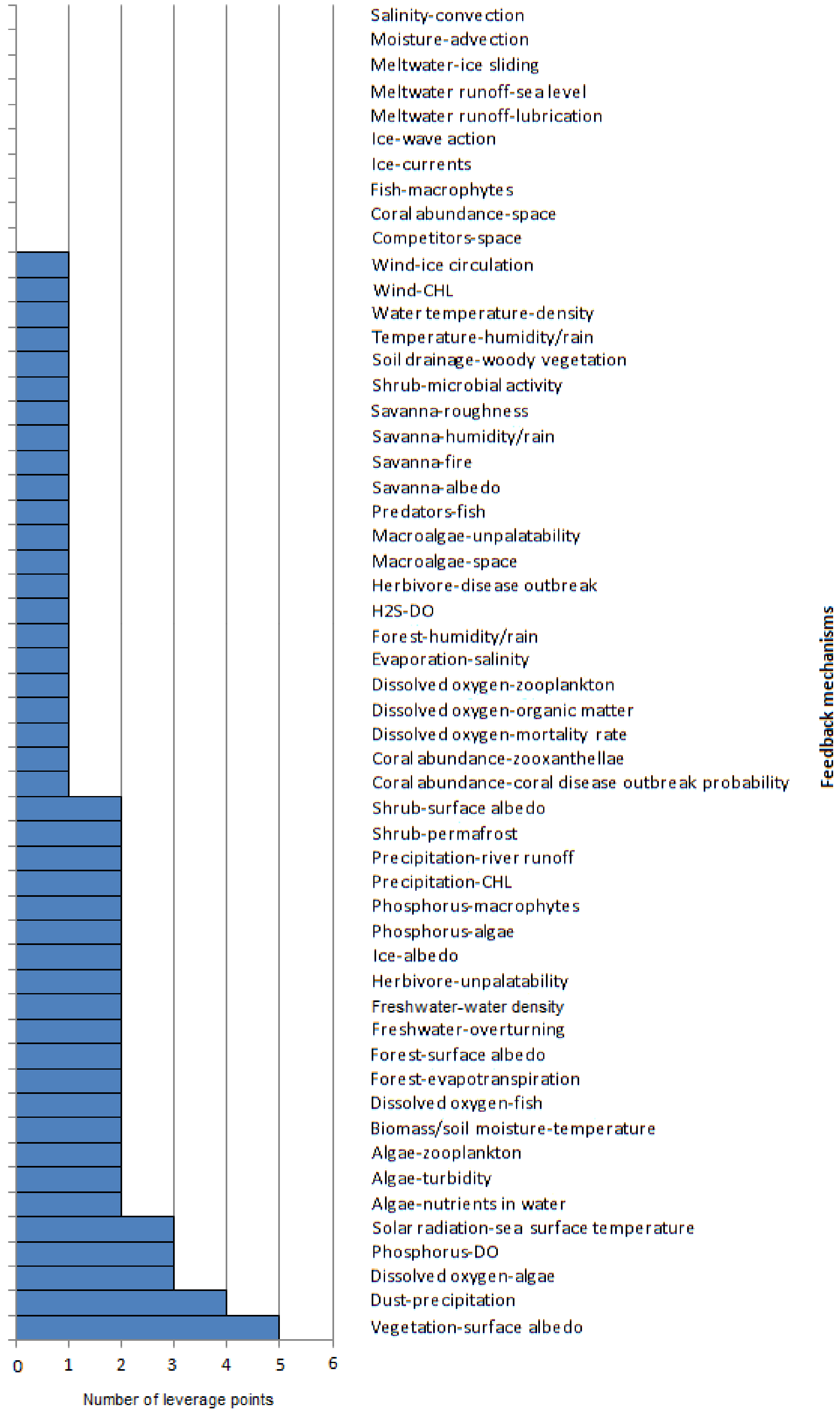

Figure 7. Leverage points in feedbacks. Number of leverage points identified in particular feedback mechanism amongst all ten regime shifts

The thermohaline, Arctic, Coral bleaching, Coral transitions regime shift feedback mechanisms include only two of the key variables that is the least among all other systems. The most key variables – five, can be found in Monsoon and Forest-savanna regime shift feedback mechanism. Hypoxia and Eutrophication regime shift feedback mechanisms both include 4 leverage points.

One can also look at the number of occasions where particular leverage points can be found amongst all the feedback mechanisms (Table 8). This could suggest the leverage points that potentially could affect the most systems in the case of their management.

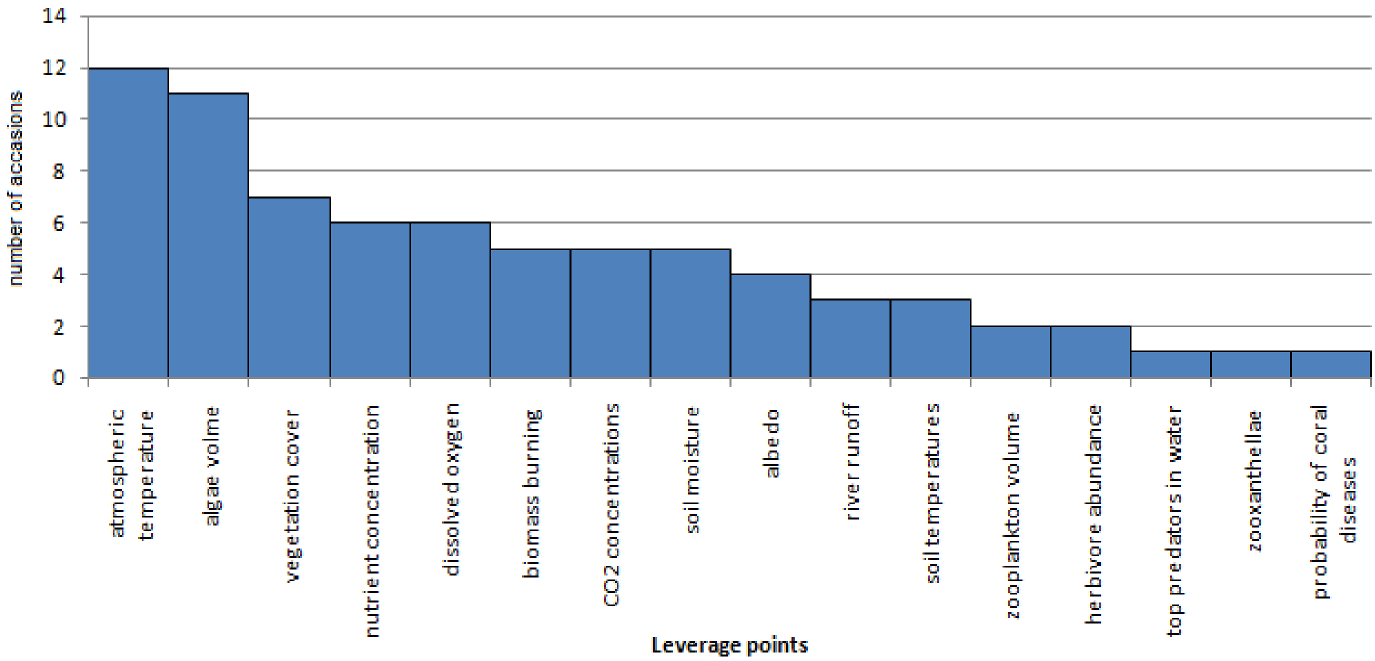

Figure 8. Number of occasions a particular leverage point is identified in feedback mechanisms amongst all ten regime shifts

Atmospheric temperature is the most common key variable that was found amongst 12 of the 54 feedback mechanisms in all systems. Algae volume is the second most identified key variable that is identified in 11 feedback mechanisms. Vegetation cover is also common as it can be found in 7 feedback mechanisms. Dissolved oxygen and nutrient concentrations were both identified in 6 mechanisms. Biomass burning, soil moisture and CO_2 concentrations were all recognized for being important in 5 of the 54 feedback mechanisms. Albedo was identified as essential variable in 4 mechanisms. Soil temperature variable as well as river runoff were both identified in 3 mechanisms. Zooplankton volume and herbivore abundance as core part of a particular system both were found in 2 mechanisms. The least included variables that are considered part of a "leverage point" are top predators in water, zooxanthellae and probability of coral diseases that all were found in 1 mechanism of a particular system.

Q4: What are the effects of mitigation strategies proposed by the IPCC on the risk of regime shifts?

Figure 9 outlines the effects of IPCC climate change mitigation strategies on direct drivers. The strategies concerning the reduction of CO_2 emissions are having the most positive effect on drivers compared to other strategies. In this case management strategies on 6 drivers will increase the resilience and help to avoid a regime shift. This strategy significantly affects the regime shifts in Arctic: Thermohaline, Arctic ice collapse, Greenland and Tundra-boreal regimes as their main driver is altered resulting in increased resilience of the desirable regime.

One should recognize that CO_2 mitigation strategy mostly affects different drivers than the other two strategies (see Figure 9). From the 8 drivers affected by increasing the resilience of the desirable system only 3 of them are also being affected by one of the other IPCC strategies.

Forest area strategy has both positive (4 drivers affected directly, 1 indirectly) and negative effect on building resilience as two of the drivers (fertilizers use and food production) could also indirectly decrease the resilience of the system. In general this strategy directly or indirectly increases resilience for the desirable regime by affecting its drivers in 7 of the 10 regime shifts.

Looking at cropland area strategy one can see two patterns. First, most of the drivers have not been affected or the effect is unknown. Second there are four systems that increase resilience to the initial desirable regime as the drivers are affected by this mechanism.

Seven drivers were also identified that are not influenced by any of the mitigation strategies suggested by IPCC.

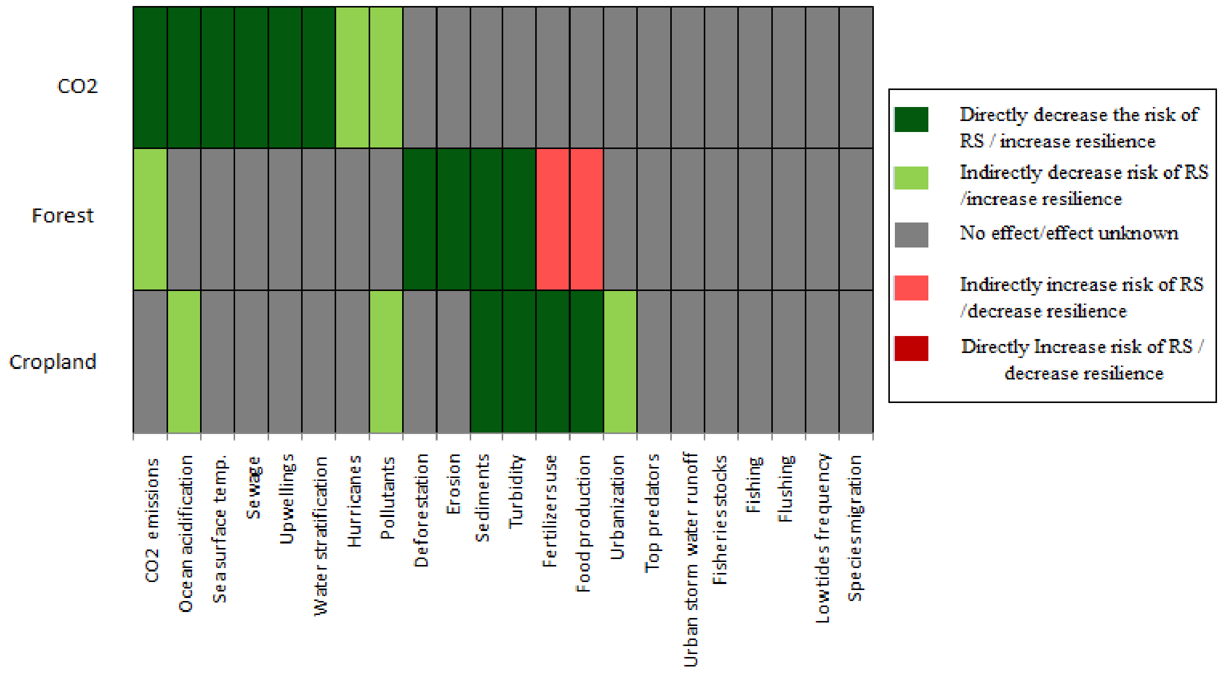

Figure 9. Effect of mitigation strategies discussed by IPCC on feedback mechanisms arranged in clusters. Each cell represents a particular driver affected by particular strategy. Each row represents all three mitigation strategy effects on particular direct driver. Each colour corresponds to particular effect to climate change impact.

Altogether by implementing the suggested mitigation strategies by IPCC it would directly affect 12 and indirectly 3 of the 22 identified drivers resulting in increased resilience to the desirable regime (see Appendix 11 Table A4).

Forest area management is the most influential of the strategies having various effects on 8 of the 16 leverage points. In order to present the potentially different outcomes of particular mitigation activity on a particular variable that can be found in different systems the location of the leverage point was specified in the case of albedo and atmospheric temperature thus multiplying that particular variable (see Appendix 11 Table A5). When applied forest area management strategy will indirectly increase the resilience affecting 5 leverage points. Applying this strategy can also indirectly increase risk of RS if used for managing 4 of the variables. Forest area strategy both increase and decrease risk of RS depending on the system where two of the leverage points are part of. Those two variables are albedo and atmospheric temperature.

Forest area management and cropland management have more positive effects on leverage points than the CO_2 management strategy. To illustrate this 11 occasions were identified where the forest area management and cropland management strategies directly or indirectly increased the resilience of the system while affecting these variables. In comparison only in 4 occasions is CO_2 strategy to be positively affecting these variables. There are only 3 occasions when any of the suggested strategies directly decrease risk of RS and all of them are linked with the monsoon system.

Given that the number of different effects on drivers and leverage points are identified, one can look in Figure 10 at the percentage of drivers and leverage points from the total amount among all RS affected by particular strategy.

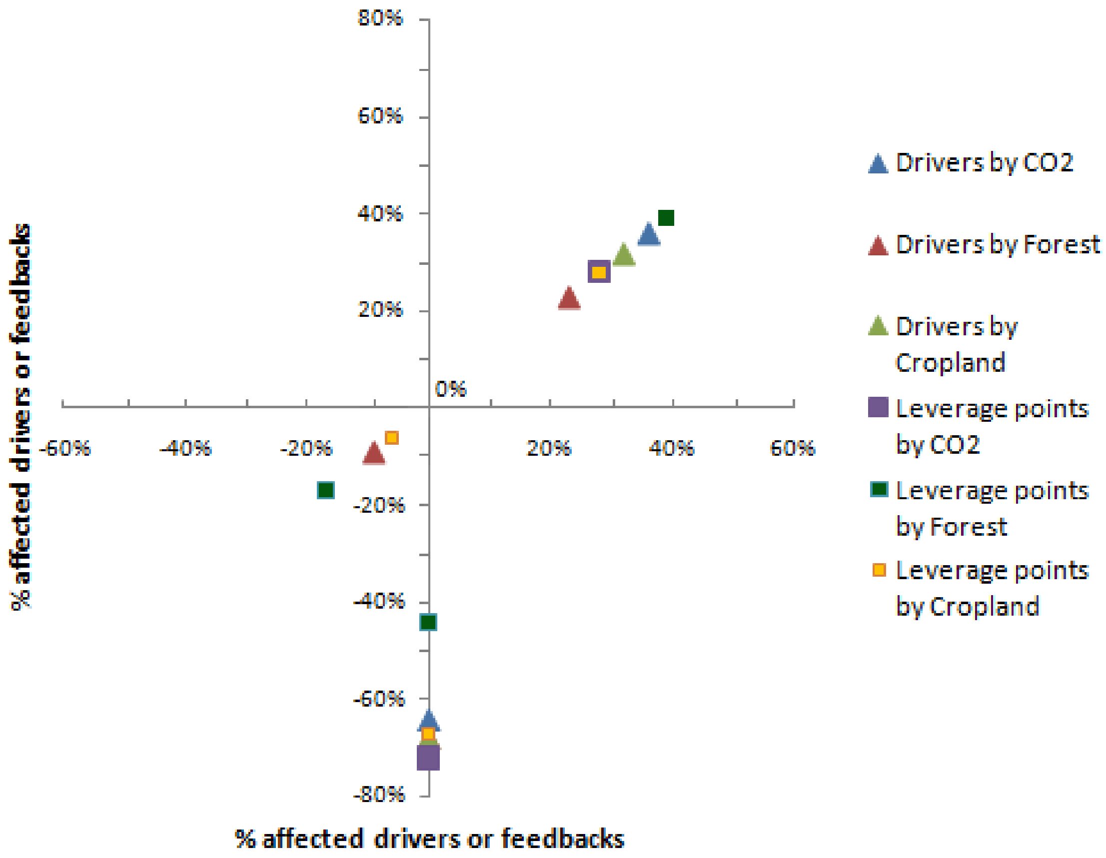

Figure 10. Percentages of direct drivers and leverage points of all ten RS affected by the strategies discussed through IPCC. The positive % values on both axes show the extent of positively affected drivers and leverage points. Values on the main vertical axis present the extent of unknown effect and the negative % values the negative effects on drivers and leverage points from the three IPCC discussed mitigation strategies.

From all the drivers the most influential is CO2 mitigation strategy that positively affects 36% of all the drivers by increasing the resilience of the desirable regime. The least effective is Forest area strategy that has only 23% of the drivers affected thus increasing resilience of the desirable regime. This strategy is the most effective among all other strategies when increasing the resilience of the desirable regime by affecting 39% of all the leverage points. Though, forest area strategy has also the most negative effect on resilience of the desirable regime by affecting 17% of all the leverage points.

Another way to see the effect of each strategy is by comparing their effects on direct drivers and leverage points for particular system to identify any win-win situations, trade-offs or overall uncertainties. For CO_2 mitigation strategy there are two effects identified if analyzing all of the RS. Figure 11 illustrates the percentage of drivers or leverage points affected by this particular mitigation strategy. The most common pattern is systems where CO_2 strategy has positive effect on drivers but unknown effect on leverage points. It the case for Arctic ice collapse (drivers 100% positive, leverage points 67% unknown), Thermohaline circulation (drivers 100% positive, leverage points 100% unknown) and Greenland ice sheet (drivers 100% positive, leverage points 50% unknown). Second pattern identified is when this strategy has unknown effect dominating both on drivers and leverage points in a particular system. For example eutrophication (drivers 100% unknown, leverage points 100% unknown), monsoon (drivers 100% unknown, leverage points 80% unknown) and forest-savanna drivers 100% unknown, leverage points 75% unknown) regimes.

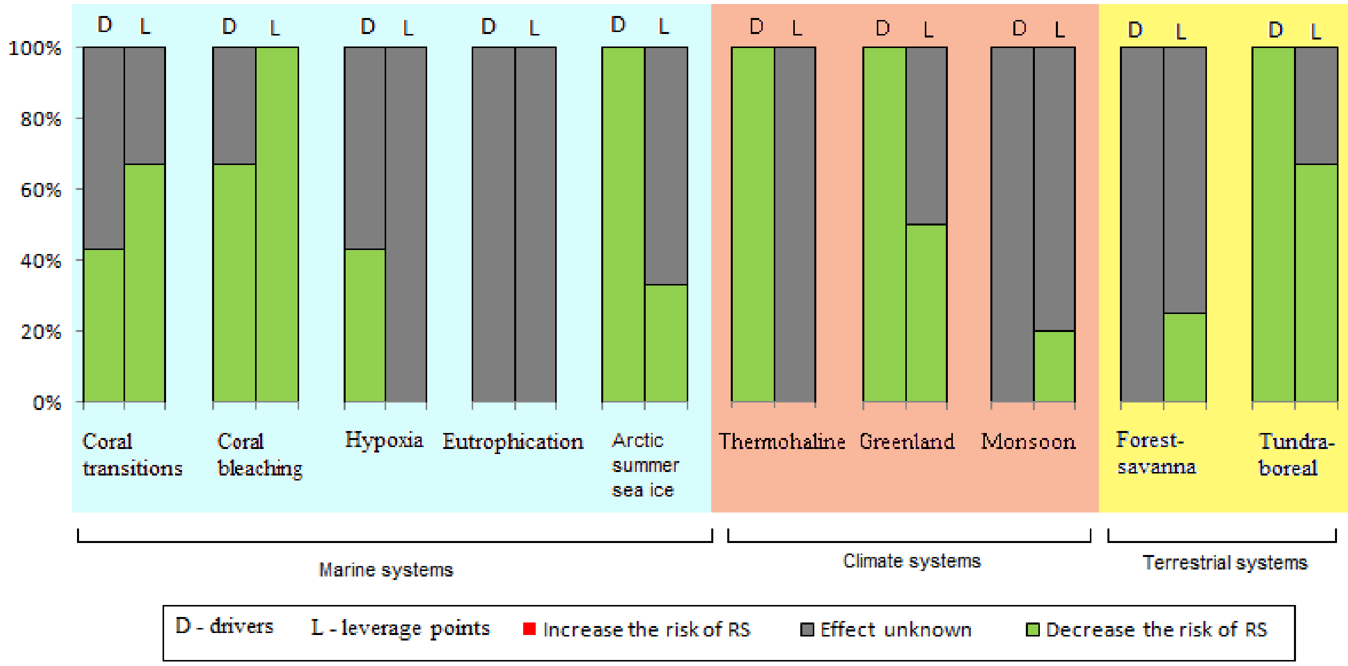

Figure 11. Percentage of drivers and leverage points affected by CO_2 mitigation strategy

For the Forest area mitigation strategy one can also identify two patterns of the differences between the effects on drivers and leverage points shown in Figure 12. The most notable is the trade-off between the positive effect of this strategy on drivers, but negative on leverage points for the same system. This trend can be found in Arctic ice depletion (drivers 100% positive, leverage points 100% negative), Greenland ice sheet collapse (drivers 100% positive, leverage points 100% negative) and Tundra-boreal (drivers 100% positive, leverage points 100% negative) regime shifts. The other pattern that is similar to the one seen for the CO_2 strategy is when this strategy has unknown effect dominating both on drivers and leverage points in a particular system. Coral transitions, coral bleaching, hypoxia and eutrophication are the RS where this pattern can be seen.

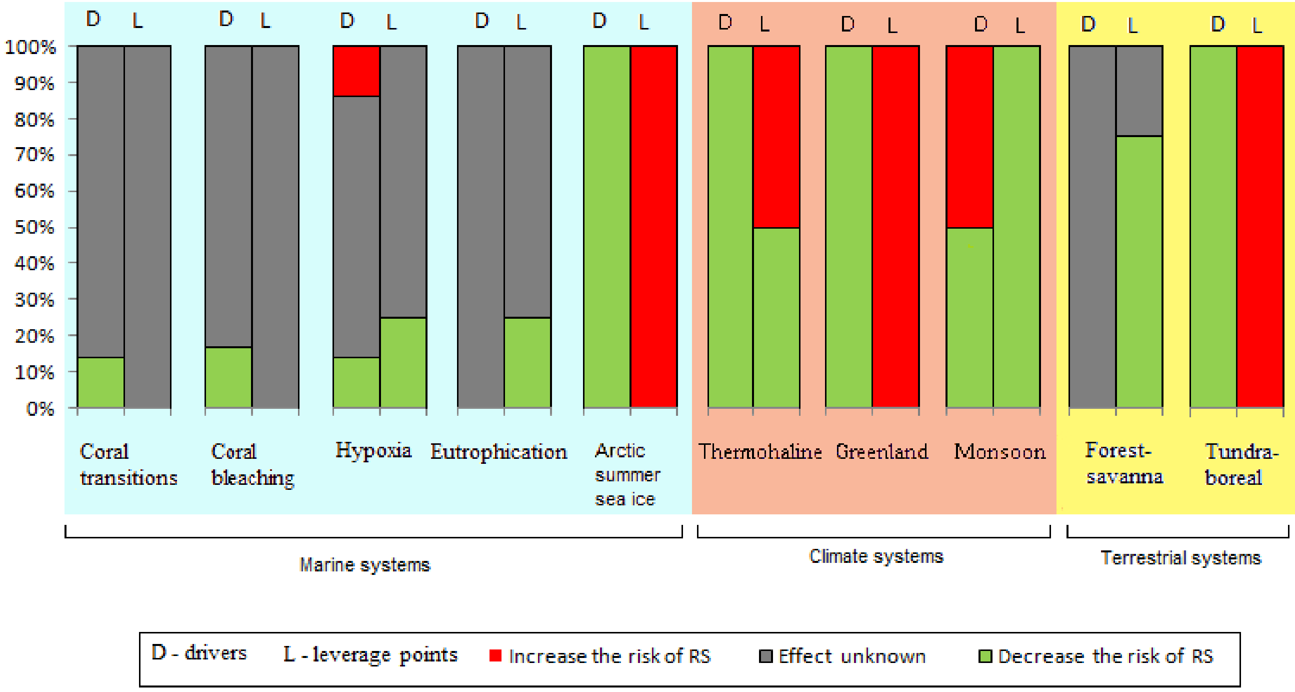

Figure 12. Percentage of drivers and leverage points affected by Forest area mitigation strategy

The only pattern that is dominant when looking at cropland area mitigation strategy effect between drivers and leverage points presented in Figure 13, is the unknown effect dominating both on drivers and leverage points in a particular system.

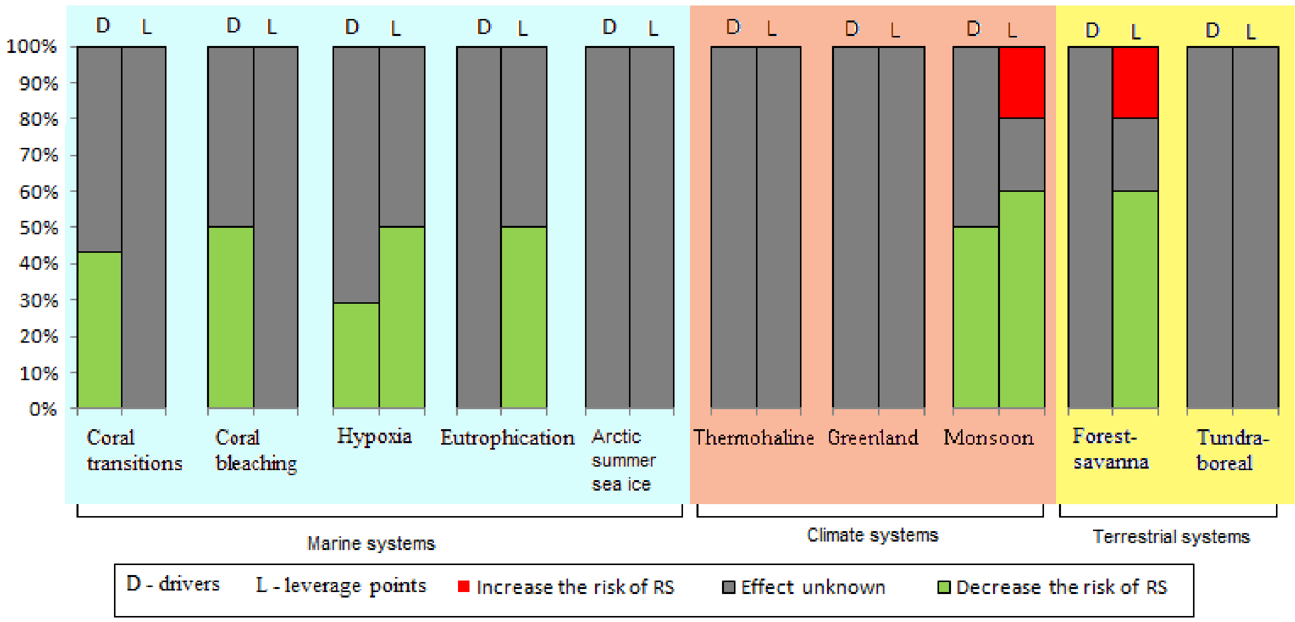

Figure 13. Percentage of drivers and leverage points affected by Cropland area mitigation strategy

This pattern can be found for Arctic ice depletion, Greenland ice sheet collapse, Thermohaline, Tundra-boreal RS (all have 100% unknown effect on the drivers and leverage points). Coral transitions, coral bleaching, eutrophication and hypoxia RS all are having unknown effect on majority of their drivers and leverage points.

DISCUSSION

In this section results will be discussed in the context of our 4 core questions.

Q1: What aspects of climate change most affect the feedbacks that could trigger regime shifts?

Temperature change alone affects more regime shifts than the other three events together. Most indirect decreases in resilience also originate from temperature change. Therefore extreme events are not very influential compared to slow changes such as temperature change. This finding agrees with most of the scientific studies performed that identify atmospheric temperature change as the key impact of climate change on systems that are essential to human well being. On the other hand, it can be that current aggregate estimates of climate change tend to ignore extreme weather events (Tol et al. 2004). Smith (2011) argues that there is a lack of knowledge on how ecological systems will respond to these extreme interactions and more research is needed. These potential factors are observed in our study were the number of unknown effects on mechanisms for extreme events are exceeding those for temperature and precipitation change (see Figure 2).

Similar patterns can be observed regarding the climate change impact on drivers (see Figure 3). Nevertheless extreme events are commonly perceived as the direct initial impacts on human well being from climate change (Haines et al. 2006, Dolinar et al. 2010). Furthermore recent studies recognize that global climate change is expected to increase both the frequency and the intensity of climate extremes therefore there is an urgent need to understand their ecological consequences (Smith 2011). Interestingly however these two extreme events have an insignificant impact on decreasing the resilience of desirable regimes in our study. In fact occurrence of droughts is the only event that significantly has positive impacts on some of the mechanisms and enhances the resilience of Hypoxia, Eutrophication and Thermohaline circulation regime shifts to climate change. Yet, these positive impacts for one system at the same time can be negative for others at the same location.

It was found that precipitation and increased droughts and floods indirectly affect systems that are linked with agriculture. In the case of temperature change it only affects some mechanisms that could be explained by the slow nature of temperature change compared to the rapid impact of the occurrence of precipitation, floods and droughts.

Climate change impacts and in particular temperature change directly decrease the resilience of the desirable regime in polar systems in most of the identified mechanisms. The latest IPCC climate projections also highlight the Polar regions as the most vulnerable to atmospheric warming (IPCC 2007).

The patterns that appear when separating all the regime shifts in marine, climate and terrestrial groups suggest the key areas of climate change impacts where mitigation strategies should emphasize on in particular type of system. Nevertheless it has to be considered that even for one regime shift the main negative climate change impact can vary between different cases. This is due to potential change in strength of particular climate change impacts on the specific case that can vary both on spatial and temporal scales.

According to the results these four events linked to climate change overall have negative impacts on human well being by directly and indirectly reducing resilience to most of the mechanisms that maintain the desirable regimes in different systems. However, studies may also have overlooked positive impacts of climate change (Tol et al. 2004) and not adequately accounted for how the other events could reduce climate change negative impacts. An example is the occurrence of droughts that was identified for having a positive effect on several feedback mechanisms thus reducing the risk of regime shifts such as hypoxia, eutrophication and weak thermohaline circulation.

Q2: What aspects of climate change most affect the direct drivers of regime shifts?

Results regarding the effect of climate change impacts on drivers as well as mechanisms clearly present the necessity to find these leverage points as they directly or indirectly increase the risk of regime shifts in most of the occasions.

Most of the affected drivers – food production, soil erosion, pollutants and flushing of nutrients that lead to increased risk of regime shift of the desirable regime are closely linked to agriculture. Studies suggest that agriculturally driven change can produce regime shifts in various systems, for example freshwater eutrophication and hypoxia (Carpenter 2005, Diaz and Rosenberg 2008). These results highlight the importance of improving agricultural management that could reduce the impact of climate change on systems where these drivers are present.

It appears that the majority of the drivers directly and indirectly affected by climate change resulting in increased risk of regime shifts are linked with marine systems. This would suggest that drivers for marine systems are more vulnerable to climate change compared to those of terrestrial systems. Nevertheless it might be that drivers in marine systems are better explored and their quantity is greater compared to the terrestrial drivers.

Interestingly the two extreme climate change events have more negative impact on drivers by directly and indirectly increasing the risk of a regime shift compared to feedback mechanisms. This observation might also be a consequence due to the many regime shifts related to agriculture systems where occurrence of floods and droughts can be seen as indirect drivers for the regime shift thus affecting the direct drivers.

Identifying areas that are most vulnerable to climate change driven regime shifts is essential for the managers in order to limit their influence. In this study one can look at the areas that are most vulnerable to climate change impacts. This could be achieved by analyzing the effect of these impacts on drivers and feedbacks for the particular system. Managers should be aware that for a majority of the regime shifts, feedbacks are most vulnerable to climate change impacts thus having a greater likelihood for potential shift. The most vulnerable systems (Figure 6) acknowledge the vulnerability of all the three types of systems. One can see, that the two most vulnerable systems are Monsoon circulation (climate) and Coral bleaching (marine). The next most vulnerable system is forest-savanna (terrestrial) system. All these systems are regional or global therefore it would affect large territories in the case of the potential regime shifts. The IPCC projections for this century emphasize on the vulnerabity of systems that are linked to Polar regions – thermohaline circulation, Greenland ice sheet, Tundra regions and Arctic summer sea ice depletion (IPCC 2007). While looking at these 10 regime shifts in this study it can be suggested that the majority of initial impacts would occur in Arctic regions and tropical areas as most of the regime shifts are likely to occur there.

Managers should also consider connectivity between regime shifts when looking at the locations where these large scale regime shifts would be more likely. For example, the Arctic sea ice collapse regime shift is linked with the thermohaline circulation regime shift that could lead to changes in monsoon circulation therefore linking these two regions. While looking at areas that should be most concerned with the occurrence of several climate driven regime shifts it is difficult to identify only one particular region or system. For different managers coming from different regions the perspective of their own systems change could be considered the most vulnerable and important. However, even if one region is not considered highly vulnerable to climate change driven regime shift it can rapidly change in the future if global regime shifts are not managed, as these regime shifts will have a global effect on human well being.

Q3: Which are the key feedbacks (leverage points) to bolster or weaken to reduce risks of regime shifts in a particular system?

Interestingly most of the leverage points identified can be linked with agriculture. This contrasts with studies carried out by climatologists that emphasize the importance of temperature change as the most important variable to ecosystem change (Thompson 2010). The importance of managing variables linked to agriculture to build resilience to regime shifts, has been suggested by Gordon et al. (2008) emphasizing the effect of these processes on global regime shifts. Nevertheless this study also highlights the importance of atmospheric temperature as being one of the most common leverage points among the feedback mechanisms in different systems. However, the existence of other leverage points has to be recognized. Some of the leverage points such as algae volume, vegetation cover and dissolved oxygen in water are also very common in different systems thus showing different pathway to mitigate climate change impacts on the risk of regime shifts.

It is worth noting that leverage points in marine systems can be found more frequently than in climate or terrestrial systems. For managers this could suggest that marine systems could be easier to approach in order to reduce the risk of regime shifts. Nonetheless in this study the strength of the variables or mechanisms and certainty of some of the links between these variables and mechanisms has not been considered. Therefore it is difficult to affirm that altering marine systems that include key variables more frequently would increase the probability of desirable results than in terrestrial systems.

It was unexpectedly identified that the majority of the recognized feedback mechanisms include at least one leverage point. Initially this seems to be encouraging if system managers identify ways in how to manage these 16 variables to decrease the risk of regime shifts. Nevertheless the behaviour of a system cannot be known just by knowing the elements of which the system is made (Meadows 2008). To give an example of the different nature of one leverage point in different systems one can look at surface albedo that is identified among various systems. This variable in Arctic summer ice loss regime needs to be bolstered to enhance resilience of the desirable regime, but in monsoon system weakened.

Q4: What are the effects of mitigation strategies proposed by the IPCC on the risk of regime shifts?

Mitigation strategies assessed by IPCC were explored by analyzing their effect on direct drivers and feedback mechanisms.

Comparing the effect of these strategies on drivers and leverage points in regime shifts it is clear that they are evenly distributed. The low percentage of the positive effect of strategies on drivers and leverage points (between 23 and 39%) suggests that there is no universal strategy that could decrease the risk of regime shifts. Another important pattern that is essential when looking at the effect of these strategies is the large percentage of unknown effects that these strategies have on drivers and leverage points. Therefore it is evident that more research is necessary to monitor the possible effect of these strategies on particular systems. This uncertainty also presents a necessity to apply different strategies apart from CO_2 reduction on climate change driven regime shifts. Nonetheless the same IPCC suggested strategies are targeting very diverse types of systems with the aim of avoiding the decrease in human well being from climate change. This approach could potentially lead to increased risk of regime shifts as in the example of albedo. Our current understanding of building resilience to climate change events does not provide us with a “blueprint” that can be applied to all the systems. For that reason each of the mechanisms, even those including the same leverage point, cannot be managed with the same method. Thus leverage point management analyzing each systems feedbacks could be a way to improve already existing attempts to avoid these regime shifts that affect human well being in regional or global scale.

It is worth looking at the effects of each strategy on drivers and leverage points to see the potential win-win situations, trade-offs or major uncertainties when managing these two variables in a particular system. Table 5 summarizes the results of these three essential patterns.

Table 5. Occasions of mitigation strategy effects on direct drivers and leverage points in three patterns for particular system

Mitigation strategies	Win-Win	Trade-off	Uncertainty
CO_2	2	0	3
Forest area	0	3	3
Cropland area	1	0	5
	3	3	11

The first important trend is the few occasions when any of the three strategies effecting drivers and leverage points of a particular system results in a win-win situation. The most occasions that a strategy has a win-win effect on drivers and leverage points is linked to CO_2 mitigation. In this case this strategy affects two of the ten RS by both affecting all drivers and leverage points that result in increased resilience of the desirable regime. The lack of win-win situations should be concerning for managers that could suggest the necessity of introducing additional strategies how to build resilience for the desirable regime.

Interestingly the only strategy that is linked with trade-offs when applied to managing climate change driven systems is Forest area where it has been observed on 3 occasions. This pattern demands that managers be aware of the consequences when applying this strategy. Peterson (2009) also highlights the difficulties to manage tradeoffs due to the social and ecological complexities involved, and managing them will be made even more difficult in a changing climate. One should recognize that the same management strategy applied for managing the same variable can increase resilience in one system but decrease it in other. For example albedo in arctic by applying forest area management will increase the risk for RS as the dark surface of trees will lower the albedo. In the case for albedo in tropical areas the same management strategy will decrease the risk of RS as vegetation cover will ensure the temperature difference between land and ocean maintaining monsoon system.

Uncertainty of the effect of all three strategies on both drivers and leverage points in a particular system are more common. CO_2 and Forest area mitigation strategies both have unknown effects on the majority of drivers and leverage points in three of the ten regime shifts. The fact that this pattern is almost twice as common as the win-win and trade-off patterns could highlight the lack of knowledge or ignorance of the effects that these strategies have on particular systems.

Importantly the unexpected high number of leverage points and feedback mechanisms that include at least one of them is encouraging as it leaves space for manipulation to maintain the desirable regime or alter the one that is undesirable. As seen in the analysis the strategies discussed by IPCC could be useful in certain systems that are affected by these climate change impacts, but they cannot be perceived as the only solution. It is necessary to learn about these leverage points in particular systems and see if different approaches could be useful. Locating key variables that can be found in regional or local scales should not be ignored as these variables can also be useful to maintain resilience of the desirable regimes.

Contributions and Limitations of the approach

This study reveals new insights on alternative pathways of building resilience to climate change driven regime shifts that have not been addressed by the mainstream climate change research. The results of this study while using the approach of causal loop diagrams and the data from Regime shift database could benefit the managers dealing with climate change driven systems. One of the benefits of using CLD is the opportunity for managers to see the linkages between different systems and feedbacks. Understanding the internal system structure and locating leverage points with the help of CLD for particular RS could improve the managers understanding of the appropriate management options.

The potential future improvement of this study relates to developing more rigid criteria for identifying leverage points. It is also necessary to develop a database for feedback mechanisms to avoid overlapping when including the same feedback mechanism under different name.

Lack of data and research or speculative suggestions on particular links between variables in regime shifts could have affected the construction of CLD and identification of leverage points in this research. This links to the uncertainty of the systems boundaries and potential hidden feedback loops in CLD. It could be that these feedbacks might not be significant, but they could affect the system's behaviour in long term.

Other important factors such as the strength of the feedback mechanisms and variables were left out as it was assumed that all links are proportional. Including this could improve the understanding if the leverage points are strong enough to cause change in particular mechanisms if altered by the suggested mitigation strategies. Therefore these two factors are important to consider in future studies to improve the identification of leverage points. For these two factors to be introduced a quantitative study could be applied. It would be interesting to combine the currently used approach with a more quantitative one, where variables would be given values thus giving new insights on identifying leverage points. This could help and acknowledge the necessary effort to alter these feedbacks and show if the identified leverage points are effective to alter and the actual outcome result in desired increase in building resilience of the desirable regime.

Although the identification of leverage points in systems has been discussed and some advice is provided (Meadows 2008), this is the first time when CLD are being used to analyze the climate change driven systems to identify these key points.

CONCLUSIONS

The purpose of this study was to synthesize the potential pathways for building resilience to climate change driven Regime Shifts. To achieve that four key questions were identified: a) what aspects of climate change most affect the feedbacks that could trigger regime shifts? b) what aspects of climate change most affect the direct drivers of regime shifts? c) which are the key feedbacks (leverage points) to bolster or weaken to reduce risks of regime shifts in a particular system? d) what are the effects of mitigation strategies proposed by the IPCC on the risk of regime shifts?

The use of CLD to identify the effect of climate change impacts on systems and locate the leverage points gave us some new insights of where to intervene in the systems to avoid regime shifts and build resilience. The overall effect of the four impacts related to climate change and particularly the increase in atmospheric temperatures has directly and indirectly reduced resilience to most of the mechanisms thus increasing the risk of undesirable regime shifts.

Agriculture seem to be important system to intervene as most affected drivers – food production, soil erosion and flushing are all linked to agriculture and also most of the leverage points identified can be linked with it. The results show that most of the feedback mechanisms amongst all 10 regime shifts include at least one leverage point which is encouraging for managers as it leaves more room for manipulation. This has not been considered by the IPCC as its attention is focused on the strategies of reducing CO_2 emissions.

This study shows that the current climate change mitigation strategies do not alter most of the leverage points directly. There is a concerning number of occasions when the current strategies effect on drivers and leverage points is unknown. This is concerning for managers as research has to be extended or more attention has to be devoted on the unknown processes that could affect regime shifts. Considering the specific characteristics of particular systems including key local and regional variables (leverage points) in those climate change mitigation strategies could help to achieve the aim of human well being and avoid undesirable regime shifts.

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