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ORIGINAL ARTICLE

A transdisciplinary typology of change identifies new categories of adaptations and forms of co-adaptation in coupled human and natural systems

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Abstract

Adaptation in human and natural systems has received growing attention in sustainability scholarship. Co-adaptation, when coupled human and natural systems (CHANSs) adapt in congruence, is receiving much less attention. Not only are various forms of co-adaptation difficult to disentangle, adaptations are also conceptualized very differently by scholars of human and natural systems. One aspect of adaptation that scholars agree on, however, is that it is first and foremost a change. We offer a new transdisciplinary typology of the four most basic types of change, internally and externally driven non-structural and structural changes, that bridges perspectives in the natural and social sciences and through which we introduce new categories of adaptations and forms of co-adaptation in CHANSs. We first describe the typology's foundations and its four types of change. We then organize forms of adaptation in human and natural systems according to the types of change they exhibit to identify new categories of adaptations and forms of co-adaptation. Finally, we illustrate the application of the new categories and forms in a real-world CHANS—the privately managed Northwoods in the Upper Midwest, USA. This new typology paves the way for robust and cross-disciplinary research on CHANSs.

Keywords Adaptation · Change · Co-adaptation · Coupled human and natural system · Social–ecological system · Typology

Introduction

The destabilizing influence of global climate change is challenging the sustainability of many of Earth's biotic and abiotic systems (Ellis et al. 2013; Steffen et al. 2018). Efforts to help human and natural systems adapt, that is, change in a way that improves their suitability to the current or some anticipated environment (Matthews 2018), are at the forefront of sustainability scholarship (IPBES 2019; Martens et al. 2016; Smit et al. 2001). A major challenge, however, is understanding the process of co-adaptation, when coupled human and natural systems (CHANSs) adapt in congruence. Not only are various forms of co-adaptation difficult to disentangle, but scholars of human and natural systems also tend to conceptualize adaptation very differently. Moreover, recognition of co-adaptation in natural and social sciences is uneven.

Natural scientists usually study adaptation from the perspective of its underlying biological processes (acclimation, acclimatization, mutation, and selection) (e.g., Dobzhansky 1956; Gittleman 2019; Somero 2010; Thomashow 1999). Co-adaptation is typically studied in relation to selection (e.g., Angilletta Jr. et al. 2006; Butterfield et al. 2020; Dobzhansky and Pavlovsky 1958; Prakash and Lewontin 1968; Wallace 1953). Social scientists, on the other hand, tend to study adaptation from the perspective of its timing (proactive vs. reactive), scale (autonomous vs. planned), and scope (incremental vs. transformational) (e.g., McCarthy et al. 2001; Smit et al. 1999, 2000). Co-adaptation is rarely studied in the social sciences. Such disciplinary differences in perspectives and focus often pose a challenge for the study of adaptation and co-adaptation in CHANSs, which is inherently cross-disciplinary (MacLeod 2018). However, both natural and social scientists view adaptation as first

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and foremost a *change* (e.g., Gittleman 2019; Hine 2019a, b; Matthews 2018; McCarthy et al. 2001; Smit et al. 2000, 2001),[1] which, in line with Ashby (1956) and Klir (2001a), may be broadly defined as a transition of any component of a system to either a previously existing or an entirely novel state.

Here, we introduce a new transdisciplinary typology of change that contributes to a new "meta-language" (UNESCO 1998, p. 21) for describing types of change within and between CHANSs. As such, the typology helps bridge perspectives related to change in the natural and social sciences and offers potential opportunities for "[s]timulating synergies … [and] integrating knowledge" (UNESCO 1998, p. III) across the relevant disciplines and non-academic actors. The typology provides new terminology for clearly differentiating among types of change in a CHANS, supporting a more rigorous study of the similarities and differences among both changes and CHANSs, and advancing the study of change beyond whether or not change has occurred and toward how it has occurred.

In this manuscript, we apply the typology toward identifying new categories of adaptations and forms of co-adaptation in CHANSs. This expands the possible analysis of their respective similarities and differences, creating new opportunities for research. However, the usefulness of the typology extends beyond these applications. For example, its new terminology is also useful in clarifying concepts such as adaptive capacity (which we do in "A transdisciplinary typology of the four most basic types of change"), and, in turn, other concepts that incorporate it (e.g., resilience, vulnerability [Gallopín 2006]). Such clarifications have the potential to increase productivity in cross-disciplinary collaborations.

We first describe the typology's foundations and the four types of changes that comprise it. We then organize the various forms of adaptation in human and natural systems according to the types of changes they exhibit to identify new categories of adaptations and forms of co-adaptation. Finally, we illustrate an application of the new categories and forms in a real-world CHANS—the privately managed Northwoods in the Upper Midwest, USA.

[1] The term "adjustment" is also used instead of "change" in defining adaptation (e.g., Matthews 2018; Smit et al. 2001), which is a *change* that improves suitability.

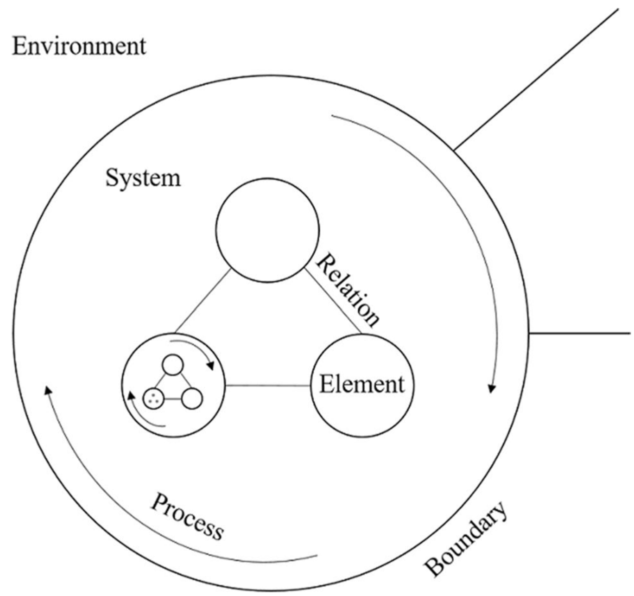

Fig. 1 A conceptual representation of a system, its structure (elements, relations, and processes), and the boundary between the system and its environment. Each of its elements can be further analyzed as a system with its own structure and boundary

A transdisciplinary typology of the four most basic types of change

We present the transdisciplinary typology of change constructed from the relationship between change and two of the most basic characteristics of any system, its structure and boundary. We take a systems perspective (Klir 2001b) because of its transdisciplinary nature (Hirsch Hadorn et al. 2008), i.e., it provides "a meta-language, in which the terms of all the participant disciplines are, or can be, expressed" (UNESCO 1998, 21). From a systems perspective, the structure of a system is composed of elements, relations among elements, and the processes that both arise from the relations among elements and transition them through space and time. A systems perspective also highlights the importance of boundaries, which are scale dependent (Fig. 1). This multilevel perspective facilitates the study of any system and its interaction with other systems at similar, higher, and lower scales. Any element of a system may also be analyzed as a system itself, composed of its own elements, relations, and processes, while being embedded within (and interacting with) other higher level elements, as well as possibly other systems. The boundary of a system emerges from the structural conditions that separate its (internal) components from its (external) environment. Its environment is composed of all the external drivers of its change and any external conditions that came about due to changes within the system. These system-based definitions of structure and boundary are compatible with definitions of structure in the natural

Table 1 A typology of the four most basic types of change

	Internally driven	Externally driven
Non-structural	Any variation within the range permitted by system structure, due to regular internal functioning	Any variation within the range permitted by system structure, as a reaction to the environment
Structural	Any modification of system structure, due to regular internal functioning or as a proactive effort to adjust to environmental change	Any modification of system structure by the environment

(e.g., McElhinny et al. 2005; Nadkarni et al. 2008; Thom et al. 2020) and social (e.g., Bunge 1974; Kappeler 2019; Martin and Lee 2015) sciences, which are often focused on the measurable characteristics of relevant elements, relations, and processes.

Based on the aforementioned characteristics of systems, change in a human or natural system may be either structural or non-structural, and internally or externally driven. Structural change is any change that occurs in a system when there is any addition to or subtraction from its elements, relations, or processes. In adaptive systems, such as CHANSs (Holling 2001; Levin 1998, 2010), structural change may occur either through external forces acting on the system or through second- and possibly higher order processes, called meta-processes (Klir 2001a) that exist specifically to alter structure. In contrast, non-structural change in a system occurs within the range that the structure permits. For example, a natural system, such as a forest, may be defined as being composed of trees (elements), their spatially determined competing and facilitating relations, and their biological processes. One example of structural change, from this perspective, would be the addition or subtraction of trees. A change in the average age of a forest, therefore, would be structural if the cause is the addition or subtraction of trees and non-structural if the cause is the aging of trees. This should not suggest that structural change could not have occurred at some other level. For example, aging would be considered a structural change when the tree itself is taken as a system with its cells as the elements. With a human system, such as a forest manager, structure may be composed of interconnected subsystems of cognitive and behavioral elements, such as management practices, personal goals, and personal values, the relations among them (e.g., neural links), and the mental processes that apply and transform them. The addition of a previously unknown management practice to a multi-step forest management strategy (e.g., adding prescribed fire to an existing fuel reduction strategy) would therefore be structural, whereas switching from one practice to another known practice as part of the same management strategy would be non-structural.

Change in a human or natural system may also be driven from within or beyond its boundary. Change driven from within the system may be either part of its regular functioning or proactive, as in an effort by a system to adjust to either its current or some anticipated environment. On the other hand, change driven from beyond the system is either reactive to or imposed by the environment of the system. For example, change in the composition of a forest is internally driven if it is predominantly due to (regular) competition among its native species. It is externally driven if it is predominantly imposed by a new invasive species. Similarly, in the case of a forest manager, switching practices in pursuit of a personal goal is an example of an internally driven change, while switching them as a reaction to the environment is an example of an externally driven change. Scholars in both the natural (e.g., Williams et al. 2011) and social (e.g., Ryan and Deci 2000) sciences have found that the (internal or external) origin of the primary drivers of a change in a system has a significant influence over how the system undergoes that change. Failure to consider the differences imparted by the origin of a change challenges the understanding of CHANSs (Walker et al. 2012).

By organizing change according to these two dimensions, the structure of a system and its boundary, the typology identifies four fundamental types of change: (a) internally driven non-structural, (b) externally driven non-structural, (c) internally driven structural, and (d) externally driven structural (Table 1). The main difference between internally and externally driven non-structural change is that the former occurs as part of regular system functioning, while the latter occurs in reaction to a system's environment. Change in the average age of trees in a forest due to aging (as opposed to harvest or mortality from disturbance) is an example of an internally driven non-structural change (Table 2). A forest manager changing between known practices as a reaction to the current environment, on the other hand, is an example of an externally driven non-structural change (Table 3). How a system undergoes externally driven non-structural change depends on its current state, as well as the change that its environment is undergoing [e.g., linear, abrupt and persistent, abrupt but temporary (Ratajczak et al. 2018)]. A change in the environment of a system that drives its non-structural change may also, at least temporarily, limit the range within which the system's future non-structural change may occur (Scheffer and Carpenter 2003). Both human and natural systems have shown great capacity for non-structural change; however, the specific ranges

Table 2 Definitions, descriptions and examples of the four types of change in relation to forest ecosystem dynamics

Type of change	Definition	Description	Example
Internally driven non-structural	Any variation within the range permitted by system structure, due to regular internal functioning	A change in a forest site that is part of regular functioning and does not involve the addition or subtraction of trees, relations, or processes	Change in the average tree age, primarily due to the aging of trees Change in the level of shade (angular canopy density), primarily due to the growth of trees Change in the soil–water balance, primarily due to the dynamics in the moisture regime
Externally driven non-structural	Any variation within the range permitted by system structure, as a reaction to the environment	A change in a forest property that is in response to external drivers and that does not involve the addition or subtraction of trees	Change in productivity, primarily due to a change in precipitation Change in soil quality, primarily due to a change in precipitation Change in the rate of decomposition, primarily due to a change in precipitation
Internally driven structural	Any modification of system structure, due to regular internal functioning	A change in a forest property that is part of regular functioning and involves the addition or subtraction of trees	Change in community composition, primarily due to a change in the relative rates of species mortality Change in composition, primarily due to a change in the relative rates of species establishment Change in the average tree age, primarily due to succession
Externally driven structural	Any modification of system structure by the environment	An external factor changes a forest property by adding or removing certain trees	Fire changes composition by burning more fire-intolerant than -tolerant trees Severe wind event changes the average tree age by uprooting trees Planting or harvesting changes composition or average tree age by adding or removing trees

Table 3 Definitions, descriptions and examples of the four types of change in relation to forest management

Type of change	Definition	Description	Examples
Internally driven non-structural	Any variation within the range permitted by system structure, due to regular internal functioning	A forest manager switches between familiar practices under what they perceive as normal forest and other conditions	Switches from one practice to the next as part of a regular fuel treatment procedure Switches from one practice to the next as part of a regular monitoring procedure Switches from one practice to the next as part of a regular harvesting procedure
Externally driven non-structural	Any variation within the range permitted by system structure, as a reaction to the environment	A forest manager reacts to a change in forest or other conditions by switching to an alternative familiar practice	In response to changes in growing season length, adjusts the timing of fuel management practices In response to what is perceived as a normal fire regime, switches from fuels management to post-fire regeneration management practices In response to what is perceived as a normal fire, temporarily reprioritizes familiar practices
Internally driven structural	Any modification of system structure, due to regular internal functioning or as a proactive effort to adjust to environmental change	A forest manager initiates a change in the quality and/or quantity of their practices	In the process of experimenting with practices, develops a new one In the process of developing a forest management plan, alters the effectiveness of a familiar practice In the passing of years, changes values and correspondingly goals and practices
Externally driven structural	Any modification of system structure by the environment	A forest or some external factor changes the required practices	Change in forest or some external factor changes the effectiveness of a practice Change in forest or some external factor changes the cost of a practice Change in forest or some external factor changes the manager's ability to implement a practice

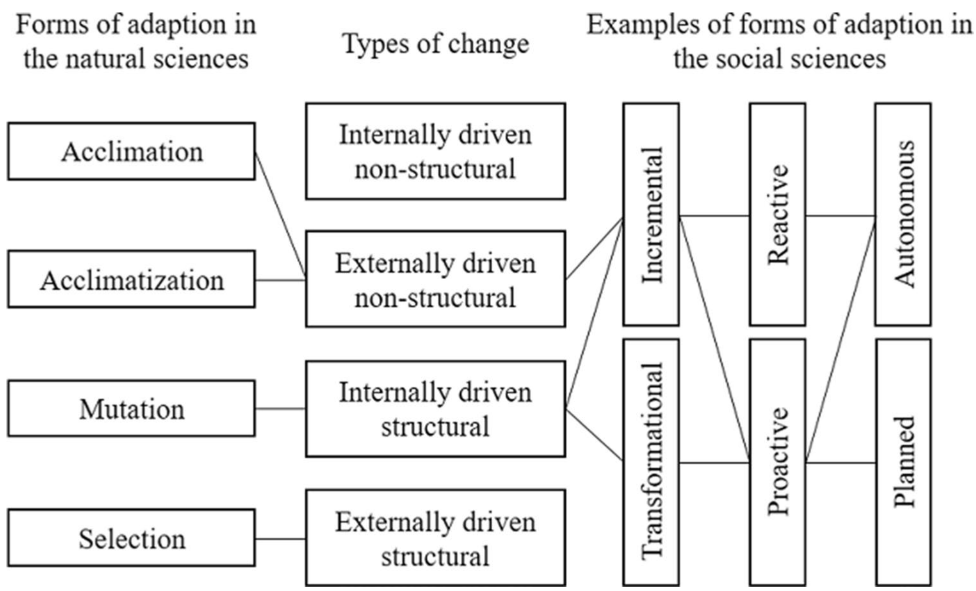

Fig. 2 Forms of adaptation in the natural and social sciences organized by their type of change

of variation for most human and natural systems remain unknown.

A system may also undergo either internally driven structural change that is caused by regular functioning or as a proactive effort to adjust to current or anticipated environmental change, or externally driven structural change that is imposed by its environment. Changes in the composition of a forest because of competition among species or the appearance of a new genotype are examples of internally driven structural changes that are produced through regular functioning (Pickett 1976) (Table 3). Change in forest management practices because of experimentation or innovation is another example of internally driven structural changes, resulting from a proactive effort by managers to adjust to the current or anticipated environment (Table 3). Similarly, a forest management practice becoming obsolete because of changes in forest conditions (e.g., logging on snow-covered ground becoming infeasible because of a warming climate) is an example of an externally driven structural change (Table 3).

Notably, structural change has the potential ability to directly shape future structural change. Because the structure of a system forms the bounds within which the system undergoes non-structural change, a structural change may also potentially permanently alter the range within which future non-structural change might occur. For example, a forest management practice becoming obsolete because of changes in the forest reduces the number and, possibly, the variety of practices available to a forest manager (Table 3). Because these changes alter the structure of the system, they also have a greater potential of persisting than their non-structural counterparts.

These four types of changes may affect one another within any given system. For example, forest-level structural changes, such as from forest disturbances, like fire or insect infestation, may speed up tree mortality and, in turn, forest regeneration, an internally driven non-structural change. Forest regeneration may, in turn, lead to a higher frequency of mutation, an internally driven structural change (Park et al. 2014), which may influence the frequency and/or magnitude of the disturbances. Each of these four types of change may also affect changes in other systems. CHANSs are nested n-level hierarchies of human and natural systems (Gunderson and Holling 2002; Holling 2001) and, thereby, change in one system may directly or indirectly affect change in another system at the same or a different level as part of the other system's externally driven change.

The next two sections apply the typology in the identifying of new categories of adaptations and forms of co-adaptation. However, as mentioned in the introduction, the typology is also useful in clarifying relevant concepts, such as adaptive capacity. Sustainability scholarship broadly defines adaptive capacity as the ability of a system to adapt (e.g., Matthews 2018). From the perspective of change, it may be further interpreted as the extent to which the range of variability in a system (non-structural change) (Ashby 1956, 1958) and the ability of a system to modify this range (an internally driven structural change) permit it to sufficiently match or modify the selection pressures of its current and/or anticipated environment (an externally driven structural change).

Table 4 New categories of adaptations in human and natural systems

Types of change	Categories of adaptations	Ability to change the range within which future adaptation might occur	Forms of adaptation in natural systems	Forms of adaptation in human systems
Externally driven non-structural	Non-structural	No	Acclimation Acclimatization	Autonomous (non-structural) Incremental (non-structural) Reactive
Internally driven structural	Structural	Yes	Mutation	Autonomous (structural) Incremental (structural) Planned Proactive Transformational
Externally driven structural			Selection	NA

New categories of adaptations in human and natural systems

Adaptations in human and natural systems may be differentiated by the basic types of change they represent (Fig. 2). Scholars studying natural systems commonly recognize the following four forms of adaptation:

- Acclimation—a reversible change in an individual organism's physiology or behavior in response to a single change (e.g., temperature) in its environment (Park and Allaby 2017a);
- Acclimatization—a reversible change in an individual organism's physiology, which may in turn affect behavior, in response to multiple changes (e.g., temperature, access to food) in its environment (Allaby 2014a);
- Mutation—an irreversible and spontaneous change in the genetic material of an individual organism, cell, or virus (King et al. 2013; Pagel 2002a);
- Natural selection—an irreversible change in a population of organisms in response to one or more changes in its environment (Allaby 2014b; Hine 2019b; Pagel 2002b; Park and Allaby 2017b).

Acclimation and acclimatization are externally driven non-structural changes because they are driven by either an existing mismatch with, or a change in the environment of, a system and they occur within the range permitted by the structure of a natural system. Mutation is an internally driven structural change because it occurs as part of a regular internal process and modifies the structure of a natural system. In contrast, selection is an externally driven structural change because it is imposed by an external force that modifies system structure. These forms of adaptation occur at many levels of natural systems and vary primarily by the different processes involved in producing the change. Internally driven non-structural change does not have a corresponding form of adaptation in the natural sciences because it captures expected changes that occur with regular functioning. Nevertheless, recognizing this type of change in the typology is critical because it establishes the norm from which changes deviate.

These four forms of adaptation in natural systems can be further categorized based on their ability to change the range within which future adaptation of a natural system might occur (Table 4). Mutation and selection are both structural changes in a system and thereby have the ability to permanently alter this range ("A transdisciplinary typology of the four most basic types of change"). Acclimation and acclimatization are both non-structural and therefore do not.

Scholars studying human systems recognize an even more diverse set of adaptations. They include the following:

- Proactive and reactive (Burton et al. 2006; Fankhauser et al. 1999; Fischer 2019; McCarthy et al. 2001; Smit et al. 2000), which differ based on whether the adaptation occurs before or after a disturbance (in cases of an externally driven structural change);
- Autonomous and planned (Fankhauser et al. 1999; Fischer 2019; Füssel 2007; McCarthy et al. 2001; Rahman and Hickey 2019; Smit et al. 2000), which differ based on the level of mental effort required to implement the adaptation and the duration of implementation;
- Incremental and transformational (Fedele et al. 2019; Fischer 2019; Moore et al. 2014; Pelling et al. 2015; Westley et al. 2011, 2013), which reflect the impact level of an adaption on the system;
- Others (e.g., private and public, purposeful and spontaneous, localized and widespread), one of which is "structural," referring specifically to adjustments in technology (Burton 1996; McCarthy et al. 2001).

These too may be associated with the most basic types of change (Fig. 2). As with natural systems, adaptation in human systems may occur at many levels, such as the individual, household, community, and institution. However, in contrast to the forms of adaptation in the natural sciences, forms in the social sciences often contain other forms.

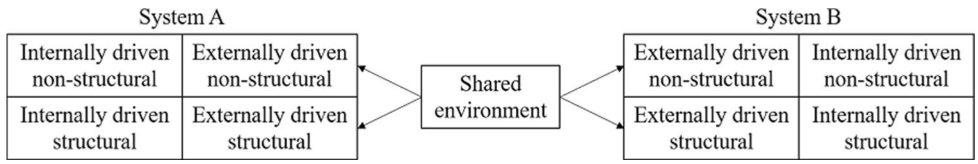

Fig. 3 The imposed form of co-adaptation without interaction. The shared environment drives externally driven adaptation in both of the coupled systems (Systems A and B)

Proactive adaptations are goal-driven (Braver 2012), making them internally driven changes, capable of producing a structural change in decision-making and resulting behavior. Reactive adaptations are disturbance-driven (Braver 2012), making them externally driven changes within the bounds of the existing system structure. However, autonomous adaptations, which are those implemented by individuals, may be reactive or proactive, depending on what is driving them. On the other hand, planned adaptations, which also include those implemented by institutions, are necessarily proactive, as they involve intentional mental activities. Most forms of adaptation in human systems are incremental. The proactive and planned forms, however, may also be transformational (e.g., Walker et al. 2004). As in the natural sciences, the social sciences do not perceive an internally driven non-structural change as an adaptation. Moreover, externally driven structural change, which is associated in the natural sciences with selection, is likewise not perceived as an adaptation in the social sciences due to its association with the discredited theory of Social Darwinism (Leonard 2009).

Forms of adaptation in human systems can also be further categorized based on their ability to change the range within which future adaptation of a human system might occur (Table 4). Planned, proactive, transformational, and variants of other forms of adaptation in the social sciences (e.g., autonomous, incremental) that are structural changes have the ability to permanently alter this range ("A transdisciplinary typology of the four most basic types of change"). Reactive and variants of other forms of adaptation (e.g., autonomous, incremental) that are non-structural do not.

Based on the above categorization of forms of adaptation in human and natural systems, only externally driven non-structural and internally and externally driven structural changes in natural systems have the potential to be adaptations, whereas only externally driven non-structural and internally driven structural changes do in human systems. Also, only mutation and selection have the potential to change the range within which future adaptation in a natural system might occur, and only planned, proactive, transformational, and variants of other forms of adaptation (e.g., autonomous, incremental) that are structural have this potential in a human system (Table 4).

New forms of co-adaptation in human and natural systems

The typology of change is also helpful in differentiating three new forms of co-adaptation that we introduce here: imposed, indirect, and direct. We consider coupled systems *co-adapting when changes in them are covaried adaptations*. In other words, co-adaptation among coupled systems occurs when their changes together improve their suitability within a shared environment.

The imposed form of co-adaptation occurs outside of the coupled systems' interaction, with the co-adaptation driven by their shared environment, i.e., by a shared set of selection pressures. As a result, both of the co-adapting systems (say, System A and B) undergo externally driven and covaried adaptation (Fig. 3). This implies that acclimation, acclimatization, and selection are the only forms of adaptation in natural systems that can be part of this form of co-adaptation. In human systems, only reactive adaptations, and those autonomous and planned adaptations that are non-structural can be imposed co-adaptations. Coupled systems co-adapting through this form have no influence over their shared environment and, in turn, no influence over the type of change the other system undergoes. For example, global climate change (as part of the shared environment) prompts both a forest manager to restart a known practice to improve their personal well-being and their forest to undergo change that improves forest health. To date, this form of co-adaptation has been the one most commonly studied (e.g., Angilletta et al. 2006; Butterfield et al. 2020; Dobzhansky and Pavlovsky 1958; Prakash and Lewontin 1968; Wallace 1953).

The indirect form of co-adaptation occurs through indirect interaction (Fig. 4), with at least one of the coupled systems (say, System A) undergoing an externally driven non-structural or an internally or externally driven structural adaptation that influences a shared environment in a way that drives externally driven and covaried adaptation in another system (System B). All forms of adaptation in human and natural systems can be part of this form of co-adaptation. Which form of adaptation can be part in any specific case depends on which of the coupled systems (System A or System B) is human and which of them is natural. At least one of the coupled systems co-adapting through this form (say, System A) has some influence over

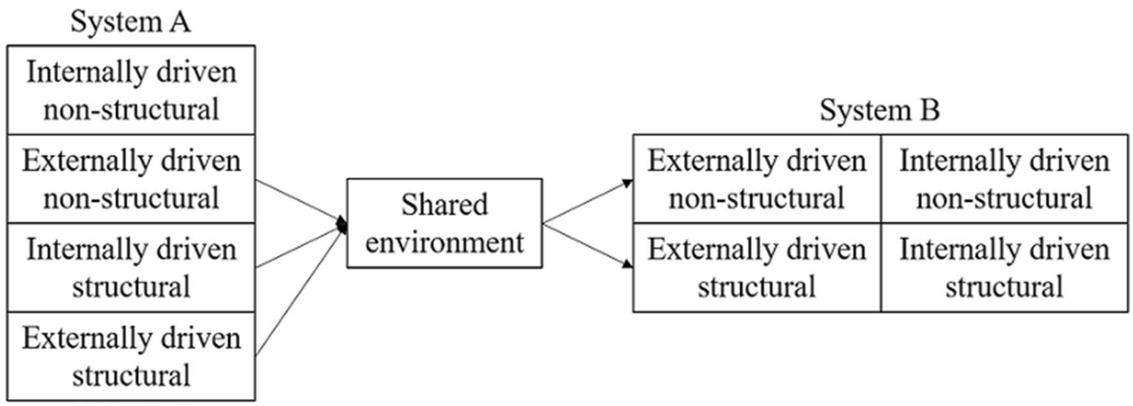

Fig. 4 The indirect form of co-adaptation that occurs through indirect interaction. An externally driven non-structural or an internally or externally driven structural adaptation in one of the coupled systems (System A) influences change in the shared environment that, in turn, influences externally driven adaptation in the other system (System B)

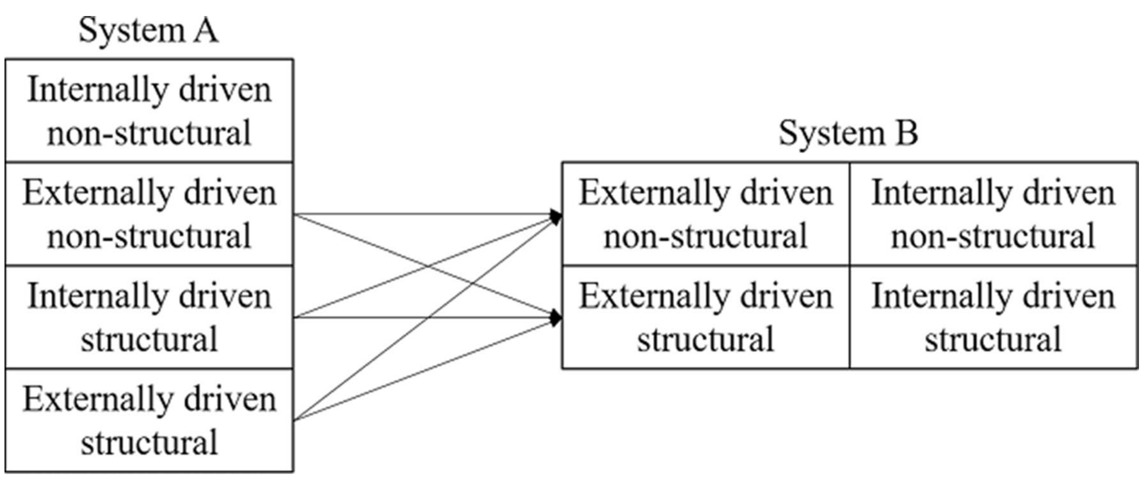

Fig. 5 The direct form of co-adaptation that occurs through direct interaction. An externally driven non-structural or an internally or externally driven structural adaptation in one of the coupled systems influences externally driven adaptation in the other system

the shared environment and, in turn, potentially over the type of change that occurs in the other system (System B). For example, a forest manager (System A) starts implementing a new management practice that improves wildlife habitat on their land (the shared environment) and, as a result, wildlife (System B) adjusts, improving the well-being of both the manager and that of the wildlife on their forestland. This form of co-adaptation allows for both of the coupled systems (System A and B) to influence their shared environment in a way that influences change in the other system. Outside of a few exceptions (e.g., Savit et al. 2013), this form has received much less attention in the sciences than the imposed form of co-adaptation.

The direct form of co-adaptation occurs through direct interaction (Fig. 5), with at least one of the coupled systems (say, System A) undergoing an externally driven non-structural or an internally or externally driven structural adaptation that influences externally driven and positively covaried adaptation in the other system (System B). As with the indirect form of co-adaptation, which form of adaptation takes part in this form in a specific case also depends on which of the coupled systems is human and which of them is natural. Unlike with the indirect form, at least one (say, System A) of the coupled systems co-adapting through this form has direct influence over the type of change the other system (System B) undergoes. For example, a forest manager starts implementing a new management practice that both improves their well-being and brings about a change in their forest that improves forest health. This form of co-adaptation allows for both of the coupled systems (System A and B) to influence

Table 5 New forms of co-adaptation in human and natural systems

Forms of co-adaptation	Possible forms of adaptation in natural systems	Possible forms of adaptation in human systems	Can be multi-directional	Can be stimulated from within	Can provide direct influence
Imposed	Acclimation Acclimatization Selection	Autonomous (non-structural) Incremental (non-structural) Reactive	No	No	No
Indirect	All	All	Yes	Yes	No
Direct	All	All	Yes	Yes	Yes

the other. Outside of a few exceptions (e.g., Wolf and Brodie 1998), this form too has received much less attention in the sciences than the imposed form of co-adaptation.

All three forms of co-adaptation occur in CHANSs. However, only two of the forms (indirect and direct) can be multi-directional (System A ↔ System B) and stimulated from within the coupled systems. Only one of these forms (direct) can provide direct influence over whether and what type of change might occur (Table 5). Furthermore, whether a co-adaptation has the ability to change the range within which future adaptation and co-adaptation might occur depends on whether the underlying adaptations are structural. In some cases, the adaptation in the human system might be structural, but not the one in the natural system. In other cases, it might be the other way around. In some cases, both or neither of the underlying adaptations might be structural.

As a result, some forms of co-adaptation might be of greater interest in some contexts than in others. Co-adaptations that are of the direct form might be of great interest in contexts such as forest management, where a manager directly interacts with forestland. Co-adaptations that have the ability to change the range within which future adaptations and co-adaptations might occur may be of greater interest in contexts where there is a need to expand this ability. This typology of change helps differentiate among the three forms of co-adaptation based on the types of changes that are involved and the interactions among them. As demonstrated in the next section, this is especially relevant in a real-world context when attempting to differentiate among a large variety of potential adaptations and co-adaptations.

New categories of adaptations and forms of co-adaptation in the Northwoods

To illustrate the new categories of adaptations and forms of co-adaptation in a real-world context, we apply to the Northwoods, a CHANS in the Upper Midwest, USA, consisting of temperate deciduous forests managed largely by private landowners. The Northwoods comprises five interspersed forest types: maple–beech–birch, jack–red–white pine, spruce–fir, oak–hickory, and aspen–birch. Approximately one-third of the forestland area is in public ownership; the remainder is privately owned. We focus on the forestlands owned by individuals and families, also known as small woodland owners, composing approximately half of all forestland—23.4 million acres[2]—across Michigan, Minnesota, and Wisconsin in relatively small parcels (i.e., between 10 and 1000 acres in size) (Butler and Ma 2011). Small woodland owners rely on these woodlands for their homesites, sources of timber, habitat and biodiversity, scenery, recreational opportunities, and investment value (Butler and Ma 2011; Erickson et al. 2002; Potter-Witter 2005; Pugh et al. 2009), so they are sensitive to global climate change impacts. However, unlike institutional land managers (e.g., public agencies, private corporations), which are slow to respond to changes in the environment because of the complex social, technical, and political processes that mediate the human-forest relationship, small woodland owners make decisions directly in response to environmental changes that they experience and perceive, creating opportunities for rapid adaptation and co-adaptation. This tightly coupled relationship between small woodland owners and their forests makes the Northwoods an intriguing CHANS for study.

Climate change is expected to challenge ecosystem dynamics in the Northwoods by altering disturbance, moisture, and temperature regimes. Specifically, climate models project a warmer, wetter climate in the region over the next century, with increasing temperatures in winter and spring and increasing precipitation and heavier rainfall events in summer and autumn (Handler et al. 2014a, b; Janowiak et al. 2014). Climate models also project more frequent and severe wildfires and droughts (Duveneck and Scheller 2016; Handler et al. 2014a, b; Hayhoe et al. 2010; Janowiak et al. 2014; Seidl et al. 2017). Insects and diseases, which proliferate more easily in warmer and wetter conditions, may be the greatest threats to forestland in this area (Hubbart et al. 2016; Poland and McCullough 2006). Emerald ash borer (Poland and McCullough 2006), beech bark disease (Koch 2010; McCullough et al. 2005) and other diseases

[2] Based on data in Butler (2008, pg. 52) for Michigan (8.96 mill ac), Minnesota (5.39 mill ac), and Wisconsin (9.08 mill ac).

and pests (e.g., oak wilt, hemlock woody-adelgid), no longer controlled by long, cold winters, have already infested much of the area's forestland. The long life span of trees does not allow for rapid biological adaptation to these stressors (Kolström et al. 2011), so enduring shifts in the composition of many tree species are expected. For example, suitable habitat for spruce (*Picea spp.*), fir (*Abies spp.),* paper birch (*Betula papyrifera*), and quaking aspen (*Populus tremuloides*) is expected to decline (Swanston et al. 2018). Elevated carbon dioxide levels and warmer temperatures may extend growing seasons and increase growth and productivity for other species, such as the red maple (*Acer rubrum*) (Handler et al. 2014a, b).

Climate change will likely create new challenges for forest managers as well. Declines in some forest types, such as some economically important oak and conifer species (Gómez-Mendoza and Galicia 2010; Hanewinkel et al. 2013; Jönsson et al. 2009; Keenan 2015), will require woodland owners to reorient their forestry operations around different tree species and wood products (Irland et al. 2001; Lal et al. 2011; Rittenhouse and Rissman 2015). Warmer, wetter conditions may complicate thinning, harvesting, and other forest management activities, often conducted on the frozen ground (Maracchi et al. 2005). As a result, woodland owners may experience declining profits and land values (Maracchi et al. 2005). Climate change may also create opportunities for owners in areas where suitable habitat for desirable species has been enhanced or growing seasons have been extended. Recent empirical research suggests that some woodland owners have responded to climate change in the Northwoods by altering their forest management and planning behaviors. Owners have planted new species to establish mixed stands; cultivated species and varieties that are better adapted to changing site conditions; shifted the timing of planting, thinning, and pruning to ensure colder and drier conditions more favorable for forestry operations; thinned stands to reduce stress from drought and wind; and harvested some species earlier than planned to reduce the likelihood of loss to pests, diseases, and storms (Fischer 2019).

Woodland owners' efforts to manage for more climate-adapted forests will, in turn, have consequences for forest conditions and processes. For example, harvesting tree species that may be damaged in the future could reduce seed availability for some species, thereby reducing forest diversity and shifting forest functionality. Thinning trees to protect stands from future events could slow insect and disease spread (Hood et al. 2016; Retzlaff et al. 2018) and reduce drought stress (Bottero et al. 2017; D'Amato et al. 2013; Kerhoulas et al. 2013; Vernon et al. 2018); it could also accelerate succession, increase forest complexity, and speed carbon uptake and storage (Flathers et al. 2016; Sullivan and Sullivan 2017). Planting diverse species could decrease the likelihood of insect outbreaks (Jactel and Brockerhoff 2007), reduce disease virulence (Haas et al. 2011), increase structural complexity and resilience (Anderegg et al. 2018), and accelerate shifts in composition and function (Aquilue et al. 2020). Planting stress-resistant trees could increase forest robustness and resilience. Avoiding work during warm wet conditions to prevent damage could slow the spread of insects and diseases; it could also perpetuate stress-related mortality.

Some of these changes in forest ecosystem dynamics and forest management behaviors in the Northwoods might constitute adaptations, others might constitute co-adaptations. Take, for example, the spread of beech bark disease and some of the woodland owners' management responses. Beech bark disease has been on the rise in Michigan (Koch 2010) and is fatal for beech species, but it can be managed, in part, by reducing the amount of overstory beech (Koch 2010; McCullough et al. 2005). First, consider changes within the human system. If a woodland owner has preemptively harvested susceptible beech trees for years to avoid the spread of beech bark disease, the practice is already a part of their management strategy, implemented under what they perceive to be normal forest conditions. Therefore, from the perspective of the woodland owner's behavior, implementation of the practice is an internally driven non-structural change (Table 3) that does not have the potential of being an adaptation. However, if the owner restarts the practice after observing new evidence of the disease, then it becomes an externally driven non-structural change. It, therefore, has the potential of being an adaptation, although of the non-structural category that cannot change the range within which future adaptation might occur. Yet another scenario is when a woodland owner decides to start harvesting susceptible beech trees as a result of a new initiative to improve their strategy to control the spread of beech bark disease. This would constitute the change as internally driven structural, with the potential of being an adaptation of the structural category and thereby having the ability to change the range within which future adaptation might occur.

Within the natural system, and from the perspective of the entire forest, if growth in a forest increases because of an increase in precipitation, the change is externally driven non-structural (Table 2). It, therefore, has the potential of being an adaptation, although of the non-structural category and thereby not one that can change the range within which future adaptation might occur. Alternatively, if the increase in growth is primarily because of the woodland owner's practice of preemptively harvesting susceptible beech trees, the change in the forest is externally driven structural, and, in this case, it has the potential of being an adaptation with the ability to change the range within which future adaptation in the forest might occur.

The potential of two or more adaptations to constitute co-adaptation rests on whether they covary. Continuing with the example of beech bark disease and management responses, if the woodland owner's practices and the corresponding increase in forest growth have the potential of being adaptations (have the potential to increase both the owner's well-being and the health of the forest), then the changes have the potential of being a co-adaptation of the direct form. Since the change in the forest is structural (because the woodland owner is removing trees), the co-adaptation has the ability to change the range within which future adaptation in the forest might occur. If the change in the woodland owner's behavior is also structural (a result of a new initiative to improve strategy), then the co-adaptation also has the ability to change the range within which future adaptation in management might occur.

Conclusion

Helping CHANSs adapt in a way that allows for their sustainable interaction requires cross-disciplinary collaboration among natural and social scientists that is often challenged by their differences in perspectives and areas of focus. We proposed a transdisciplinary typology of change that overcomes these differences and applied it to identifying new categories of adaptations and forms of co-adaptation. We then illustrated these new categories and forms in a real-world CHANS—the Northwoods in the Upper Midwest, USA. The new categories of adaptations are non-structural and structural, with the latter including adaptations that have the ability to change the range within which future adaptation might occur. The new forms of co-adaptation are imposed, indirect, and direct. The indirect and direct forms can be multi-directional and stimulated from within the coupled systems. The direct form can also provide at least one of the system's with direct influence over whether and what type of change might occur in one or more of the other coupled systems.

It is worth noting that the typology's reliance on a systems perspective, which is what lends it a transdisciplinary scope, requires the definition of system boundaries, which are subjective human constructs. This, in turn, makes the description of the four most basic types of change also subjective. However, this issue is general to the study of complex systems (San Miguel et al. 2012) and affects all CHANSs and other system-based frameworks (e.g., Holland 2012). The proposed typology attempts precisely to minimize subjectivity by systematizing descriptions of change in CHANSs. It is also worth noting that the typology does not (and is not intended to) resolve differences in perspectives on adaptation or co-adaptation within the human and natural sciences. Nor does it (or is it intended to) designate whether or not a change is an adaptation or part of a co-adaptation. Instead, the purpose of the typology is to bridge perspectives of disciplines involved in studying the interaction among CHANSs and to pave the way for more robust and much-needed collaboration.

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