Using the 'regime shift' concept in addressing social-ecological change

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ABSTRACT

'Regime shift' has emerged as a key concept in the environmental sciences. The concept has roots in complexity science and its ecological applications and is increasingly applied to intertwined social and ecological phenomena. Yet, what exactly is a regime shift? We explore this question at three nested levels. First, we propose a broad, contingent, multi-perspective epistemological basis for the concept, seeking to build bridges between its complexity theory origins and critiques from science studies, political ecology, and environmental history. Second, we define the concept in a way that is consistent with this epistemology, building on previous emphases on speed, scale, stickiness, and interrelationships, but also emphasizing human perceptions and the rhetorical uses of the notion. Third, we propose a novel typology of the ways in which the regime shift concept is used in analysing social-environmental phenomena in geography and beyond. These uses are categorized

along two axes. On the one side we distinguish between description of past or present changes, versus normative prescriptions for the future. On the other side we distinguish whether the focus is on material shifts (social and ecological) or conceptual shifts (discourses and ideas). We illustrate the typology with reference to social-environmental changes in landscapes around the world dominated by plantations or widespread naturalization of Australian *Acacia* species. We conclude that the regime shift concept is a boundary object with value as both an analytical and communicative tool in addressing social-environmental challenges.

KEY WORDS
biological invasions; regime shifts; epistemology; systems theory; social-ecological changes; tipping point

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1. INTRODUCTION

Sudden changes in the environment, human activities and their interactions are increasingly in the spotlight (Russill, 2015, Leadley et al., 2014, Chapin et al., 2010). Observers point to the unpredictable dynamics of ocean fisheries, the conversion of peat lands to palm plantations, the transformation of grasslands by alien trees, or major climate change with fundamental effects on humans and their livelihoods. The term 'regime shift' has emerged as an unavoidable tool in conceptualizing and analysing such profound changes, along with related concepts like 'tipping points', 'irreversible thresholds', or 'critical transitions' (Andersen et al., 2009: 50).

The term 'regime' is used here, as we develop below, to denote behaviours, conditions, and interconnected processes that are perceived to be characteristic, stable and self-sustaining in reference to a particular phenomenon of interest. This understanding of 'regime', characteristic of generic definitions, is distinct from more specific usages – especially as a mode of political rule or governance (cf. OED, 2017, Merriam-Webster, 2017). In the social-environmental realm a regime might incorporates people's behavioural patterns, social relationships, economic exchanges, cultural values, as well as natural processes and patterns relating to a particular phenomenon of interest. The term 'shift' is then used to refer to major, rapid, fundamental, and persistent transformations of such a regime.

The regime shift concept has been used to address different phenomena, ranging from

natural resource management (Biggs et al., 2009, de Zeeuw, 2014) or the transformations of energy-provision systems (Strunz, 2014, Westley et al., 2011, Kemp, 1994), to broad-scale interactions of human societies with the environment (Kinzig et al., 2006, Wrathall, 2012, Aoki, 2015). The concept has been used to investigate causality, multi-scalar internal feedbacks and interactions, or linkages between regime shifts in different sub-systems (Kinzig et al., 2006, Cumming et al., 2014, Leadley et al., 2014, Sims and Finnoff, 2016). There is often a normative aspect: for instance in some research the analysis of past and on-going changes may implicitly be described as going from a more desirable state to a less desirable one (Kinzig et al., 2006), whereas other research might explicitly seek to facilitate or steer desired future transitions towards sustainability (Westley et al., 2011, Geels and Schot, 2007, van den Bergh et al., 2011).

Despite its rapid uptake in diverse contexts, the use of the regime shift concept faces several challenges. In particular, the need to bring multiple disciplines together to address major social-environmental challenges, often across social and natural science divides, raises problems of transferability, communication, and epistemology. Interdisciplinary integration, as exemplified by the Future Earth project launched at the Rio +20 conference, is difficult. This was exactly our experience as a team with disciplinary connections to human geography, biogeography, forestry, invasion ecology, and landscape planning that came together to study the spread and management of Australian acacias in human-shaped landscapes around the world. 'Regime shift' was proposed as an analytical concept for the project, yet provoked different reactions from different participants. This was particularly so because the regime shift concept as used in the study of social-ecological systems has quite specific roots in dynamical systems theory and has been developed in complexity theory (Hui and Richardson, 2017). This epistemological background has, as we review below, given rise to a variety critiques from alternative perspectives.

In geography, the integration of ideas from systems approaches has a troubled history. An earlier wave of enthusiasm for analytical approaches inspired by first-generation systems theories took place in the 1960s and 1970s, promoting system theory's holism and thus avoidance of the pitfalls of reductionism, and its potential unifying application across the field's human-physical divide (Ackerman, 1963, Harvey, 1969, Chorley, 1978, Johnston, 1991, Haggett and Chorley, 1967, Huggett, 1980). This was met by stinging critiques from other epistemological points of view worried about system theory's aggregate nature, its difficulty incorporating non-rational aspects such as actors' perceptions, its application of a mechanical or ecological analogy to social dynamics, and, most trenchantly, for its ideology of control (Kennedy, 1979, Gregory, 1980, Lilienfeld, 1978).

The current rise of the 'regime shift' concept accompanies a more recent wave of enthusiasm for later-generation systems ideas in the study of society-environment phenomenon, exemplified by the social-ecological system and resilience approaches (Berkes et al., 2003, Gunderson and Holling, 2002) which have become popular in a variety of fields, including geography. These ideas have again led to some epistemological friction, notably with scholars from political ecology critiquing the lack of attention to power and values in these approaches (Cote and Nightingale, 2012, Beymer-Farris et al., 2012, Kull and Rangan, 2016).

The present paper aims to build bridges across the above-mentioned epistemological and disciplinary gulfs. Researchers from diverse academic backgrounds are using the regime shift notion as a tool for deconstructing the elements of complex environmental phenomenon to understand the range of possible human responses. We ask what the 'regime shift' term means once it has been borrowed from describing phenomena such as lacustrine ecology or fire regimes, and applied to complex social-ecological phenomena involving politics, economics, culture, and more? Through such a transfer of the usage of the concept, it gains an important *metaphorical* aspect (Merriam-Webster, 2017). That is, analogies are made between biophysical and socioecological phenomena, as well as between their respective modes of analysis. We ask just how far such analogies can go before they become problematic, and promote an explicit reflection of regime shift as a means, through its use as a boundary object, of sparking inter- and transdisciplinary dialogue.

More specifically, we ask what conception of 'regime shift' might be both internally consistent and generalizable to broader studies of human-environment dynamics in geography and beyond? We take a critical, yet constructive, perspective to refine the concept and promote dialogue towards better interdisciplinary understanding. To facilitate interdisciplinary integration, it is necessary to better understand how such concepts with roots in the systems and complexity sciences can become more accessible to a broader range of scientists with different epistemological and methodological perspectives. We aim to show how the concept and its metaphorical usage can be useful as boundary objects to communicate about and analyse society-environment phenomena, by reviewing its epistemological and ontological underpinnings and by establish a typology of different uses.

The paper is addressed at nature-society scholars in general, inside and outside of geography, who can see in the discussion of regime shifts an instructive case of interdisciplinarity. It is also addressed more specifically at scholars of 'social-ecological systems' of the resilience school, to encourage better interdisciplinary collaboration and dialogue. The regime shift concept can be a useful tool not just for research analysis, but also as the basis for communication to stakeholders and decision-makers. By refining the concept, our aim is thus to contribute to 'translational' research on society-environment phenomena (Schlesinger, 2010).

This review essay explores three dimensions. First, we place the regime shift concept in its epistemological contexts. In doing so, we propose a new approach that builds upon the strengths of systems and complexity theories but also on critiques of the application of this epistemology to the social world. This alternative approach considers a regime shift as a boundary object that can enable contingent, multi-perspective and testable hypotheses, debatable assertions, and communicable ideas. Second, we investigate the ontology of social regime shifts: what is this thing that we claim exists? We review the ways in which the term has been defined in the study of social-ecological systems, and propose a refined definition relevant to our alternative approach. Third, building on these epistemological and ontological foundations, we propose a novel typology based on a critical engagement of the ways in which the concept as we define it has been used in the analysis of social-environmental phenomena. We illustrate it with the case of the spread and governance of Australian acacia trees around the world.

2. EPISTEMOLOGY: SYSTEMS AND METAPHORS

The predominant conceptualization of social-ecological regime shifts builds on a relatively specific epistemology arising out of systems thinking. In this section we introduce a different understanding, adapted to the social realm, of a regime shift as a contingent, multi-perspective metaphor. This new understanding seeks to address some of the challenges encountered when applying systems-based ideas to the social realm.

The regime shift concept, as currently used in the study of social-ecological systems, emerged just over a decade ago, at first in discussions of lacustrine ecology, marine ecosystem properties, and climate change, and then in discussions of diverse social-ecological challenges (Russill, 2015, Scheffer et al., 2001, Parker and Hackett, 2012, Cote and Nightingale, 2012, Berkes et al., 2003). The term 'regime' was explicitly chosen instead of 'stable state' or 'equilibrium' to better characterise regions of stability in systems that are inherently dynamic, stochastic and chaotic, exhibiting non-linear dynamics. A 'regime shift', then, was defined as a sudden, profound change in one or more processes that sustain the dynamic patterns and conditions that characterize and maintain a particular regime (Scheffer and Carpenter, 2003, Biggs et al., 2012).

It should be noted that the term 'regime shift' has also emerged in the intertwined literatures on sustainability transitions, socio-technical transitions, and transitions management. Notably authors using the 'multi-level perspective' use regime to refer to constellations of rules, practices, and institutions that maintain stability in society-technology configurations, and looks at how cross-scalar influences can provoke important shifts (Geels, 2002, Kemp, 1994). This work shares some similar assumptions with studies of social-ecological systems, but there are also some important differences (Smith and Stirling, 2010). A 'regime shift' concept (though not always with that name) has also been used in the political sciences, largely in the historical institutionalism school which specifically addressed path dependencies and critical junctures how humans organize themselves (Pempel, 1998, Skocpol, 1979). Finally, regime shift (or, more accurately, 'regime change') is common in public discourse, notably referring to the forcible removal of a government, often an authoritarian one (OED, 2017).

The concept of regime shift upon which we focus, which arises out of the study of social-ecological systems, is drawn from non-linear systems theory, as made explicit by several authors (e.g. Gaertner et al., 2014, Biggs et al., 2012). Systems thinking sees the world as made of systems, each being "an integrated whole distinguished by an observer whose essential properties arise from the relationships between its parts" (Ison, 2010 p. 22). Systems thinking has evolved over the past half-century across diverse disciplines and following different albeit related intellectual lineages including cybernetics, network science, and complex adaptive systems. Systems approaches range from the ontological – those that seek to analyse and model phenomena by characterizing them as systems – to the epistemological, that is approaches focused more on systems in terms of learning, control, and communications (Becker and Breckling, 2011, Ison, 2010, Checkland, 2000). Systems perspectives vary also in their reliance on closed versus 'radically' open concepts of

systems, on equilibrium versus non-linear behaviour of complex systems over time, on realist versus constructivist understandings of systems, and on deductive to inductive approaches (Holling and Meffe, 1996). Despite the variety of conceptualisations, common concepts across all forms of system thinking include ideas like boundaries, emergent properties, hierarchy, thresholds, feedback loops, inputs and outputs (Voigt, 2011, Csete and Doyle, 2002, Ison, 2010, Liu et al., 2007, Newell et al., 2005, Briske et al., 2010).

The regime shift concept, as noted by Biggs et al. (2012, p. 611), traces its origins to mathematics, specifically dynamical systems theory and René Thom's catastrophe theory. It arrived in the field of social-ecological systems via Holling (1973)'s pioneering work on ecological resilience. In the social realm, the same concept, though labelled 'tipping point', was harnessed by economist and complex systems theorist Schelling (1971) in his work on residential segregation. Despite these more formal, quantitative origins, some of the uses of the regime shift concept have – as Stone-Jovicich (2015) shows for social-ecological resilience ideas more broadly – "moved a long way from their ecological origin" and "broadened both their theoretical lens and methodological toolkit". Nevertheless, they are still rooted in the analysis of non-linear behaviour of complex systems over time.

While we build on the social-ecological regime shift concept as developed within the above mentioned forms of systems thinking, several constraints with its underpinning epistemology lead us to introduce a modified understanding. A substantive literature presents critiques of the use of systems approaches in the social sciences in general (Giddens, 1979, Lilienfeld, 1978), and more specifically in geography (Gregory, 1980, Kennedy, 1979, Watts, 2011, Kull and Rangan, 2016), ecology (e.g., Taylor, 2005, Taylor, 2011) and in resilience thinking (e.g., Brown, 2014, Porter and Davoudi, 2012, Kirchhoff et al., 2010, Biermann et al., 2015). In Table 1, we review some of the challenges or perceived incompatibilities with systems approaches identified in the social sciences. Our goal in Table 1 is not to be comprehensive in reviewing these critiques, but rather to remind readers of controversial aspects underlying the use of the regime shifts concept for social systems that we thus must address in our proposed approach.

Table 1. A summary of challenges and social science and humanities critiques encountered when applying different forms of systems approaches to social contexts.

Fundamental differences from natural systems	Social scientists contest mechanistic applications of systems approaches that see the world in ways that can appear reified, un-reflexive, and which reduce the world to inputs and outputs (Kirchhoff et al., 2010, Palsson et al., 2013). Furthermore, they argue that there are fundamental differences between social systems and biophysical systems, particularly with respect to the system structure, behaviour, and the multiplicity of interpretations (Brown, 2014, Cote and Nightingale, 2012, Turner, 2014, Adger, 2000, Bentley et al., 2014).
Difficulties in incorporating modulating influences and contingency	In a more formal sense, strict systems approaches based on mathematical relationships allow only for direct causal effects between separated elements. These do not allow for a modulating influence of contexts on interactions, and they require the definition of discrete elements. In particular, they do

	not allow for historical contingency, in the sense that the same cause-effect relationship may work differently in time, space, and between individuals, depending on the social context (Frawley, 2014, Taylor, 2011, Turner, 2014, DeLanda, 2006). Some forms of complexity theory explicitly incorporate what they call 'contextuality' (Chu et al. 2003), and some social-ecological systems authors seek cross-fertilization from other social science approaches (Stone-Jovicich, 2015). But contingency and the irreducible uniqueness of each case are not in the epistemological core of systems thinking, which in contrast is the case for certain intellectual traditions in the humanities.
Poor compatibility with multiple perspectives, feelings, and interpretations	Social systems are *multi-perspective*, with certain aspects like perceptions, beliefs, memories, and culture that shift across time, domains, levels, persons, and generations. There are multiple perspectives of what constitutes a particular system and makes it function. Despite recognition of this in some forms of system analysis (e.g. when Ison 2010, p. 22 defines systems as "an integrated whole *distinguished by an observer* …"), and the recognition of the "constructive role of variation" in work on adaptive management (Holling and Meffe, 1996), this multi-perspectivity remains constrained within the bounds set by a systems perspective. Aboriginal worldviews, for instance, simply do not fit into a systems epistemology (Howitt, 2001, Trudgen, 2000). Relativity of perspectives, and incorporation of the humanistic domain of feelings, interpretations, and worldviews, remains only poorly compatible with most applications of systems ideas (Palsson et al., 2013).
Discomfort with emphasis on generalization and simplification	Systems approaches tend to emphasize *generalization*, at least at an intermediate level (Pahl-Wostl, 2009, Ostrom, 2007), rather than *context dependence, differentiation, individual agency,* and *geographical context* (Coenen et al., 2012). This can require strong simplification and reduction to a few variables and interactions. Such abstraction and simplification means that the experiences of individual organisms – differentiation, pain, struggle, injustice – are largely ignored (Turner, 2014).
Difficulties in addressing questions of power	Systems approaches have been critiqued for poorly addressing notions of *power* and *equity*: who has power, why, how it operates, who wins, who loses, whose interests are affected, and what ideas accompany these changes (Brown, 2014, Michon, 2011, Smith and Stirling, 2010). For instance, systems-based resilience thinking has been accused of being technocratic and 'apolitical' (Beymer-Farris et al., 2012, Cote and Nightingale, 2012, Turner, 2014, Watts, 2011, Birkenholtz, 2012). Although the question of "resilience for whom" has been addressed within a social-ecological systems approach (Lebel et al., 2006) and innovative recent work has created strong overlaps between social-ecological systems science and other social science traditions on power (e.g., Ahlborg and Nightingale, 2012, Stone-Jovicich, 2015), system science approaches nevertheless privilege certain perspectives on agency – those that are measurable and explicit – over others. Furthermore, many systems-based approaches implicitly give power to the experts who perceive and describe the system, to the detriment of others (e.g. it is not sufficient to ask "resilience for whom" but also "resilience seen by whom and how").

Problems with a perceived ideology of control	The tendencies of early systems theory approaches to reduce complex systems into legible and manageable components has been criticized for facilitating an *ideology of control* – a presumption that the beholder of the system has sufficient knowledge to tweak the dials to reach certain outcomes. This can reproduce structures of domination and begs questions about why, and for whom, certain systems regimes are seen as desirable (Beymer-Farris et al., 2012, Gregory, 1980). The ideology of control has been critiqued from *within* different systems paradigms, notably by Holling and Meffe (1996) who argue that non-equilibrium, non-linear, and multi-scalar concepts of system dynamics suggest that management should not seek to control, but instead adaptively "facilitate existing processes and variabilities". Theories of complexity and adaptive systems, notably, integrate a sentiment that systems dynamics are inherently uncontrollable and complex (Folke et al., 2002, Chu et al., 2003).

Due to critiques such as those reviewed in Table 1, systems-based approaches are only one subset of approaches used in studies of the social world, for instance in ecological anthropology (particularly in the 1970s), in world systems theory (Stone-Jovicich, 2015), or in economics. For some worldviews and epistemologies, it is difficult, or even inappropriate, to reduce and synthetize the diversity and richness of human experience to boxes and arrows, balls and cups, or quantitative variables. While certain systems approaches address historicity, multiple perspectives, power relations, control ideologies, and so on, they do so in particular ways. In other words, the common history of systems thinking approaches, the pre-dominant relationships and interactions with particular disciplines or epistemological traditions within disciplines, and the metaphors used – often from information and complexity theory or engineering – limit the intellectual space that the systems traditions provide. This can hinder inter- and transdisciplinary collaboration with experts with contrasting epistemological backgrounds. Recent social sciences research on scientific practice in fields such as science and technology studies or transdisciplinarity has recurrently shown the pervasive but often implicit and therefore difficult-to-uncover performativity of scientific traditions and metaphors in the sciences, including systems science thinking (Miller et al., 2008, Castree et al., 2014, Feyerabend, 2010 [1975], Taylor, 2005, Rasmussen and Arler, 2012).

We argue here for a different perspective that is at least partly incommensurable with a systems analysis framework and therefore cannot simply be subsumed under it. A critical realist epistemology may be one way forward, as it finds a third way between positivist research and relativist, constructivist stances. It allows for tacking back and forth between empirical realities and the social processes that produce our understandings of those realities (Forsyth, 2003, Stone-Jovicich, 2015, Turner and Robbins, 2008, Sayer, 2000, Taylor, 2005, Mingers, 2014). We suggest a broader understanding, or epistemology, to underpin the regime shift idea. It sees a "regime shift" as a contingent, multi-perspective boundary object that enables the creation of hypotheses or ideas that can be appropriated, tested, and debated by different approaches (including, of course, systems-based analyses). The concept needs to be *contingent* in the sense that it must allow for the expression of non-deterministic, context-dependent, and historically particular conjunctures of causes and effects. It needs to be *multi-perspective* in legitimizing different points-of-view, experiences,

and analytical moments with respect to the events being discussed. Finally, it can serve as a *boundary object* that promotes debate, the advancement of knowledge, and sometimes surprising outcomes by its power of bringing into conversation a variety of different participants and worldviews (Brown, 2014, Cohen, 2012, Kull et al., 2015, Baggio et al., 2015).

Boundary objects are either concrete objects or abstract notions that are accessible to different social groups with (partly) non-overlapping epistemologies and/or interests. They are, in the words of Star and Griesemer (1989, 393), "plastic enough to adapt to local needs and the constraints of the several parties employing them, yet robust enough to maintain a common identity across sites". Boundary objects such as regime shifts must strike a balance between robustness and plasticity (Star and Griesemer, 1989) in that they should refer to an ontological core that is both specific and flexible. As Brand and Jax (2007) argue regarding the notion of 'resilience' – another boundary object – clarity and specificity aid specific scientific use as an analytical concept; malleability and broadness aid in fostering communication.

A specific way in which the regime shift concept serves as a boundary object is as a heuristic *metaphor* used to communicate a certain interpretation of reality (Chew and Laubichler, 2003, Larson, 2011). Metaphors create analogies between one kind of object or idea and another (Merriam-Webster, 2017). The regime shift concept as applied to social-environmental phenomena makes exactly such analogies, both at the ontological level between biophysical and social-ecological systems, and at the epistemological level between how such phenomena are analysed. As we review above, these analogies can become problematic, necessitating the kind of alternative framing we advocate. Instead of understanding a regime shift as a type of systems behaviour that can be described and analysed through systems models, we propose that regime shift be defined specifically enough to facilitate dialogue and research about a bounded range of phenomena, but flexible enough to allow for people with different worldviews and epistemologies to contribute to the debate. For instance, as we note in Section 4 below, factors including rural outmigration, forestry policies, and invasive behaviour have shaped non-native acacia landscapes in Portugal (Appendix 2). This situation can be productively modelled as a regime shift within system approaches (e.g., Figueiredo and Pereira, 2011, Santos et al., 2016), but such approaches could be productively complemented by others that build on the identified regime shift as a communicative tool to investigate historical contingencies in the process, different perceptions of what exactly is the shift of concern, and whose ideas of future pathways and adjustments can or should hold sway.

3. ONTOLOGY: WHAT IS A SOCIAL-ECOLOGICAL REGIME SHIFT?

After describing a type of knowledge system that might be useful for the 'regime shift' concept as applied to social systems, we now propose 'what it is that can be known' as a regime shift, or, loosely said, its ontology. In this section, we establish the essential elements of a generic core 'regime shift' definition consistent with the alternative critical realist epistemology described above. We then demonstrate the relativity or malleability of the concept, and why we defend that it is best seen as a perception. In this sense, we advocate regime shifts as boundary objects to communicate as well as analytical constructs to analyse differentially-situated and

always political (Smith and Stirling, 2010) human perceptions of specific types of dynamics in the world in which we live.

Publications invoking the 'regime shift' concept in the study of (social-)ecological systems display a relatively tight conformity in definition. They also cite a limited number of key references, with the work of Marten Scheffer and several authors associated with the Resilience Alliance (www.resalliance.org) attracting most attention (Appendix 1). For instance, Kinzig et al. (2006 p.1) describe the central idea as applied to both social and natural systems:

> "The seemingly stable states we see around us in nature and in society, such as woody savannas, democracies, agro-pastoral systems, and nuclear families, can suddenly shift out from underneath us and become something new, with internal controls and aggregate characteristics that are profoundly different from those of the original. The types of changes that involve alterations in internal controls and feedbacks are often called 'regime shifts' (Scheffer and Carpenter 2003, Folke et al. 2004)."

In a review of articles containing the key words 'regime shift' (see Appendix 1 for sources), almost all definitions of regime shift included, in one way or another, four key ideas:

i. *Speed*. The change is sudden, abrupt, or rapid.
ii. *Scale.* The change is dramatic, large, non-linear, or passes thresholds to profoundly different states (or has substantial impacts).
iii. *Stickiness*. The change is long-lasting, persistent, difficult or impossible to reverse, hysteretic.
iv. *Systemic change*. The change is characterized as being from one regime (or 'quasi-equilibrium', 'stable state', 'apparent homeostasis', 'basin of attraction') to another, resulting in reorganized internal controls, feedbacks, and characteristics (structures, functions, rule sets…).

A systems-based epistemology is not mandatory to characterize particular phenomena with the first three key traits listed above. The fourth, however, uses a terminology specific to systems thinking. In the spirit of surpassing the epistemological boundaries identified in the previous section, we suggest using terminology such as 'tightly interrelated patterns, functions and processes', instead of explicit systems-based concepts like homeostasis. What is meant by this is that several, and often wide-ranging, aspects of a society-environment phenomenon are tightly interconnected across scales and sectors, which typically adds to the coherence of a regime and enhances the dynamics of regime shifts. In that case, a 'regime shift' could usefully be defined as *a major, sudden, and persistent change in the tightly interrelated patterns, functions and processes that are perceived to characterize and/or maintain particular society-environment phenomena of interest*. Furthermore, this understanding of regime shift emphasizes *relativity, multiple perspectives,* and the *metaphoric* or *boundary object role* of the concept. In this definition, patterns, functions and processes can be physical or social, including perceptions, ideas or ideologies.

The above definition begs some important questions: how big is *major*, how fast is *sudden*, how strict is *persistent*, and what *patterns, functions, and processes* are of importance? Given that regime shifts are heuristic constructs used to analyse a given

phenomenon of interest, the spatial or temporal scale should depend upon the phenomenon the observer is seeking to describe or understand. It is thus by definition a relative and situated concept, a regime shift *with respect to something* and *at a given scale* (Carpenter et al., 2001). So for instance, the conversion of a hectare of *fynbos* shrubland in South Africa through the planting of, or invasion by, Australian acacias is a dramatic landscape change *for that plot*, but could be perceived as insignificant *at broader spatial scales* unless many such changes occur within a given timeframe. Conversely, a minor policy decision in a country's Ministry of Forests may not constitute a regime shift in the workings of that Ministry, but could be seen as such if the scale of interest is a plot of land that is wholly cut, planted or developed because of that decision. Similarly, the definition of 'sudden' depends on whether the temporal frame of reference is geological, archaeological (Aoki, 2015), or a three-year policy program or management plan. The socio-technical transitions literature usefully provides a model for making such analyses, in identifying pathways to regime shifts in relation to higher scale (landscape) and lower scale (niche) phenomena, and in doing so focusing attention on slow moving and fast moving variables (Geels, 2002, Geels and Schot, 2007).

Similar caveats apply to irreversibility. Leadley et al. (2014 p. 665) argue that many "regime shifts lack the nonlinear characteristics and difficult-to-reverse nature of regime shifts mediated by tipping points". For instance, the regime shifts identified by Gee and Burkhard (2012: 193) for offshore wind energy farms in Germany are arguably reversible. The development of artificial reefs at the foot of each wind turbine can be undone by the removal of the platforms; and public perceptions about the seascape may reverse (e.g., Eltham et al., 2008). Irreversibility is particularly problematic as a concept in social systems, as it depends on human agency, a combination of behaviours, intentions and capacity to act, conditioned by various structures (Giddens, 1979). In principle, any social system can to different degrees be made to change in different directions, though this does not always occur (Nykvist and von Heland, 2014).

The relativity of the regime shift concept is heightened by the fact that it is humans who perceive regime shifts. Any representation is a simplification of reality. The idea that regime shifts are relative, or heuristic, leads to a philosophical debate. Is a regime shift "real" or is it a human conception? As noted earlier, we adhere to a critical realist philosophy that notes that entities or phenomena are autonomous from the conceptions we have of them (DeLanda, 2006), but that we are also constrained to use our conceptions to analyze, compare, and talk about phenomena, however real they are. Heuristics matter, and they do not deny realities. The people perceiving a regime shift do so from their perspective, which is shaped by their views of *which* patterns, functions, and processes maintaining *which* society-environment phenomenon are of interest or important. Thus, any regime shift argument will emphasize some processes and downplay others, and is therefore only a partial, provisional and ephemeral interpretation of reality. Furthermore, a representation of reality is always a rhetorical instrument and must be considered in the context of political and social discourses (Forsyth, 2003). To paraphrase Lebel et al. (2006)'s comments about resilience, it is important to ask *who decides* whether something qualifies as a regime shift, and *for what purpose*.

The relativity of the concept does not deny realities nor hinder its utility as a heuristic and rhetorical model to guide research, hypothesis formulation, and debate. It is an evocative boundary object to communicate perceptions that a particular society-environment phenomenon is rapid, major, and consequential enough to warrant the label 'regime shift'. For instance, we might label the rapid establishment of a plantation of 1.1 million hectares of acacia trees in Vietnam, coincident with major policy changes beginning with the Đổi Mới reforms (see Supporting Information - Appendix 2 for details) as a regime shift, for this had important consequences of relevance to household livelihoods, social justice, national economics, biodiversity conservation, and invasion biology. In this case, our purpose in generating awareness or concern over the shift makes the use of the label apt, useful, and a powerful communication tool that can inspire further investigation and debate. It is a heuristic shorthand for a more detailed, contextual, contingent set of processes. As a shorthand boundary object, and as a metaphor, however, it is important to note that its usage is context-specific and could lead to confusion, for instance about the speed of change or its spatial heterogeneity, and could lead to spurious interpretation and inappropriate policy responses (Leadley et al., 2014, p.676).

4. TYPOLOGY: DIFFERENT USES OF REGIME SHIFTS

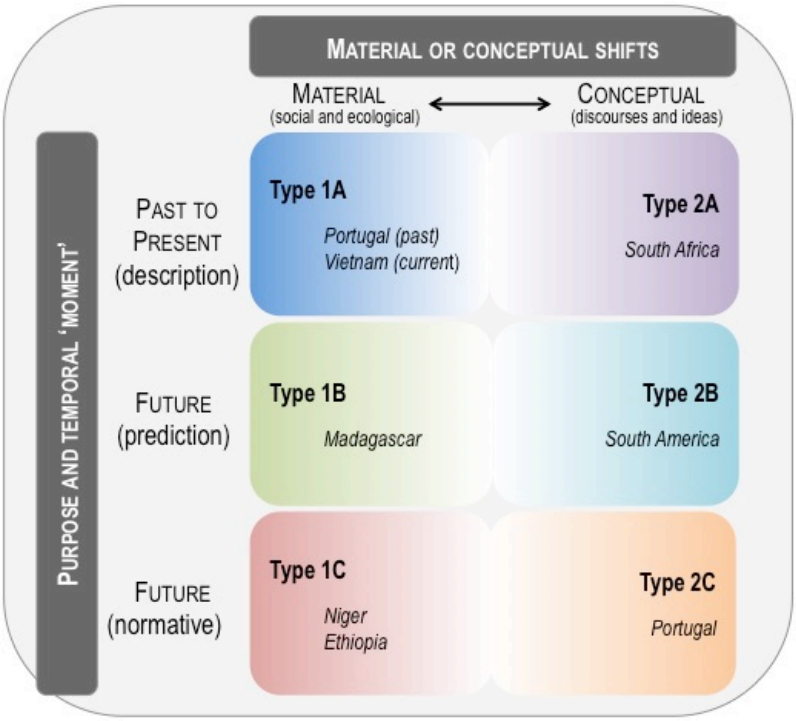
We have established that regime shifts are a human construct, relative in character, but that they can be defined in such a way as to make the concept a useful diagnostic tool and boundary object for analysis, rhetoric, and debate about profound changes perceived to be occurring in environment and society. Here, we build on these postulates and on observations of the use of the concept in the literature on acacia invasions to propose a new typology (Figure 1) of the ways in which the regime shift concept could be employed in addressing social-environmental phenomena. The typology rests on two axes, as described below. We considered other axes, such as whether the drivers are ecological, economic, or socio-political, or whether the regime shift is intentional or non-intentional (Moore et al., 2014) – but we found that the two axes discussed below most efficiently conceptualize the uses of the concept. By distinguishing between different purposes and temporal moments, as well as between material and conceptual shifts, we reinforce the necessity for an inclusive, flexible, and contingent epistemology as outlined above.

The y-axis of the typology distinguishes between different purposes and temporal 'moments' for which analysts mobilize the concept of regime shifts (Figure 1). It recognizes that the description of a regime shift is always part of a discourse with a purpose. Are we *explaining* a regime shift in the past or present, *predicting* a future shift, or *intending to catalyse* a future shift? Each is different. Many scholars use the regime shift idea as an analytical tool for analysing historical trends, explaining the current situation, or predicting future events. Yet the term is also used in an explicitly normative sense. For instance in the literature on sustainability transitions, the focus is on how to facilitate a change in societal structure, economy, and attitudes to navigate a transition along a desired pathway to sustainability (Chapin et al., 2010, Westley et al., 2011, Moore et al., 2014).

The x-axis distinguishes between the main types of dependent variables, that is, the central units of analysis, or the focal components of the phenomenon seen to be

undergoing regime shifts (Figure 1). While it is tempting to separate social-ecological systems into the social and the ecological sub-systems, the more pertinent division in the literature surveyed and in our case study research (Supporting Information Appendix 2) is between material and conceptual shifts. By material shifts, we refer to shifts in material flows and processes that can typically be observed empirically, and which can include both ecological (Biggs et al., 2012) and social variables (Westley et al., 2011). For acacia-dominated landscapes, these may include elements such as land cover, land use, seed dispersal, timber trade, wood-fuel harvesting practices, and project activities for agroforestry or weed control. By conceptual shifts, we refer to shifts in the less tangible realm of ideas, discourses and ideologies. For example, Gee and Burkhard (2012) describe tipping points in regional identities, and Andrachuk and Armitage (2015) propose a method that focuses on fishermen's perceptions of thresholds for social-ecological transformations. Of course, material and conceptual shifts are often intertwined (Sluyter, 2001), particularly with respect to changes in rules, institutions, and policies; here, however, we construct them as separate ideal types to facilitate the clarity of the typology; in the Figure we visually illustrate the continuum between these ideal types. The resulting typology (Figure 1) highlights six categories of how researchers mobilize the regime shift concept.

Figure 1: A novel typology of social-ecological regime shifts, applied with respect to different case studies of non-native acacia landscapes.



We illustrate the typology by applying the six categories to case studies of places around the world with landscapes containing Australia acacia species, a prime example of a contemporary society-environment challenge (Richardson et al., 2011) (see Supporting Information Appendix 2 for case study details). Commonly known as wattles, Australian acacias have been transferred over the oceans by traders, scientists, settlers, foresters, and gardeners for over 200 years, planting them for ornament, for profit, and for environmental management. As fast growing, nitrogen fixing, and copious seed-producing trees, they expanded rapidly in many places. The resulting 'acacia landscapes' exhibit a number of regional particularities, differing in terms of social perceptions and expectations, ecosystem services provided, and problems caused (tree members of genus Acacia; Kull and Rangan, 2008, Kull et al., 2011, Richardson et al., 2011, Vicente et al., 2013).

These landscapes can be considered as a set of 'model systems' useful for testing ideas about social-ecological regime shifts (Bennett, 2014, Kueffer et al., 2013). Indeed, a shared interest in these landscapes is what brought the author team together and what explains this choice of case study. Acacia landscapes are textbook social-ecological phenomena, with humans active in creating plantations and facilitating invasions, in perceiving associated environmental issues, and in deciding when, how, and where to intervene. As with invasions of non-native trees in general (van Wilgen and Richardson, 2014, Dickie et al., 2014), invasions of acacias, in many situations, pose a "wicked problem" in that the complexity of issues surrounding the presence, abundance and perceived costs and benefits make it difficult to define the management problem and decide on interventions to the satisfaction of all stakeholders (Woodford et al., 2016). By refining the regime shift concept as applied to the social-ecological dynamics in question, we hope to promote deeper understandings and dialogues that facilitate adaptive and resilient management of acacia landscapes. Below, we describe the typology in terms of the acacia case studies.

Type 1A refers to the use of regime shifts by researchers and others as a way to characterize past or on-going shifts in the material components of a social-ecological system. For instance, the dramatic changes in the landscape, rural economy, and demography of Portugal from roughly the 1930s to the 1980s are arguably fundamental and irreversible (Radich and Baptista, 2005). Likewise, it can be productive to speak of the economic, policy, and forestry transitions of Vietnam from the 1990s to the present as a regime shift or fundamental transition (Meyfroidt and Lambin, 2008, Thulstrup et al., 2013). Doing so emphasizes the dramatic scale and speed of the changes. But calling the situation in Vietnam a regime shift opens an important debate about its irreversibility and persistence, of relevance to current forestry policy in the country. From an ecological perspective, experience with acacias and their massive persistent seed banks (Richardson and Kluge, 2008) suggests that substantial problems of biological invasiveness with potentially negative consequences could result (Richardson et al., 2015). Alternatively, the material conditions in Vietnam differ from those in South Africa, highland Madagascar, and Portugal (prime cases used to document the range of problems associated with acacia invasions), and perhaps, instead, acacia plantations will be replaced in a few decades by other crops and intensive land use (given the population density) that check invasive potential. Indeed this was the case with 1920s plantations of *Acacia mearnsii* in upland Java (Berenschot et al., 1988).

Type 1B refers to the utilization of the regime shift concept by analysts to illustrate a possible, or predicted, scenario of dramatic material change, such as to the land system. For instance, while silver wattle (*Acacia dealbata*) is ubiquitous in highland Madagascar, its spread over the past century arguably does not really qualify as a broad-scale regime shift to the land system, because the tree has been integrated into relatively 'traditional' rural livelihoods, where it grows in scrubby clumps subjected to heavy harvesting and pasture fire (Kull et al., 2007). A regime shift could, however, be envisaged in the future. As Kull et al. (2007) note, rising incomes could permit urban and rural Malagasy to use non-biomass energy sources for cooking, reducing the harvest pressure on the trees, thereby transforming both the rural economy and landscape, with the invading wattles occupying vastly more terrain at higher densities.

Type 1C refers to an analytical stance that is different from the previous ones centred on description and prediction of material changes. Instead, it encompasses instances where people describe wished-for changes to the material system. For instance, in several cases, development projects are actively trying to encourage what could be seen as a regime shift in the local land systems. In many African countries known for both land degradation and problems of famine, aid agencies and foresters specifically seek to encourage landscape changes involving tree planting and new livelihood practices (Weston et al., 2015). In both Niger and Ethiopia, projects have encouraged planting of Australian acacias such as *A. colei* and *A. saligna* for land rehabilitation, fuelwood, windbreaks, soil fertility, and even human nutrition (Kull et al., 2011). The hope is that such practices will take hold and replicate themselves in farmer practices broadly, and in some cases through the self-reproduction of the plant itself, leading to a regime shift in the resilience of both the land and the local communities. In this case aid agencies imagine a very different future social-ecological system, or regime, shaped by acacia species, that they use rhetorically to promote change.

Type 2A is the first of three types referring to the use of the regime shift concept to indicate *conceptual* changes, that is, important shifts in ideas, discourses, and their manifestations in institutions and policies. Type 2A refers to the analysis and description of past and current changes in this regard. The case of South Africa's 'Working for Water' program is a good example (again, see Supporting Information Appendix 2). This program can be analysed as a major, rapid, and sticky policy transition with respect to acacias, fashioned out of a unique political and ideological moment in the country's history coincident with the global rise of invasion biology (see, for instance, Carruthers et al., 2011, Turpie et al., 2008, Urgenson et al., 2013, van Wilgen et al., 2011, Woodworth, 2006). The veritable political 'regime shift' at the end of Apartheid facilitated the alignment of multiple ideas and interests that made it possible to conceive of – and institutionalize – weedy tree control as an activity for poverty reduction, development, and water resource management.

Type 2B describes a situation where analysts *predict* a plausible major, sudden, and persistent shift in the conceptual realm. For instance, it has been shown that concern over invasive species like acacias is absent or low in South America (Speziale et al., 2012). An analyst might draw on parallels with the South African case mentioned above, or cite an increasing body of regional scientific literature on invasions, or even survey social media on the topic, and predict that the rise of invasion biology as a

globally-accepted body of knowledge would cause a shift in attitudes. Given that attitudes towards non-native and invasive species are tightly linked to ideologies related to national borders or balance in nature, such a shift in attitude might only happen if one stabilizing, interrelated, conglomerate of ideologies switches to another one.

Finally, **Type 2C** describes the use of the regime shift concept not to predict, but to *articulate a 'wished-for' change* in the political or ideological context with respect to acacia landscapes. Discussions with stakeholders in many of the acacia landscapes described earlier reveal normative framings of future changes that combine predictive scenarios of change with normative desires for changes in mind-sets, worldviews, and associated policy pathways. Such desires are also expressed in the concluding sections of scientific articles about biological invasions (e.g., Speziale et al., 2012, Low, 2012, Richardson et al., 2015). Where such shifts require relatively major, broad-scale, and consequential changes, they can legitimately be thought about as normative regime shifts. For instance, at a conference on biodiversity and global change attended by the authors in Portugal in 2015, interlocutors spoke of the need for radical rethinking of forest policy that might result in a very different ideological and regulatory space for dealing with acacia landscapes.

The above exercise has shown that the use of the regime shifts notion can be analytical, predictive, and normative, and refer to either the material or conceptual sphere. Each usage is somewhat different, calling on diverse assumptions and forms of explanation. Clarity about the type of usage of regime shift will facilitate better interdisciplinary communication and analysis (Eigenbrode et al., 2007). For instance, it will help researchers to differentiate between actual changes in the landscape (material shifts) and changing perceptions (conceptual shifts) as a basis for analysing feedbacks between these different realms. Or, it will help to make explicit the value judgements implicit in a particular analysis. Adopting a more shared epistemology, and a refined definition of regime shifts, like the one we propose, means that our typology has been able to expand beyond the traditional limits of systems-based viewpoints. Notably, the fact that regime shifts are used for not only material shifts, but also conceptual ones reinforces the need for epistemologies that can cope with different ways of knowing. The fact that we defined regime shifts as large, sudden, persistent changes in interrelated patterns and processes provides questions and points-of-entry for hypothesis making and debates within each of the typologies.

This typology could easily be applied to other social-ecological phenomena, as is not restricted in its validity to acacia landscapes. Take for instance the question of bushfires, where the use of the term 'regime' even has a long-standing tradition. Researchers have described both material and conceptual regime shifts in bushfires. Material shifts might include new management activities or the arrival of a flammable invasive weed. Conceptual shifts include the arrival of colonial anti-fire ideologies in places that used to use fire, or the post-1970s re-acceptance of fire as natural in ecological science. These are applied analytically to historical events, predictively to future trends, or normatively to desired future states (Bowman et al., 2011, Kull, 2004, Pyne, 2009, Taylor et al., 2016).

5. CONCLUSION

Humans – geographers included – communicate what they observe and think using terms, metaphors, and conceptual frameworks; in turn, these concepts structure their analyses (Larson, 2011, Binder et al., 2013, Kueffer and Larson, 2014). The 'regime shifts' idea and related metaphors like 'tipping points' and 'thresholds' are increasingly applied to describe, explain, predict, or seek to influence phenomena at the interface of society and the environment. Yet it is important to tread carefully when applying a concept drawn from systems theory and systems ecology to the social world. The application of systems metaphors to social processes and associated institutions – with all their contradictions, dynamism, flexibilities, power relations, inconsistencies, feelings, and more – can be difficult (Table 1). This explains, in part, the visceral reactions of some social scientists at the sometimes uncritical, un-reflexive adoption of systems concepts by social-ecological systems researchers (Smith and Stirling, 2010, Turner, 2014, Watts, 2011). Hence, we sought to build on the classic systems-based epistemology upon which the regime shift idea is based, and to push its boundaries to make room for more contingency, relativity, and human perception. We defined the regime shift concept in a broader way that still retains the fundamental insights of 'speed, scale, stickiness, and coherence' in describing changes to the patterns, functions, and processes underlying a particular social-environmental phenomenon, but we also defined it so as to acknowledge its context-specificity and its origins as a human conception. It is a *perception* of major, fast, persistent and interconnected changes – to facilitate communication and analysis.

In applying these ideas to society-environment phenomena – in our case to landscapes dominated by non-native acacias – we made several observations. First, we corroborate the value of the 'regime shift' concept as a *communicative tool* for framing, negotiating, and communicating phenomena among diverse experts and actors. In the Anthropocene, with ever more dramatic shifts in society-environment relationships, a term such as this is clearly of broad importance, as the debates over the use of term 'tipping point' in climate science have shown (Russill, 2015). Second, we demonstrate the value of 'regime shift' as an *analytical tool*. The very relativity of the concept forces attention to definitional aspects such as speed, scale, stickiness, and coherence. In addition, creating regime shifts as an analytical category allows for the posing of detailed questions about causality, e.g. between 'regime shifts' in one phenomenon on another. Third, we propose a *framework to specify different kinds of uses of 'regime shift'* in the context of social-environmental phenomena (Figure 1), distinguished by a material-conceptual continuum and by the purpose and temporal moment.

The beauty (and frustration) of terms like 'regime shift' is that, as metaphors and boundary objects, they take on a life of their own and are used in different ways by different people. They are powerful emblems, facilitating communication and analysis, apt for both quantitative models and qualitative narratives. If a particular model of 'regime shifts' is applied without attention to fit, definition, and epistemology – if it is used as a proverbial square peg in a round hole – then it may fall to the wayside, broken, like so many other buzzwords. If, on the other hand, the concept is carefully used to facilitate communication, discussion, prediction and more detailed analysis, it has clear utility. Debates around regime shifts are taking place at the same time as debates about other constructs such as 'novel ecosystems', 'wicked

problems', 'adaptive management', 'ecosystem stewardship' and other challenges relating to managing ecosystems in the 'Anthropocene' (Kueffer and Larson 2014). One can see these all as attempts to create benchmarks and straw men to promote constructive dialogue.

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Appendix 1:

Definitions of 'regime shift' in context of social and/or ecological systems. Based on a selection of articles appearing with search terms 'regime shift' in Web of Science and Google Scholar. Listed in date order.

Source	Type of regime shift being defined	Definition	Key sources cited in article
Scheffer and Carpenter (2003): *TREE*	regime shift in ecosystems	"a sudden dramatic change in nature" (p. 648-650)	Scheffer et al. 2001; Anderson et al. 1999; Mantua et al. 1997; Steele 1998
Kinzig et al. (2006) *Ecology and Society*	regime shifts in social-ecological systems	"shifts in stable states, with internal controls and feedbacks and aggregate characteristics that are profoundly different from those of the original (p. 1, paraphrased)	Scheffer and Carpenter (2003); Folke et al. (2004)
Andersen et al. 2009 *TREE*	ecological regime shifts (review article)	"abrupt changes on several trophic levels leading to rapid ecosystem reconfiguration between alternative states. These shifts are generally thought to be driven by external perturbations (e.g. climatic fluctuations, overexploitation, eutrophication and invasive species) or by the system's internal dynamics, but the exact mechanism is often unclear. " (p49)	Lees et al. 2006
Biggs et al. 2009 *PNAS*	ecological regime shifts (fisheries example)	"Ecological regime shifts are large, abrupt, long-lasting changes in ecosystems that often have considerable impacts on human economies and societies." (p826)	Scheffer et al. 2001; Carpenter 2003
Polasky et al. 2011 *Journal of Environmental Economics and Management*	natural resource stocks (e.g. fisheries)	"changes in interactions between constituent components that cause a shift to different system dynamics… may be difficult to reverse"	[selected] Scheffer (1997), Carpenter (2003), Perrings and Walker (1997); Hughes et al. (2003); Gladwell (2000); Scheffer et al. (2001); Guo et al. (2005)
Westley et al. 2011 *Ambio*	transitions between regimes (social and technical innovations for environmental sustainability)	"Regimes are the dominant rule-sets supported by incumbent social networks and organizations and embedded in dominant artifacts and prevailing infrastructures, of say, particular industries or social problem arenas." Transitions (they don't use the term regime shifts) imply "a non-linear process of change in which, after passing critical thresholds, elements of a previously dominant regime recombine with successful niches into a new dynamically stable configuration" (p. 767-768)	Walker et al. 2004; Folke et al. 2010; Geels and Schot 2007; Markard and Truffer 2008; Romans and Loorbach 2009]
Gee and Burkhard 2012 *Resilience and the Cultural Landscape* (Cambridge Univ. Press)	social-ecological regime shifts (example of off-shore wind farms)	"shifts that propel social-ecological systems to another state… they occur when certain system thresholds are crossed and the fundamental internal controls and feedbacks of the system are altered in such a way that the system cannot return to its original state… Regime shifts involve a cascade of effects, with numerous thresholds being crossed in the process across domains…	Folke et al. 2002; Scheffer and Carpenter 2003

		Even minor perturbations in one part of the system, therefore, can trigger a chain of events that irretrievably alters the identity of the social-ecological system." (187-188)	
Vandermeer and Perfecto 2012, *Ecology and Society*	(agricultural transformations)	"tendency of ecosystems that may appear to be quite stable and homeostatic to suddenly change dramatically into a completely different state that then begins to look quite stable and homeostatic" (p1) non-linear changes between different 'syndromes' (*longue durée* "modes and tempos" of agriculture "within which a kind of social-technological homeostasis can be recognized")	Beddoe et al. 2009; Scheffer 2009
Wrathall 2012 *Human Ecology*	social-ecological system (coastal villages, flooding, migration)	sudden non-linear transitions in couple human-natural systems	Folke et al. 2004; Kinzig et al 2006 and more.
Lade et al. (2013) *Theoretical Ecology*	social regime shift	"as not (necessarily) a political regime change but rather any recognisably sudden, large and persistent change in the behaviour of relevant actors." (p359)	Scheffer et al. 2001, 2009; Biggs et al. 2012a)
de Zeeuw 2014 *Annual Review of Resource Economics*	natural resources (economic analysis)	large, abrupt, and persistent changes in structure and functioning of ecosystem.	Scheffer 1997; Carpenter 2003; Hughes et al. 2003; Stern 2007, Lenton et al. 2008, Biggs et al. 2012…
Gaertner et al. (2014) *Diversity and Distributions*	regime shifts (caused by invasive species on ecosystems)	"altered states of ecosystem structure and function that are difficult or impossible to reverse". They are "large, often abrupt, changes in ecosystem structure and function associated with a reorganization of the internal feedback mechanisms…. Regime shifts either occur due to a change in the balance between existing feedbacks in the system or the introduction of new feedbacks to the system…. regime shifts are often hysteretic or 'sticky': once the system is in a particular regime, it tends to remain there even if the exogenous drivers that caused the shift are reduced or removed" (733, 734)	Scheffer et al., 2001, 2012; Rietkerk et al., 2004; Bennett et al., 2005
Leadley et al. 2014 *BioScience*	ecological, socio-economic, and biophysical systems (Review)	regime shifts are "are characterized by rapid shifts in the state of the system that are difficult to reverse" (p665) "Socioeconomic regime shifts are related to the vulnerabilities, adaptive capacities, and transformative capabilities of societies in the face of local and global pressures" (p667)	Folke et al. 2004; Scheffer 2009
Müller et al. 2014 *Global Environmental Change*	(land systems)	Sudden system change to an alternate state when critical thresholds are crossed. p. 76 continues: "We define a land-system regime as a quasi-equilibrium phase during which a land system remains relatively stable.... Land systems can reside in a regime for a long time; however, they can also undergo abrupt and unexpected state shifts that are persistent and difficult to reverse. During the transitional period between two regimes, feedback and	Biggs et al. 2009; Scheffer et al. 2001

		interactions within the land system are reconstructed and reorganized. We define this process as a regime shift in land systems, in analogy with a regime shift in ecosystems"	
Sakamoto 2014 *Journal of Environmental Economics and Management*	resource management (from economic perspective)	sudden and drastic changes in the underlying regimes of complex dynamic systems	Scheffer et al. 2001, Scheffer and Carpenter 2003, Folke et al. 2004
Aoki 2015 *Theoretical Population Biology*	prehistoric cultural regime shifts	abrupt, hysteretic switch between alternative stable states/regimes	Lee 1986, Richerson and Boyd 2013, Ghirlanda and Enquist, Scheffer and Carpenter 2013
Strunz 2015 *Ecological Economics*	the German energy transition (technological, political, economic)	"If a regime's resilience decreases, it becomes prone to disturbances and possible shifts to another regime"	Walker et al. 2004; Holling 1973; Scheffer et al. 2001

Appendix 2:
Case studies of social-ecological regime shifts in acacia landscapes

The main paper text, particularly in the section on Typology (including Figure 1), refers to case studies of landscapes around the world with significant presence of Australian acacias. Below, we briefly present background details on these case studies. The discussions vary in length, justified by the availability of descriptions elsewhere in the literature (available for Vietnam, Madagascar, and South Africa, less directly so for Portugal) and by the depth of information needed to make the argument presented in the main article (e.g., cursory references suffice for the South American and Niger/Ethiopia cases).

Northern Portugal

The countryside of Braga and Viana do Castelo districts in northern Portugal (former Minho province) consists of villages, towns, and farm fields in the valleys, with eucalypts and pine production woodlots on hillslopes. Australian acacias (principally *Acacia melanoxylon, A. dealbata*, and *A. longifolia*, with the former two in more inland sites and the latter closer to the coast) grow in the understory and along the edges of these plantations, and as invasive stands promoted by disturbance such as fire or harvesting in these plantations with no subsequent management.

This landscape marks a clear shift from what one would have encountered seventy years ago. At that point, the hills were dominated by grassland and scrub vegetation, with scattered stands of oak or pine and occasional exotic plantations. Cultivated and uncultivated land were tightly linked in the agro-pastoral production system, with hills widely used for grazing sheep and goats, harvesting firewood for household use, and supplying vegetation (like gorse, heath and broom) used in livestock bedding and compost production (Black, 1990). Today, hillside forestry production is largely decoupled from farming.

A conjuncture of a number of processes has facilitated this transition in land systems. As early as the middle of the 19th century, landowners and foresters introduced and propagated small numbers of eucalypts and acacias for diverse reasons, including curiosity and ornamental use. Concerns over dune erosion, deforestation and soil degradation, together with economic speculation in forest products like timber and tanbark, led to more systematic, but still limited, private plantation attempts by the turn of the last century (Fernandes and Rangan, 2014; Radich and Baptista, 2005). This laid the groundwork for the dramatic later changes in two ways: it familiarized people with the trees, their propagation, and use, and it began to spread acacias and their seeds around the countryside. By 1937, the government had already issued its first legal restrictions on cultivating eucalypts or acacias too close to crop fields or waterways, yet in the 1970s and 1980s the early spring presence of charismatic acacia blossoms was used to promote tourism in the region (Fernandes and Rangan, 2014).

Several specific socio-economic phenomena lay behind the more fundamental shifts of the second half of the 20th century. From the 1930s onwards, and accelerating in the 1950s, the authoritarian government established large-scale forest plantations – particularly of *Pinus pinaster* – on the poor and rocky soils of community lands, and

supported the establishment of a pulp and paper industry. While some local leaders and entrepreneurs benefited, the social marginality of small producers increased. The expansion of the forest plantations led to strict regulations and reductions of grazing and collection of firewood and scrub on the former common hill lands; acacias spread in the understories and edges of such plantations, aided by widespread seed dispersal and periodic fires (Black, 1990; Devy-Vareta, 1980; Fernandes and Rangan, 2014; Lopes et al., 2013; Radich and Baptista, 2005).

From the 1960s into the 1990s, Portugal became increasingly integrated into the European labour market (EEC membership was in 1986), the economy grew rapidly, and rural outmigration both to urban areas and other countries reached unprecedented levels. These forces pushed a process of land abandonment and depopulation in rural areas, with plantation forests and invasive stands continuing to replace marginal pasture and farmland. Private landowners and the pulp companies increasingly turned towards eucalyptus plantations (again, often with acacias appearing in the understory or after fires), particularly as the pulp and paper industry was by then strongly implanted in the region (e.g. the Europac paper mill in Viana do Castelo, with a capacity of 375,000 t/yr)[1] (Black, 1990; Radich and Baptista, 2005; Radich and Monteiro Alves, 2000).

Taking a step back, one can make the case that the demographic, economic, and social structures and processes (feedbacks and flows) of rural Portugal have changed in a fundamental and irreversible way. A dominant physical outcome of these changes is the landscape of eucalyptus and pine plantations peppered with acacia invasions, which itself contributes to the irreversibility of the transformation through changes to fire regimes, soil chemistry, water cycle, and plant community dynamics. This irreversibility is not only biophysical, but also social. For instance, while the 1974 revolution led to the return of the control of common lands to rural municipalities, most municipalities chose to maintain the official forest services as managers of their common land forest assets (Black, 1990; Lopes et al., 2013; Radich and Baptista, 2005). One could argue that the social-ecological memory (Nykvist and von Heland, 2014) of managing the uplands as commons for grazing and thatch was lost.

Vietnam

Approximately 1.1 million hectares of tropical Australian acacias (especially *Acacia auriculiformis* and *A. mangium*) have been planted in Vietnam beginning only two decades ago. This can be seen as emblematic of a currently on-going 'regime shift' in the land system towards profit-oriented, privatized, acacia-based forestry landscapes with intense links to a regional and global wood products industry. It comes after a series of earlier disruptions to 'traditional' peasant agricultural and agro-forestry systems, including colonial plantations and forest appropriations, collectivization and de-collectivization, the nationalization of forests and rampant logging, and wars (McElwee, 2015). The current regime shift, since the 1990s, reflects the coming together of several factors, including reforms to land tenure with increased allocation of land rights to households; an awakening of concern over deforestation and resultant state reforestation programs; and the concomitant restructuring of state forest

[1] http://www.europacgroup.com/EN/LineasNegocio/Papel/Pages/productosyservicios.aspx, consulted 12 June 2015.

enterprises (de Jong et al., 2006; McElwee, 2009; Meyfroidt and Lambin, 2008; Nambiar et al., 2015; Thulstrup et al., 2013; Cochard et al., 2017). Today, many industries, rural entrepreneurs, and poorer villagers alike are dependent on the acacia economy. Vietnam has more than 3000 wood processing companies and exports globally as a top producer of wood furniture and hardwood chips for the pulp industry (Phuc and Canby, 2011).

Highland Madagascar

Authorities distributed the silver wattle (*Acacia dealbata*) widely in the grasslands of central highland Madagascar from 1900 to the 1960s. Their goals included re-greening a perceived degraded landscape, supplying fuel to villagers and the railway, and roadside shade. Villagers soon appropriated the tree for their own woodfuel needs, facilitating its invasive qualities. The species is now ubiquitous above 1200 m altitude, touching an estimated 300,000 ha in various densities (Kull et al., 2008). It makes a valuable contribution to rural subsistence livelihoods (Kull et al., 2011; Kull et al., 2007; Tassin et al., 2009). Villagers heavily exploit spontaneous stands of silver wattle, particularly for domestic woodfuel. In higher altitude zones, where alternative incomes are fewer, farmers seed acacia woodlots for the purpose of charcoal production sold in cities. Acacias also provide fertility, through the use of leaves in compost or field rotations. While the tree has largely been incorporated into 'traditional' livelihoods and landscapes, a regime shift could be envisaged in the future. For instance, if rising incomes permit a switch to alternative energy sources for cooking, and if rural areas begin to depopulate as a result of urban economic growth, then harvesting pressure could reduce, leading to a much larger scale invasion of the landscape.

Niger and Ethiopia

After the devastating 1970s and 1980s droughts and famines, development agencies undertook several trials of Australian acacias in an attempt to assess their potential as woodfuel, as windbreaks, and for land rehabilitation in the Sudano-Sahelian regions (Cossalter, 1986; Kull et al., 2011). These were not particularly successful, yet renewed attempts at promoting Australian acacias from semi-desert regions, such as *Acacia colei* and *A. torulosa*, have taken place in the past two decades through NGO projects. They promote the incorporation of these trees into agroforestry systems with the goal of shielding villagers from environmental shocks like droughts. The trees are planted in order to improve soil fertility, protect against wind, and as resources for making poles or tool handles, and, of course, as woodfuel. Furthermore, acacias are promoted as a source of human food based on the example of Aboriginal Australian communities (Brown et al., 2011; Rinaudo and Cunningham, 2008).

South Africa

Australian acacias were enthusiastically introduced and diffused in South Africa from an early stage (Carruthers et al., 2011; Kull et al., 2011). In the Cape, they were promoted from the early 19th century for fuel, sand stabilisation, and ornamental purposes. Twentieth century concern over the tree-poor country's need for self sufficiency in wood led to government grants, free seeds, and promotion of large-scale woodlots of acacias, eucalypts, and pines (Bennett, 2011; Witt, 2005). At their

peak in 1981, industrial black wattle (*Acacia mearnsii*) plantations covered 146,000 ha, reducing to less than two thirds of this figure today. Widespread plantation and appropriate habitats has lead to problems with invasiveness, and concern over these invasions emerged at a national level by the early 1980s (Bennett, 2014). While acacia woodfuel, charcoal, poles, and planks are important resources for large numbers of poorer South Africans, their negative effects on biodiversity and ecosystem services are widely condemned (Richardson et al., 2011; van Wilgen et al., 2011a).

A dozen acacia species are now listed by the government as "major" or "emerging" invaders. These species are targeted by bio-control programs that release selected pathogens or insects that harm acacia growth or reproduction (de Lange and van Wilgen, 2010; Wilson et al., 2011) and by the environmental management program known as "Working for Water". This program balances multiple goals, including enhancing ecological integrity, water security, and social development (Aitken et al., 2009; Turpie et al., 2008; van Wilgen et al., 2011a). A unique political moment in the country's history led to the alignment of multiple ideas and interests and the initiation of this program. These included the departure of the Apartheid government and beginning of majority rule (in 1994), the new government's priority for poverty alleviation and job creation, and the realization of the impacts of exotic tree plantations and invasions on water resources in a water-scarce country. As a result, in 1995, the government established Working for Water as a public works program that employs marginalized people to clear invasive species that impact on water availability. The program provides waged work, training and education to low-skilled and unemployed people, largely through projects to remove invasive trees from water catchments. The annual budget only somewhat lower than that allocated to parks and conservation, and the program is still running strong 20 years later (van Wilgen et al., 2011b).

South America

Australian acacia landscapes on the South American continent are most prominent in Chile, where widespread forest plantations of *Acacia dealbata* have led to problems of invasiveness (Fuentes-Ramirez et al., 2010), and in Brazil, where some 156,000 hectares of *Acacia mearnsii* are grown for tanbark and pulp (Mochiutti et al., 2008). Yet, social and scientific concern over invasive species in general is low, according to Speziale et al. (2012).

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