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Comment on 'In complexity we trust: learning from the socialist calculation debate for ecosystem management'

Logan Robert Bingham^{1,*} , Lucy Van Kleunen² , Bohdan Kolisnyk³ , Olha Nahorna⁴ ,
Frederico Tupinambá-Simões⁵ , Keith Reynolds⁶ , Rasoul Yousefpour^{7,8} and Thomas Knoke¹ ¹ Technical University of Munich, TUM School of Life Sciences Weihenstephan, Institute of Forest Management, Hans-Carl-von-Carlowitz-Platz 2, Freising 85354, Germany² Department of Computer Science, University of Colorado, Boulder, CO, United States of America³ Department of Silviculture, Institute of Forest Sciences, Warsaw University of Life Sciences, Warsaw, Poland⁴ Faculty of Environmental Sciences and Natural Resource Management, Norwegian University of Life Sciences, Ås, Norway⁵ iuFOR, Sustainable Forest Management Research Institute, University of Valladolid, Palencia, Spain⁶ United States Department of Agriculture, Forest Service Research, Pacific Northwest Research Station, Corvallis, OR, United States of America⁷ Institute of Forestry and Forest Conservation, John H. Daniels Faculty of Architecture, Landscape, and Design, University of Toronto, 33 Willcocks St, Toronto, ON M5S-3B3, Canada⁸ Chair of Forestry Economics and Forest Planning, University of Freiburg, Tennenbacherstr. 4, 79106 Freiburg, Germany

* Author to whom any correspondence should be addressed.

E-mail: logan@tum.de**Keywords:** complexity, uncertainty, ecosystem management, central planning, decision support systems, trade-offs, polycentric governance

Abstract

Using a metaphor based on a historical debate between socialist and free-market economists, Salliou and Stritih (*Environ. Res. Lett.* **18** 151001) advocate for decentralizing environmental management to harness emergent complexity and promote ecosystem health. Concerningly, however, their account seems to leave little room for top-down processes like government-led sustainability programs or centrally-planned conservation initiatives, the cornerstone of the post-2020 biodiversity framework. While we appreciate their call for humbleness, we offer a few words in defense of planning. Drawing on evidence from ecology, economics, and systems theory, we argue that (1) more complexity is not always better; (2) even if it were, mimicking minimally-regulated markets is probably not the best way to get it; and (3) sophisticated decision support tools can support humble planning under uncertainty. We sketch a re-interpretation of the socialist calculation debate that highlights the role of synthesis and theoretical pluralism. Rather than abandoning big-picture thinking, scientists must continue the difficult work of strengthening connections between and across multiple social, ecological, and policy scales.

1. Introduction

If we want to make ecosystems better, how should we conceptualize the role of the manager? In their recent article (henceforth 'the Perspective'), Salliou and Stritih [1] consider (socio-)ecological systems better when they are less fragile, more efficient, and more productive. Using the socialist calculation debate as a metaphor [2, 3], they advocate for a highly localized, hands-off approach to ecosystem management, trusting the combined effect of many independent choices to generate something like the spontaneous order described by the free-market economist Friedrich Hayek. The metaphor suggests that scientists should

redirect their energy away from 'large-scale top-down solutions' to the global sustainability crisis, and focus instead on small-scale processes (p 3). This argument hinges on three propositions: (1) economies and ecosystems are better when they are more complex; (2) complexity cannot be effectively designed, but emerges organically from the aggregation of many independent interactions; and (3) because planning processes are uncertainty-averse, they make systems simpler and therefore worse.

But there is a problem: none of these propositions is quite true. We highlight evidence from ecology, economics, and systems theory indicating that the most complex systems are not necessarily

more stable or productive, but can be inefficient and exceptionally fragile. Next, we point out that ignoring the big picture risks generating an ecologically impoverished ‘emergent simplicity’ in which agents all converge to the same solution. Instead, we suggest uncertainty-integrating techniques from decision science that can support resilience and adaptiveness. Finally, we outline an alternate reading of the calculation debate that emphasizes complementarities between top-down planning and emergent complexity. Scientists must continue the difficult work of strengthening connections across multiple social, ecological, and policy scales.

2. More complexity is not always better

While the era of central planning in Eastern Europe coincided with major advances in economics as scholars grappled with allocation problems in complex dynamic systems [4], its final decades also saw another discipline embroiled in a battle with complexity: ecology. Drawing on findings on the behavior of highly connected systems with gross feedbacks, Robert May [5] famously demonstrated that increasing species diversity could *de*-stabilize some ecosystems. His work sparked a debate [6] about the ecological implications of complexity that remains among the most challenging open issues in our field [7, 8]. Is there a point beyond which increasing complexity can generate not only diminishing, but strongly negative, returns in terms of ecosystem health? If so, what determines this upper bound?

Today, we know that complexity can confer many benefits to ecological communities—but it is not a panacea, either. Its influence on different dimensions of ecosystem health is uneven and context-dependent [9], varying in strength and sign [10, 11] and exhibiting non-linearities across scales [12, 13], including species richness-ecosystem functioning curves that saturate at just a handful of species [14, 15]. Interaction types and network structures vary, and even when they are robust to past disturbances, complex ecological networks can become suddenly fragile when confronted with new threats [8, 16, 17] or destabilize as they disperse across space [7]. And because the effects of introductions cascade through interaction networks, it is often difficult to predict whether they will reinforce or undermine the integrity of a given ecosystem [11, 18, 19]. Thus, attempting to artificially increase complexity can have unintended consequences [13, 20, 21] and entail trade-offs with other desirable system features, like resilience, robustness, or productivity [16, 22–24].

Grassland ecology offers notable empirical examples [25, 26]. Twenty years ago, a widely-cited experiment showed that species-poor grasslands can be more resistant and resilient to drought than species-rich ones [27]—a finding with fresh, if partial, support from Craven *et al* [28]. More recently,

a large-scale study showed that increases in species richness were not only associated with, but actually caused, declines in grassland productivity [29]. The notion that increasing complexity enhances ecosystem health is generally, but not universally, true [30].

The economic implications of ecological complexity are also uncertain [31]. Evidence regarding the impact of biodiversity on crop yield and carbon storage is mixed, and higher biodiversity sometimes reduces the provision of certain ecosystem services [32, 33]. In biocontrol, for instance, more diverse natural enemy communities can be less effective due to intraguild predation and behavioral interference [34, 35]. More generally, the cascade-mediated relationship between biodiversity and economic value exhibits functional forms ranging from positive-convex to negative-concave [36], which has important implications for coupled human-natural systems.

3. Emergent simplicity as a risk of decentralization

The Perspective proposes one simple rule for generating complexity: subsidiarity. It contends that devolving decisions to the smallest possible scale would empower ‘individual ecosystem managers’ to customize management, generating a diverse tapestry of human-nature interactions collectively superior to any top-down solution. Indeed, local communities sometimes do self-organize to sustainably manage common-pool resources, although consensus about essential considerations like scale limits [37], necessary and sufficient conditions [38], and the role of nestedness [39] has proved elusive.

While we agree that leaving leeway for adjustment is important, decentralization is not the whole answer—or even a new one. In reality, landscape mosaics consisting of many small, independently-managed ecosystems are often remarkably homogeneous [40, 41], simply because their ‘ecosystem managers’ are typically private owners like farmers or foresters, who can be conservative in their practices [42], disposed to reactive planning [43], and reluctant to cooperate to overcome collective action problems [44]. Inducing them to deviate from ‘tried-and-true’ (but unsustainable) practices often requires both technical support and financial incentives [45, 46], typically by way of government programs guided by publicly-funded research.

Consider eucalyptus plantations in Portugal [47], even-aged spruce monocultures in Germany [48], livestock-driven deforestation in Brazil [49], or grasslands converted to family-owned corn and soy farms in the US Midwest [50, 51]. Such ecological homogeneity is rarely planned explicitly from the top down. Instead, it represents a kind of ‘emergent simplicity’ wherein agents with similar knowledge and capabilities all encounter the same incentive structure and predictably arrive at the same result. Even if that result

were to support biodiversity within each management unit (α -diversity), replicating it across the landscape can still generate uniformity along other dimensions or scales (e.g. low β - or γ -diversity) [7, 52].

4. Coordination across scales

In holding up free markets as an example for ecosystem management, the Perspective fails to recognize that markets literally—not metaphorically—determine how a large proportion of the terrestrial surface is being managed right now [53–56]. Recently, for instance, one of us showed that national-scale deforestation trends in countries as diverse as Brazil, Indonesia, and the Democratic Republic of the Congo can be reproduced by simulating millions of individual choices by heterogeneous agents making satisficing decisions in response to market signals [57]. Despite its admission that ‘self-organizing markets’ are often ‘ill-suited’ to provide public goods (p. 2), the Perspective puzzlingly skips over the fact that the pervasiveness of public goods problems and transboundary processes has long been one of the defining challenges of environmental management. What does it mean to prescribe subsidiarity as an organizing principle for a set of problems—climate change, ocean acidification, telecoupled deforestation—where ‘the smallest possible scale’ is so often undefined?

Even if we dedicate ourselves to conjuring emergent complexity by abandoning the big picture for the small scale, there is little reason to think that more predatory interests would do the same. When state power recedes in the name of decentralization, major beneficiaries often include local elites and well-financed outsiders, who can find community-level decisions easier to co-opt or subvert than governmental ones [58]. For the same reason that large corporations seek to shape public policy through lobbying, they have also been known to bring asymmetric power to bear on local decision processes, whether to gain license to engage in damaging activities [59, 60], or to protect natural resources from collective degradation by economically-competing smallholders [45].

Our point here is not that bottom-up processes are without merit—only that they cannot be the whole answer. We share the Perspective’s concern that the growing popularity of large-scale modeling work powered by vast datasets sometimes produces results that are difficult to reconcile with realities on the ground, and that overreliance on such a birds-eye view could potentially contribute to heavy-handed policy interventions that ride roughshod over the diverse needs of local communities [61, 62]. But the relationship between macro research and bottom-up processes is not always antagonistic: effective, progressive municipal-level climate action is often spurred by, and capitalizes on, global issue framings that owe their credibility and salience

to birds-eye scholarship [63, 64]. The uncomfortable truth is that different kinds of environmental problems require action at different scales, posing often-messy [64] multilevel, polycentric coordination problems that—despite their many challenges and uncertainties—cannot be made to vanish simply by ignoring them and declining to coordinate at all [65].

At the policy level, we think biodiversity tends to flourish when public bodies intervene to disrupt the emergent simplicity of market-driven homogenization, including through centrally-planned interventions like environmental regulations and energy policies [66], economic incentives to adopt best management practices [67, 68], and diplomatic accords like conservation action plans to support *in, inter,* and *ex situ* genetic repositories [69–71]. At the management level, we agree that the Perspective’s favored ‘hands-off’ restoration strategies (e.g. trophic rewilding, restoring connectivity, etc) are probably underused—but stress that they can involve major interventions [72] and entail trade-offs that may not be visible at small scales. Removing a hydroelectric dam might mean trading global benefits, like reduced carbon emissions, for local ones, like freshwater biodiversity [73, 74]; promoting connectivity in fragmented landscapes can sometimes reduce resilience or the provisioning of ecosystem services [52, 75, 76]. In such cases, planning and coordination across geographic and policy scales are needed.

5. Planning under uncertainty

Environmental management in the Anthropocene demands humility: *inter alia*, leaving margins for error, supporting the capacity of systems to adapt and re-organize, and accommodating local socioeconomic and ecological realities. The Perspective suggests that this problem is too complex to solve, so attempting to chart a top-down course of action based on crude projections can only make things worse. But if complexity must be promoted selectively and decentralization is not a silver bullet, then we must decide when, where, and how to intervene—that is, to plan.

Fortunately, the tools available to ecosystem managers today are more sophisticated than either Gosplan-style material-balance planning or the sprawling linear programming models used to centralize forest planning in the US well into the 1980s [77]. Today’s tools can also be more humble, as decision science continues to innovate adaptive, uncertainty-integrating techniques. Incidentally, some of these tools actually did originate in the kind of loosely-regulated financial markets that fascinated Hayek—just not as avatars of stability-through-complexity. Instead, they were attempts to grapple with the volatility that often accompanies deregulation.

Modern portfolio theory, for instance, uses information about correlations between fluctuating asset values to optimize multi-asset investment decisions under risk [78]. Stochastic programming, a probabilistic technique, aims to balance performance under expected conditions against the need to preserve the future action space in case of unlikely events; some versions can reveal, in advance, the optimal response should such an event occur [79]. Bayesian methods, such as belief networks with updating, use similar probabilities to descriptively model complex systems, including decision-makers [80] and the dynamics of their behaviors over time [81]. If quantitative information is lacking, knowledge-based fuzzy logic networks can support decision-making under uncertainty [82]. And when planners face deep uncertainty—meaning that potential futures can be identified but not ranked by likelihood—robust optimization can be used to identify the best result that can be achieved even in a perfect storm of worst-case conditions or unexpected shifts in social values [83]. These techniques all have growing track records as more humble ecosystem management tools. Appropriately applied, they can help buffer social, economic, and ecological uncertainties [84, 85].

6. A new metaphor for ecosystem management

So far, we have argued that (1) more complexity is not always better, (2) even if it were, mimicking minimally-regulated markets is probably not the best way to get it, and (3) sophisticated decision tools can support humble planning under uncertainty. What does this mean for the socialist calculation debate as a metaphor for ecosystem management?

We think it still offers useful lessons, but a few historical and theoretical clarifications are in order. First, we should abandon the idea that the dissolution of the USSR—an idiosyncratic historical event that unfolded under an immensely complex constellation of sociocultural, economic, and geopolitical circumstances—is attributable to, or offers definitive conclusions for, an academic debate about the theoretical (im)possibility of rational economic planning [86, 87]. Many economists considered the debate closed before the Cold War even began; the premise that the Austrians were proved ‘right’ is controversial among economic historians; both the Marxian and Austrian schools made major concessions; and both are now considered heterodox [2, 3, 86].

Today, mainstream macroeconomics rests on a framework called the new neoclassical synthesis (NNS), which views market competition as powerful but imperfect tool. Market failures are common, for instance, in contexts featuring non-rivalry, non-excludability, externalities, or asymmetric information [88, 89]. The NNS also emphasizes

the volatility of complex systems, which are subject to cyclical fluctuations, real shocks, and contagion [90, 91]. Thus, rather than relegating central authorities to passively providing boundary conditions and enforcing property rights, it assigns them a more active role that includes directly intervening in markets to stabilize them [92]. In behavioral and applied economics, theory is even more pluralistic, embracing constructs like optimization, game theory, and ‘designed’ markets like auctions, while moving beyond rational-actor models to explore how cognitive factors shape economic behavior [93–95]. In short, modern economics is much more than a series of tributes extolling the virtues of deregulation and decentralization; it is a colorful, dynamic discipline deeply interested in how planning and design can structure interactions between agents to enhance social welfare.

The socialist calculation debate, then, should not be read as a Darwinian parable in which one school vanquishes another in a zero-sum game. Instead, its legacy is integration: paradigms that initially appear in diametric opposition are gradually made commensurate through a process of exchange, mutual adjustment, and synthesis, until their core insights are finally assimilated to reinforce a larger and more powerful framework.

And as for economists, so for ecosystem managers: for better or worse, we have to negotiate a shifting balance between top-down and bottom-up processes that often seem to resist one another. Small-scale dynamics and participatory frameworks will continue to play an indispensable role; we should strive to strengthen and accommodate them. But the suggestion that planning and coordination can only make things worse runs contrary to large bodies of scholarship, as well as the scientific consensus on the urgent need for coordinated international action to combat climate change and biodiversity loss [71, 96].

7. Conclusion

Centrally-planned conservation initiatives form the cornerstone of the post-2020 biodiversity framework [97]. We believe that such initiatives need more support, not less. We are concerned that the Perspective’s well-intentioned call for humbleness could instead be interpreted as an argument to do nothing.

In glossing over gray areas in economic history, its metaphor fails to capture the delicate balance that ecosystem management must strike between local and global, mitigation and adaptation, and different components of complexity and ecosystem health. It represents economics and ecology as separate realms, obscuring the reality that they are not only inextricably entwined, but also that this entwinement lies, observably and concretely, at the heart of the global sustainability crisis. The troubling (we think unintended) implication seems to be that we are so utterly helpless against the scale of that crisis that it

would be better to give up on charting a course at all: instead of working on ‘large-scale top-down solutions’, we should each choose our own path and hope it all works out in the end. Cynical actors [96] might find this reading appealing and cite it to undermine government-led sustainability initiatives or to scientifically legitimize dangerous arguments for deregulation and the privatization of nature.

We hope that our comment can offer a countervailing view. In a telecoupled world facing accelerating anthropogenic disturbance, promoting devolution based on *laissez-faire* capitalism is inadequate to safeguard the environment. So in keeping with the legacy of the calculation debate—and, we think, the larger spirit of the Perspective—we call for embracing synthesis, heterogeneity, and theoretical pluralism, from the top down and from the bottom up. Rather than abandon the big picture, we must continue the difficult work of strengthening connections across scales while investing in tools that can enable us to plan humbly, foster adaptive decisions, and leave space for self-organization—just without placing too much faith in the invisible hand of a fickle emergent complexity.

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ORCID iDs

Logan Robert Bingham  <https://orcid.org/0000-0003-2423-9676>

Lucy Van Kleunen  <https://orcid.org/0000-0003-4422-712X>

Bohdan Kolisnyk  <https://orcid.org/0000-0002-6043-3049>

Olha Nahorna  <https://orcid.org/0000-0002-5497-0315>

Frederico Tupinambá-Simões  <https://orcid.org/0000-0002-4634-5341>

Keith Reynolds  <https://orcid.org/0000-0002-5286-4754>

Thomas Knoke  <https://orcid.org/0000-0003-0535-5946>

References

- [1] Salliou N and Stritih A 2023 In complexity we trust: learning from the socialist calculation debate for ecosystem management *Environ. Res. Lett.* **18** 051001
- [2] O'Neill J 1996 Who won the socialist calculation debate? *Hist. Politech. Thought* **17** 431–42
- [3] Camarinha Lopes T 2021 Technical or political? The socialist economic calculation debate *Camb. J. Econ.* **45** 787–810
- [4] Gardner R 1990 LV Kantorovich: the price implications of optimal planning *J. Econ. Lit.* **28** 638–48
- [5] May R M 1972 Will a large complex system be stable? *Nature* **238** 413–4
- [6] Pimm S L T 1984 S The complexity tability of ecosystems *Nature* **307** 321–6
- [7] Baron J W and Galla T 2020 Dispersal-induced instability in complex ecosystems *Nat. Commun.* **11** 6032
- [8] Stone L 2018 The feasibility and stability of large complex biological networks: a random matrix approach *Sci. Rep.* **8** 8246
- [9] Pennekamp F, Pontarp M, Tabi A, Altermatt F, Alther R, Choffat Y, Fronhofer E A, Ganesanandamoorthy P, Garnier A and Griffiths J I 2018 Biodiversity increases and decreases ecosystem stability *Nature* **563** 109–12
- [10] Landi P, Minoarivelo H O, Brännström Å, Hui C and Dieckmann U 2018 Complexity and stability of ecological networks: a review of the theory *Pop. Ecol.* **60** 319–45
- [11] Maynard D S, Crowther T W and Bradford M A 2017 Competitive network determines the direction of the diversity–function relationship *Proc. Natl Acad. Sci.* **114** 11464–9
- [12] Gonzalez A, Germain R M, Srivastava D S, Filotas E, Dee L E, Gravel D, Thompson P L, Isbell F, Wang S and Kéfi S 2020 Scaling-up biodiversity-ecosystem functioning research *Ecol. Lett.* **23** 757–76
- [13] Solé R and Levin S 2022 Ecological complexity and the biosphere: the next 30 years *Phil. Trans. R. Soc. B* **377** 20210376
- [14] Meyer S T *et al* 2018 Biodiversity–multifunctionality relationships depend on identity and number of measured functions *Nat. Ecol. Evol.* **2** 44–49
- [15] Chisholm R A and Dutta Gupta T 2023 A critical Assessment of the biodiversity–productivity relationship in forests and implications for conservation *Oecologia* **201** 1–14
- [16] Strona G and Lafferty K D 2016 Environmental change makes robust ecological networks fragile *Nat. Commun.* **7** 12462
- [17] Qian J J and Akçay E 2020 The balance of interaction types determines the assembly and stability of ecological communities *Nat. Ecol. Evol.* **4** 356–65
- [18] Van Kleunen L B, Peterson K A, Hayden M T, Keyes A, Schwartz A J, Li H and Dee L E 2023 Decision-making under uncertainty for species introductions into ecological networks *Ecol. Lett.* **26** 983–1004
- [19] Hui C and Richardson D M 2019 How to invade an ecological network *Trends Ecol. Evol.* **34** 121–31
- [20] Lusardi R A, Stephens M R, Moyle P B, McGuire C I and Hull J M 2015 Threat evolution: negative feedbacks between management action and species recovery in threatened trout (Salmonidae) *Rev. Fish Biol. Fish* **25** 521–35
- [21] Genovesi P and Simberloff D 2020 De-extinction in conservation: assessing risks of releasing “Resurrected” species *J. Nat. Conserv.* **56** 125838
- [22] Pasqualetti F, Zhao S, Favaretto C and Zampieri S 2020 Fragility limits performance in complex networks *Sci. Rep.* **10** 1774
- [23] Hordijk I, Maynard D S, Hart S P, Lidong M, Ter Steege H, Liang J, De-miguel S, Nabuurs G-J, Reich P B and Abegg M 2023 Evenness mediates the global relationship between forest productivity and richness *J. Ecol.* **111** 1308–26
- [24] Nie S, Zheng J, Luo M, Loreau M, Gravel D and Wang S 2023 Will a large complex system be productive? *Ecol. Lett.* **26** 1325–35
- [25] Schäfer D, Klaus V H, Kleinebecker T, Boeddinghaus R S, Hinderling J, Kandeler E, Marhan S, Nowak S, Sonnemann I and Wurst S 2019 Recovery of ecosystem functions after experimental disturbance in 73 grasslands differing in land-use intensity, plant species richness and community composition *J. Ecol.* **107** 2635–49

- [26] Brun P, Zimmermann N E, Graham C H, Lavergne S, Pellissier L, Münkemüller T and Thuiller W 2019 The productivity-biodiversity relationship varies across diversity dimensions *Nat. Commun.* **10** 5691
- [27] Pfisterer A B and Schmid B 2002 Diversity-dependent production can decrease the stability of ecosystem functioning *Nature* **416** 84–86
- [28] Craven D, Eisenhauer N, Pearse W D, Hautier Y, Isbell F, Roscher C, Bahn M, Beierkuhnlein C, Bönisch G and Buchmann N 2018 Multiple facets of biodiversity drive the diversity–stability relationship *Nat. Ecol. Evol.* **2** 1579–87
- [29] Dee L E, Ferraro P J, Severen C, Kimmel K, Borer E T, Byrnes J, Clark A, Hautier Y, Hector A and Raynaud X 2023 Clarifying the effect of biodiversity on productivity in natural ecosystems with longitudinal data and new methods for causal inference *Nat. Commun.* **14** 2607
- [30] Thibaut L M and Connolly S R 2013 Understanding diversity–stability relationships: towards a unified model of portfolio effects *Ecol. Lett.* **16** 140–50
- [31] Hanley N and Perrings C 2019 The economic value of biodiversity *Annu. Rev. Resour. Econ.* **11** 355–75
- [32] Cardinale B J, Duffy J E, Gonzalez A, Hooper D U, Perrings C, Venail P, Narwani A, Mace G M, Tilman D and Wardle D A 2012 Biodiversity loss and its impact on humanity *Nature* **486** 59–67
- [33] Mehrabi Z, McMillan V E, Clark I M, Canning G, Hammond-Kosack K E, Preston G, Hirsch P R and Mauchline T H 2016 *Pseudomonas* spp. diversity is negatively associated with suppression of the wheat take-all pathogen *Sci. Rep.* **6** 29905
- [34] Crowder D W and Jabbour R 2014 Relationships between biodiversity and biological control in agroecosystems: current status and future challenges *Biol. Control* **75** 8–17
- [35] Laubmeier A N, Rebarber R and Tenhumberg B 2020 Towards understanding factors influencing the benefit of diversity in predator communities for prey suppression *Ecosphere* **11** e03271
- [36] Paul C, Hanley N, Meyer S T, Fürst C, Weisser W W and Knoke T 2020 On the functional relationship between biodiversity and economic value *Sci. Adv.* **6** eaax7712
- [37] Fleischman F, Loken B, Garcia-Lopez G and Villamayor-Tomas S 2014 Evaluating the utility of common-pool resource theory for understanding forest governance and outcomes in Indonesia between 1965 and 2012 *Int. J. Commons* **8** 304–36
- [38] Fleischman F, Ban N, Evans L, Epstein G, Garcia-Lopez G and Villamayor-Tomas S 2014 Governing large-scale social-ecological systems: lessons from five cases *Int. J. Commons* **8** 428–56
- [39] Villamayor-Tomas S, Thiel A, Amblard L, Zikos D and Blanco E 2019 Diagnosing the role of the state for local collective action: types of action situations and policy instruments *Environ. Sci. Policy* **97** 44–57
- [40] Socolar J B, Valderrama Sandoval E H and Wilcove D S 2019 Overlooked biodiversity loss in tropical smallholder agriculture *Conserv. Biol.* **33** 1338–49
- [41] Morteo-Montiel S, Simms S R, Porter-Bolland L and Bonilla-Moheno M 2021 Does the simplification of activity systems produce landscape homogenization? *Environ. Dev. Sustain.* **23** 5695–714
- [42] Wongnaa C A and Babu S 2020 Building resilience to shocks of climate change in Ghana's cocoa production and its effect on productivity and incomes *Technol. Soc.* **62** 101288
- [43] Blennow K, Persson J, Gonçalves L M S, Borys A, Dutcă I, Hynynen J, Janeczko E, Lyubenova M, Merganič J and Merganičová K 2020 The role of beliefs, expectations and values in decision-making favoring climate change adaptation—implications for communications with European forest professionals *Environ. Res. Lett.* **15** 114061
- [44] Villamayor-Tomas S, Sagebiel J, Rommel J and Olschewski R 2021 Types of collective action problems and farmers' willingness to accept agri-environmental schemes in Switzerland *Ecosyst. Serv.* **50** 101304
- [45] Bingham L R 2021 Vittel as a model case in PES discourse: review and critical perspective *Ecosyst. Serv.* **48** 101247
- [46] Palm-Forster L H and Messer K D 2021 Experimental and behavioral economics to inform agri-environmental programs and policies *Handbook of Agricultural Economics* vol 5 (Elsevier) pp 4331–406
- [47] Nunes L J R, Meireles C I R, Pinto Gomes C J and de Almeida Ribeiro N M C 2019 Socioeconomic aspects of the forests in Portugal: recent evolution and perspectives of sustainability of the resource *Forests* **10** 361
- [48] Jansen S, Konrad H and Geburek T 2017 The extent of historic translocation of Norway spruce forest reproductive material in Europe *Ann. For. Sci.* **74** 1–17
- [49] Schneider C, Coudel E, Cammelli F and Sablayrolles P 2015 Needs to end deforestation: insights for REDD+ in São Felix Do Xingu (Pará, Brazil) *Int. For. Rev.* **17** 124–42
- [50] Wright C K and Wimberly M C 2013 Recent land use change in the western corn belt Threatens Grasslands and Wetlands *Proc. Natl Acad. Sci.* **110** 4134–9
- [51] Socolar Y, Goldstein B R, de Valpine P and Bowles T M 2021 Biophysical and policy factors predict simplified crop rotations in the US Midwest *Environ. Res. Lett.* **16** 054045
- [52] Birkhofer K, Andersson G K, Bengtsson J, Bommarco R, Dänhardt J, Ekbom B, Ekroos J, Hahn T, Hedlund K and Jönsson A M 2018 Relationships between multiple biodiversity components and ecosystem services along a landscape complexity gradient *Biol. Conserv.* **218** 247–53
- [53] Winkler K, Fuchs R, Rounsevell M and Herold M 2021 Global land use changes are four times greater than previously estimated *Nat. Commun.* **12** 1–10
- [54] Radwan T M, Blackburn G A, Whyatt J D and Atkinson P M 2021 Global land cover trajectories and transitions *Sci. Rep.* **11** 1–16
- [55] Liao C, Nolte K, Sullivan J A, Brown D G, Lay J, Althoff C and Agrawal A 2021 Carbon emissions from the global land rush and potential mitigation *Nat. Food* **2** 15–18
- [56] Riggio J, Baillie J E, Brumby S, Ellis E, Kennedy C M, Oakleaf J R, Tait A, Tepe T, Theobald D M and Venter O 2020 Global human influence maps reveal clear opportunities in conserving Earth's remaining intact terrestrial ecosystems *Glob. Change Biol.* **26** 4344–56
- [57] Knoke T, Hanley N, Roman Cuesta R, Groom B, Venmans F and Paul C 2023 Trends in tropical forest loss and the social value of emission reductions. *Nat. Sustain.* **2** 6 1373–84
- [58] Buchy M and Maconachie R 2014 Exclusionary spaces: power, poverty and community-based natural resource management in West Africa *Governance for Justice and Environmental Sustainability: Lessons across Natural Resource Sectors in Sub-Saharan Africa* (Routledge) pp 94–109
- [59] Tindall D B, Howe A C and Mauboulès C 2021 Tangled roots: personal networks and the participation of individuals in an anti-environmentalism counter-movement *Soc. Perspect.* **64** 5–36
- [60] Walker P A and Hurley P T 2004 Collaboration derailed: the politics of “Community-Based” resource management in Nevada County *Soc. Nat. Resour.* **17** 735–51
- [61] Bingham L R, Jarisch I, Quaa M F and Knoke T 2023 How to discount monetized ecosystem services—comment on ‘High economic costs of reduced carbon sinks and declining biome stability in Central American forests’ (<https://doi.org/10.2139/ssrn.4473258>)
- [62] Ravikumar A, Uriarte E C, Lizano D, Farré A M L and Montero M 2023 How payments for ecosystem services can undermine indigenous institutions: the case of Peru's Ampiyacu-Apayacu watershed *Ecol. Econ.* **205** 107723
- [63] Oseland S E 2022 Lifting the fog of oil? Exploring the framing of ambitious local climate politics in an oil city *Geogr. Ann. B* **104** 327–40
- [64] Neij L and Heiskanen E 2021 Municipal climate mitigation policy and policy learning—a review *J. Clean Prod.* **317** 128348

- [65] Lubell M and Morrison T H 2021 Institutional navigation for polycentric sustainability governance *Nat. Sustain.* **4** 664–71
- [66] Nemet G F, Grubler A and Kammen D M 2016 Countercyclical energy and climate policy for the US *Wiley Interdiscip. Rev. Clim. Change* **7** 5–12
- [67] Piñeiro V et al 2020 Review on incentives for adoption of sustainable agricultural practices and their outcomes *Nat. Sustain.* **3** 809–20
- [68] Ricigliano V A, Mott B M, Maes P W, Floyd A S, Fitz W, Copeland D C, Meikle W G and Anderson K E 2019 Honey bee colony performance and health are enhanced by apiary proximity to US Conservation Reserve Program (CRP) lands *Sci. Rep.* **9** 1–11
- [69] Corlett R T 2023 Achieving zero extinction for land plants *Trends Plant Sci.* **28** 913–23
- [70] Kueffer C and Kaiser-Bunbury C N 2014 Reconciling conflicting perspectives for biodiversity conservation in the Anthropocene *Front. Ecol. Environ.* **12** 131–7
- [71] Scheffers B R and Pecl G 2019 Persecuting, protecting or ignoring biodiversity under climate change *Nat. Clim. Change* **9** 581–6
- [72] Perino A, Pereira H M, Navarro L M, Fernández N, Bullock J M, Ceaşu S, Cortés-Avizanda A, van Klink R, Kuemmerle T and Lomba A 2019 Rewilding complex ecosystems *Science* **364** eaav5570
- [73] Castro-Díaz L, García M A, Villamayor-Tomas S and Lopez M C 2023 Impacts of hydropower development on locals' livelihoods in the Global South *World Dev.* **169** 106285
- [74] Schmitt R J, Kittner N, Kondolf G M and Kammen D M 2021 Joint strategic energy and river basin planning to reduce dam impacts on rivers in Myanmar *Environ. Res. Lett.* **16** 054054
- [75] Mitchell M G, Suarez-Castro A F, Martinez-Harms M, Maron M, McAlpine C, Gaston K J, Johansen K and Rhodes J R 2015 Reframing landscape fragmentation's effects on ecosystem services *Trends Ecol. Evol.* **30** 190–8
- [76] Shinneman D J, Germino M J, Pilliod D S, Aldridge C L, Vaillant N M and Coates P S 2019 The ecological uncertainty of wildfire fuel breaks: examples from the sagebrush steppe *Front. Ecol. Environ.* **17** 279–88
- [77] Martell D L, Gunn E A and Weintraub A 1998 Forest management challenges for operational researchers *Eur. J. Oper. Res.* **104** 1–17
- [78] Markowitz H M 2010 Portfolio theory: as I still see it *Annu. Rev. Finance Econ.* **2** 1–23
- [79] Ferreira L, Constantino M, Borges J G, Garcia-Gonzalo J and Barreiro S 2016 A climate change adaptive dynamic programming approach to optimize eucalypt stand management scheduling: a Portuguese application *Can. J. For. Res.* **46** 1000–8
- [80] Strith A, Rabe S-E, Robaina O, Grêt-Regamey A and Celio E 2020 An online platform for spatial and iterative modelling with Bayesian networks *Environ. Model. Softw.* **127** 104658
- [81] Yousefpour R, Temperli C, Bugmann H, Elkin C, Hanewinkel M, Meilby H, Jacobsen J B and Thorsen B J 2013 Updating beliefs and combining evidence in adaptive forest management under climate change: a case study of Norway spruce (*Picea Abies* L. Karst) in the Black Forest, Germany *J. Environ. Manage.* **122** 56–64
- [82] Gonzalez-Olabarria J R, Reynolds K M, Larrañaga A, Garcia-Gonzalo J, Busquets E and Pique M 2019 Strategic and tactical planning to improve suppression efforts against large forest fires in the Catalonia region of Spain *For. Ecol. Manage.* **432** 612–22
- [83] Hörl J, Keller K and Yousefpour R 2020 Reviewing the performance of adaptive forest management strategies with robustness analysis *For. Policy Econ.* **119** 102289
- [84] Radke N, Keller K, Yousefpour R and Hanewinkel M 2020 Identifying decision-relevant uncertainties for dynamic adaptive forest management under climate change *Clim. Change* **163** 891–911
- [85] Chreptun C, Ficko A, Gosling E and Knoke T 2023 Optimizing forest landscape composition for multiple ecosystem services based on uncertain stakeholder preferences *Sci. Total Environ.* **857** 159393
- [86] Denis A 2015 Economic calculation: private property or several control? *Rev. Politech. Econ.* **27** 606–23
- [87] Caplan B 2004 Is socialism really “Impossible”? *Crit. Rev.* **16** 33–52
- [88] Sinn H-W 1997 The selection principle and market failure in systems competition *J. Public Econ.* **66** 247–74
- [89] Tirole J 2015 Market failures and public policy *Am. Econ. Rev.* **105** 1665–82
- [90] De Vroey M and Duarte P G 2013 In search of lost time: the neoclassical synthesis *BE J. Macroecon.* **13** 965–95
- [91] Justiniano A, Primiceri G E and Tambalotti A 2010 Investment shocks and business cycles *J. Monet. Econ.* **57** 132–45
- [92] Goodfriend M and King R G 1997 The new neoclassical synthesis and the role of monetary policy *NBER Macroecon. Annu.* **12** 231–83
- [93] Davis J B 2008 The turn in recent economics and return of orthodoxy *Camb. J. Econ.* **32** 349–66
- [94] Ross D 2022 Economics is converging with sociology but not with psychology *J. Econ. Methodol.* **30** 135–56
- [95] Bingham L R, Da Re R and Borges J G 2021 Ecosystem services auctions: the last decade of research *Forests* **12** 578
- [96] Lees A C, Attwood S, Barlow J and Phalan B 2020 Biodiversity scientists must fight the creeping rise of extinction denial *Nat. Ecol. Evol.* **4** 1440–3
- [97] Meng Z, Dong J, Ellis E C, Metternicht G, Qin Y, Song X-P, Löfqvist S, Garrett R D, Jia X and Xiao X 2023 Post-2020 biodiversity framework challenged by cropland expansion in protected areas *Nat. Sustain.* **6** 1–11