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PHILOSOPHICAL TRANSACTIONS B

royalsocietypublishing.org/journal/rstb

Research

Cite this article: Lavorel S, Locatelli B, Colloff MJ, Bruley E. 2020 Co-producing ecosystem services for adapting to climate change. *Phil. Trans. R. Soc. B* **375**: 20190119.
http://dx.doi.org/10.1098/rstb.2019.0119

Accepted: 14 September 2019

One contribution of 20 to a theme issue 'Climate change and ecosystems: threats, opportunities and solutions'.

Subject Areas:
ecology

Keywords:
ecosystem-based adaptation, ecosystem service trade-offs, adaptation pathway, transformation, socio-ecological dynamics, values-rules-knowledge

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Electronic supplementary material is available online at https://doi.org/10.6084/m9.figshare.c.4782609.

THE ROYAL SOCIETY PUBLISHING

Co-producing ecosystem services for adapting to climate change

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Ecosystems can sustain social adaptation to environmental change by protecting people from climate change effects and providing options for sustaining material and non-material benefits as ecological structure and functions transform. Along adaptation pathways, people navigate the trade-offs between different ecosystem contributions to adaptation, or adaptation services (AS), and can enhance their synergies and co-benefits as environmental change unfolds. Understanding trade-offs and co-benefits of AS is therefore essential to support social adaptation and requires analysing how people co-produce AS. We analysed co-production along the three steps of the ecosystem cascade: (i) ecosystem management; (ii) mobilization; and (iii) appropriation, social access and appreciation. Using five exemplary case studies across socio-ecosystems and continents, we show how five broad mechanisms already active for current ecosystem services can enhance co-benefits and minimize trade-offs between AS: (1) traditional and multi-functional land/sea management targeting ecological resilience; (2) pro-active management for ecosystem transformation; (3) co-production of novel services in landscapes without compromising other services; (4) collective governance of all co-production steps; and (5) feedbacks from appropriation, appreciation of and social access to main AS. We conclude that knowledge and recognition of co-production mechanisms will enable pro-active management and governance for collective adaptation to ecosystem transformation.

This article is part of the theme issue 'Climate change and ecosystems: threats, opportunities and solutions'.

1. Introduction

Accelerating global change is placing human societies under increasing pressure to adapt, i.e. to moderate or avoid harm, or to exploit beneficial opportunities in order to maintain their livelihoods and good quality of life. The capacity of ecosystems to support social adaptation (underlined terms are defined in the Glossary (box 1)) has been recognized through emerging concepts of ecosystem-based adaptation, ecosystem-based disaster risk reduction and adaptation services (AS) considered as nature-based solutions (reviewed by [12]). These concepts share the central theme that ecosystems, typically when in good condition, can sustain people's efforts to adapt to environmental change by regulating risks from climate change and natural hazards, and providing options for sustaining material and non-material benefits [16]. They have been operationalized to support conservation, management and restoration of ecosystems, with improved options for livelihoods and buffering of detrimental impacts of climate change, while also providing benefits to biodiversity conservation. However, it is challenging to achieve these multiple goals simultaneously, and trade-offs and co-benefits among them are at the core of adaptation. Transformative adaptation is a fundamental, system-wide reorganization across technological, economic and

Box 1. Glossary.

Adaptive capacity: the ability of a system (human, natural or managed) to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with consequences [1].
Adaptation: the process of adjustment to actual or expected climate and its effects. Climate change adaptation is the ability of a society or a natural system to adjust to the (changing) conditions that support life in a certain climate region, including weather extremes in that region [2]. Social adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects.
Adaptation service (AS): ecosystem process or ecosystem service (ES) providing benefits to people by increasing their ability to adapt to environmental change especially, though not exclusively, driven by climate change [3,4].
Adaptation option: a possible measure or action that can be implemented to improve social adaptation to climate (or other environmental) change).
Adaptation strategy: a deliberate set of adaptation options to reach a specific goal or vision underpinned by a conceptual framework of adaptation.
Adaptation pathway: course of action to reach visions from the current socioecosystem according to biophysical and social drivers of change [5] expressed as a set of sequenced adaptation actions based on alternative, uncertain developments over time [5].
Ecological/ecosystem resilience: the ability for an ecosystem to reorganize in the face of disturbance to remain in a similar state in terms of structure, functions and feedbacks [6].
Ecological/ecosystem transformation: a shift in underlying biophysical drivers resulting in a new system state and associated ecosystem processes [7].
Ecosystem transformability: an ecosystem's capacity to reorganize as a fundamentally different system in terms of structure, functions and feedbacks when disturbance makes the current state untenable [6].
Co-production: the input of citizens in the production of public goods [8]. In ES science, co-production is the interplay of natural and human-derived capitals for producing ESs [9,10].
Incremental adaptation: Adaptation actions where the central aim is to maintain the essence and integrity of a system or process at a given scale. Incremental adaptation involves marginal changes to 'business as usual' [11].
Nature-based solution (NBS): 'actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits'. Nature-based solutions involve three types of actions, which may be combined at regional and local level: (i) preserving the integrity and good ecological status of ecosystems; (ii) improving sustainable management of ecosystems used by human activities; and (iii) restoring degraded ecosystems or creating ecosystems [12].
Transformative adaptation: social/socio-ecological transformation: responses to observed or anticipated changes in environmental and social drivers that fundamentally change the properties and functions of a social-ecological system, including paradigms and world views, visions and goals, values and rules [13–15]
Window of agency: critical time window where agency plays out to inflect the trajectory of a socio-ecological system towards a given vision [5].

social factors, including paradigms, goals and values. It requires resolving current socio-ecological trade-offs, considering potential new trade-offs under adaptation and increasing future synergies and co-benefits. This paper tackles this critical gap by analysing fundamental mechanisms that foster trade-offs and co-benefits among AS.

AS are the ecosystem processes and ecosystem services (ES) that provide benefits to people by increasing their ability to adapt to environmental change especially, though not exclusively, driven by climate change [3,4]. Benefits can accrue from an ecosystem maintained in its current state or from new options created when an ecosystem structure and functions inevitably transform in response to altered climate or other factors, such as changed species dominance following altered disturbance regimes (e.g. fire or flooding) or invasion by an exotic species (figure 1). For example, throughout Africa, rangeland invasion by exotic *Prosopis* trees stabilizes soils and supports new activities of fuelwood charcoal collection [17]. Based on whether they are supported by ecosystems that persist or transform under climate change, and how their benefits are realized to reduce risks to livelihoods by creating new options, AS can be recognized as five types [18] (figure 1): (i) *ecological resilience* properties that support the persistence of current ecosystems and their services and (ii) their *latent ES* whose value is revealed for social adaptation (e.g. for mitigating new risks like storm surges or flash floods); (iii) ecological properties that underpin ecosystem *transformability* (e.g. functionally diverse species pools and landscape connectivity), which supports: (iv) *sustained supply* of existing ES from persisting or transformed ecosystems (e.g. increased food production through colonization by more productive grassland, tree or fish species) and (v) *novel ES*, emerging under new biophysical and social contexts (e.g. novel crops or construction of cultural values for new forests). This definition is consistent with the ES concept, but additionally includes ecological mechanisms that support ecosystem persistence or transformation and focuses on developing, evaluating and implementing options for adaptation [19]. Different AS are mobilized sequentially or cumulatively along adaptation pathways: ecological resilience, latent and sustained ES are essential in early stages of adaptation while the use and values of ecosystem transformability and novel ES build up as environmental changes intensify [13,18].

As with ES [20,21], the AS concept implies trade-offs and co-benefits that need to be made explicit if adaptation options are to be realized within adaptation strategies and along adaptation pathways. Increasing our understanding of trade-offs and co-benefits among AS, and between AS and current ES

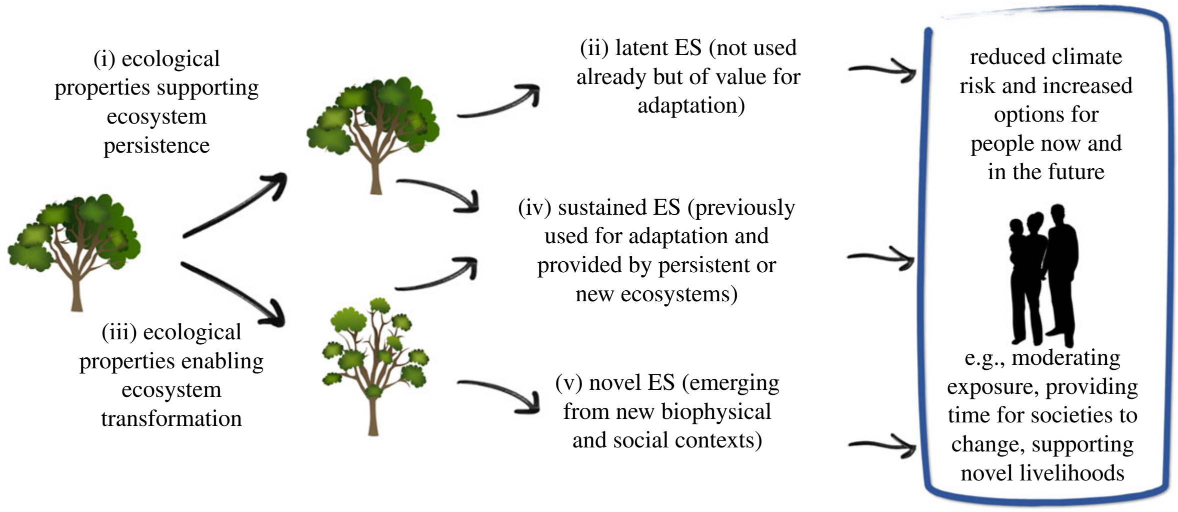

Figure 1. Typology of AS. (Online version in colour.)

is thus essential, and especially exploring the complex ecological mechanisms and management effects involved in AS supply trade-offs [22]. As a first prevailing mechanism, because climate change alters the relationship between ecosystem drivers and services, it directly or indirectly shifts ecosystems towards trade-offs in functions and services (e.g. via changes in soil resources or disturbance regimes). In temperate grasslands, drying climate shifts vegetation and soils towards more resource-conservative states. These favour drought resistance but lower productivity, and current regulating services (e.g. soil nutrient and carbon retention) at the expense of some cultural or pollination services associated with more resource-abundant and species-rich states [23]. Likewise, montane forests structured by frequency and intensity of wildfire can transform from dominance by obligate seeder species to resprouter species, with the reduced supply of quality timber and lower cultural, heritage, spiritual and tourism values [24].

Secondly, ecological properties that support ecological resilience and transformability such as patch-scale functional diversity and landscape-scale functional divergence [25] can provide co-benefits for production [26] and resilience to climate variability at the farm- or catchment-scale [27]. However, these benefits trade off with the persistence of cultural values of climate-sensitive species (e.g. trees such as mountain ash *Eucalyptus regnans* [24] and yellow cedar *Callitropsis nootkatensis* [28]). Landscape connectivity that supports persistence or transformation of ecosystems via propagule dispersal [4] also benefits those services that depend on lateral flows, such as pollination of current and novel crops and water supply [29]. However, such landscape connectivity may facilitate the spread of invasive weeds, pests and diseases with detrimental impacts on biodiversity.

Thirdly, because ecosystem transformation involves multiple dimensions of structure and function, novel ES from transformed ecosystems interact with other services provided by the previous state, and with other AS. Novel ES may be associated with specialized management, such as the production of new crops facilitated by temperature increase [18] or harvesting of new forest [30]. This may result in trade-offs with the availability of resources to non-human organisms, or with some regulating services. Conversely transformed ecosystems may support multiple benefits like timber and other forest products [31], or new regulation of natural hazards and water flows from advancing tree-lines [32].

Considering ES flows and benefits, trade-offs and co-benefits among AS reflect different demands across stakeholder groups and differences in access to resources [33,34]. New values from latent and novel services typically shift power dynamics and create winners and losers. For example, in Mali, where the transformation of a lake to a forest has shifted power over resource use and access from pastoralists to charcoal producers [30]. Recent advances in social-ecological systems science and practice have formalized the role of individuals, collectives and institutions in ES supply from intangible biodiversity and ecosystem functioning. Ostrom [8] defined co-production as the input of citizens in the production of public goods. ES co-production can be understood as the emergence of benefits from nature to people through multiple, long-term and dynamic socio-ecological interactions and the associated interplay of natural and human-derived capitals [9,10,35].

In this paper, we aim to show how the co-production of AS can actively support social adaptation to climate change by enhancing co-benefits and minimizing trade-offs along adaptation pathways. Indeed co-production is a critical component of adaptation: ecological properties support adaptation only through human input of knowledge, infrastructure, social capital and engagement of institutions [3,18]. We previously distinguished three types of AS co-production [18]: deliberate pro-active management, co-benefits from pro-active adaptation management and benefits from response/adaptation to other drivers. Here, we further propose that trade-offs and co-benefits of AS can be linked to factors involved in their co-production, thereby providing leverage for social adaptation.

In spite of the increasing recognition of the importance of ES co-production for understanding human-nature dynamics [10,36,37], the concept has been little operationalized to date. So far studies have only addressed co-production by considering the varying roles of natural and human-derived capitals across gradients of land or water-use intensity [9,10]. In this paper, to address this conceptual and operational gap, we support our analysis of AS co-benefits and trade-offs by articulating three co-production steps along the ecosystem cascade [33,37] (figure 2). First, management of resources, disturbance regimes and landscape structure enhance the supply capacity of AS by persisting or transformed ecosystems (CP1).

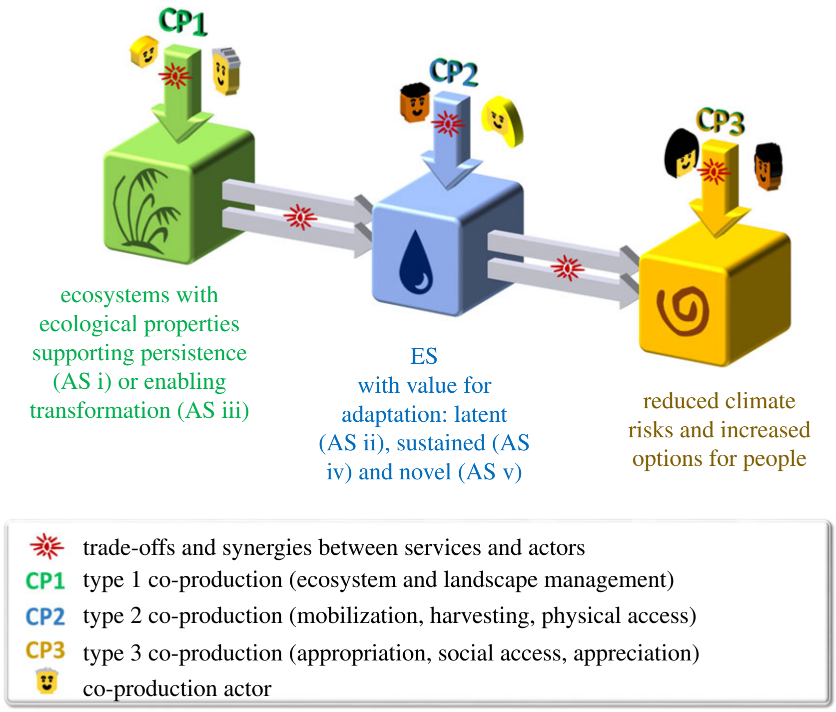

Figure 2. Conceptual framework of the co-production of AS. Three steps of co-production are highlighted along with their links to the five types of AS. (Online version in colour.)

Secondly, ecosystem structure and functions are translated into AS flows because humans mobilize them, typically by harvesting or accessing them physically or immaterially (CP2). Thirdly, AS are transformed into benefits for adaptation by appropriation, social access and/or appreciation (CP3). For example, farmers may manage grassland fertility and functional diversity (including through sowing) to enhance ecological resilience; the ecological property of resilient biomass production becomes an AS of resilient fodder production when grass is harvested in accessible fields; this in turns benefits farmers, given the ability to store and/or trade fodder across years and between farmers. For a novel ES of timber from a tree species with a shifting geographical distribution, local people may facilitate tree growth by reducing interspecific competition and limiting access by livestock; harvesting mature trees delivers timber; this yields a financial benefit that can sustain a community's livelihood if a new market is developed and logs can be transported to buyers.

We applied this analytical framework for the co-production of AS to identify mechanisms fostering their trade-offs and co-benefits using five case studies across continents, climates and social contexts. We expected this analysis to reveal some generic social and ecological mechanisms implicated in AS co-benefits and trade-offs. We developed a set of propositions on five prevalent mechanisms which we illustrate with evidence from our case studies. We end the paper by discussing how this understanding can support adaptation pathways.

2. Material and methods

We applied the three-step co-production analysis to five case studies from our place-based socio-ecological research across five continents (table 1). These case studies are documented cases of adaptation pathways supported by AS, which we use as exemplars. Case studies were selected to cover contrasting social, economic and environmental contexts for the adaptation challenge in the Northern and Southern Hemispheres in temperate and tropical zones, mesic, arid and mountain regions. For each of them, we used our in-depth knowledge and published material for identifying actors and conditions of AS co-production (electronic supplementary material). Specifically, we analysed each of the three co-production steps of a given AS (figure 2) by asking: what are the actions? who are the agents? how are these actions supported, considering as a check-list human, social, financial and manufactured capital? (electronic supplementary material). We then carried out a qualitative, deductive analysis [28] informed by prior knowledge of mechanisms on biophysical and social mechanisms of ES trade-offs and synergies as highlighted above. Qualitative analysis of common or antagonistic factors provided evidence for, respectively, co-benefits or trade-offs of AS.

From this, we developed five propositions on mechanisms of AS trade-offs and co-benefits relating to co-production (figure 3). We do not intend for these to be exhaustive, but rather highlight some common and impacting mechanisms that we understand to determine trade-offs and co-benefits among AS across a variety of social and ecological contexts. We generated the following five propositions. First, we chose to focus on broad mechanisms associated with ecological resilience, ecosystem transformability and novel ES, given that these are the most distinctive as compared to usual ES:

— proposition 1: traditional and multi-functional land/sea management targeting ecological resilience benefits multiple AS and ES;
— proposition 2: pro-active management for ecosystem transformability can avoid trade-offs and enhance co-benefits with other AS and ES by fostering diversified and connected mosaic land/seascapes;
— proposition 3: co-production of novel services is associated with potential trade-offs with other AS and ES that need to be mitigated.

Secondly, we considered two critical elements of adaptation pathways, multi-stakeholder management and feedbacks across co-production stages [46,47]:

— proposition 4: power relationships among actors involved in the management and mobilization of different AS result

Table 1. Main case study characteristics.

case study	location (lat., long.)	climate ecosystems/landscape	land use and livelihoods	relevant climate or environmental changes	ecosystem transformation	adaptation challenges (or vision)	references
French Alps	45.0N, 6.3 E	temperate montane grasslands, conifer forest, high-altitude vegetation	interdependent mountain agriculture and tourism, residential economy	decreased snow season length; increased precipitation variability; melting glaciers	increasing dominance of drought-resistant grassland species, forest colonization	locally sustainable, nature-based tourism and agriculture	[18,38]
Peruvian Andes	13.6S, 72.8 W	tropical montane mountain grasslands, native and exotic forests	mosaic of cropland, pasture and agroforestry in small-scale family farming and, in upper elevation, grasslands, wetlands and rocks	decreasing rainfall, increasing rainfall variability	anthropogenic: crop conversion, overgrazing drought effects on pasture or wetlands; combined effects: drying of wetlands	water availability for domestic & productive uses	[39,40]
Mali (Lake Faguibine)	16.8N, 3.8 W	arid landscape dominated by grasslands and scrublands and *Prosopis* forest in the former lake bed	mobile and sedentary livestock breeding, agriculture, charcoal production	declining river inflows owing to climatic drought and irrigation water use caused decreasing water volume in lake	transformation of lake bed to mesquite and acacia forest	adapting livelihoods to water scarcity & the disappearance of a lake	[30,41]
Indonesia (Kalimantan & Java)	0.6N, 112.2 E & 8.1S, 110.8 E	wet tropical dipterocarp forests with rubber plantations (Kalimantan), crops and planted forests (Java)	rubber, goldmining (Kalimantan), cattle, paid labour (Java), subsistence food crops (both sites)	increased variability of rainfall leading to soil water deficits during rice growing season (Java), floods (mostly Kalimantan)	deforestation and rubber plantation in Kalimantan, reforestation in Java	resilient food production & incomes from forests; reduction of flood risks	[33,42]
Australia (Riverina, Murray Darling Basin)	35.5S, 146 E	semi-arid inland floodplain chenopod shrubland	riverine floodplain, grazing land (sheep)	land clearing caused dryland salinity, combined with rainfall variability and drought	replacement of floodplain woodland with chenopod shrubland. land was abandoned or barely used	sustainable, drought-resistant grazing systems for lamb and wool production	[3,43–45]

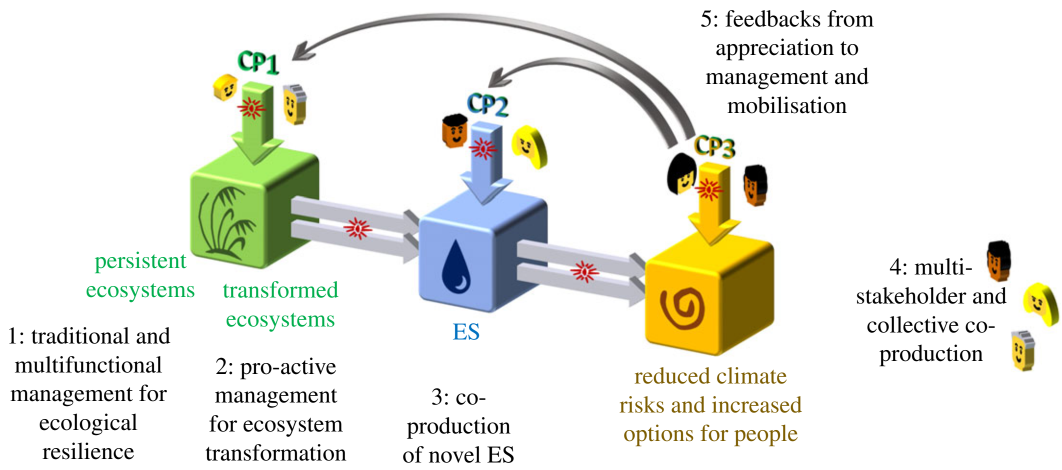

Figure 3. The five broad mechanisms of co-production of AS at three different steps of the ecosystem cascade. (Online version in colour.)

in limitation of options and induce trade-offs among AS, which can be mitigated in part by collective governance; and
— proposition 5: appropriation, appreciation and access to AS feedback into the co-production of other AS and ES.

Below we develop these propositions from generic knowledge on socio-ecological dynamics and provide supporting evidence from our case studies.

3. Results

(a) Traditional and multi-functional management

In the same way as management (CP1) determines synergies across ES [22], management can either target multiple AS or generate co-benefits from one target AS to other AS. Synergies typically occur when ecosystems are managed for resilience, because mechanisms that underpin ecological resilience (e.g. functional redundancy, functional complementarity, role of keystone species, vegetation structural heterogeneity) also contribute to the provision of multiple services [4,48–51].

We expect management based on local knowledge and traditions to foster multiple AS for several reasons. First, traditional management is often at the intermediate intensity of resource inputs and disturbances, which promotes taxonomic and functional diversity, and thus multifunctionality [51–53]. Second, traditional management often promotes heterogeneous landscapes and spatial connectivity, two important properties for multiple ES [4,54,55]. Third, traditional management has been trialled and adjusted over centuries of changing ecological, economic and cultural conditions. Over the long-term, co-production of ES may have evolved towards promoting synergies and limiting trade-offs, and at least some traditional management is foreseen to support future adaptation [56–59]. Fourth, re-vitalizing and re-inventing traditional practices in a contemporary setting is part of adaptation. This is, for instance, the case for livelihood diversification in the Canadian Arctic, based on traditional knowledge and maintaining cultural continuity through the production of art and crafts [60]. As a case in point, some latent ES might be provided by traditional management that is no longer in practice and/or that supported other ES in response to past demands. For example, the value of shade in traditional agroforestry is revealed or increased under climate change [31,56,61].

More broadly, the co-production of AS through multi-functional ecosystem or landscape management (CP1), multi-purpose mobilization (CP2) and appreciation (CP3) is less likely to create trade-offs than co-production through specialized management. In summary, we propose that increased opportunities for adaptation to global change are provided by multi-functional land management because it takes a holistic approach to ecosystem processes and co-production factors which allow the mobilization and appreciation of multiple AS.

In the French Alps mowing and manuring of terraced meadows, a management regime in place since crop conversion to grassland in the nineteenth century, directly supports fodder resilience (AS) along with ES of fodder quantity and quality, and aesthetic value. It also provides co-benefits for the latent ES of erosion control, the persistent ES of supporting identity (traditional terraces attachment) and future expansion of tourism based on nature contemplation (novel ES) [18]. It relies on full- or part-time labour with both traditional and new knowledge and skills. It may incorporate novel technology and innovation for fertilizing and maintaining/upgrading terraces and requires maintenance of access to parcels. In the future, collective terrace management and participation in harvests (CP2) and financing by other residents motivated by attachment to mown terraces and benefits for tourism, may be required. Traditional collective governance already ensures equitable land distribution across farmers and regulates management. The persistence and evolution of this traditional management system will rely on financial capital from sales of agricultural products and from tourism, public subsidies if they are maintained, financial support for young farmers, and loans and/or collective funding for new equipment.

In the Peruvian Andes, ancestral water management encompasses multiple practices, such as canals (*amunas*) transporting water from temporary rainy season streams to grasslands where it infiltrates into soils, recharges aquifer and eventually feeds year-round springs. Such land management (CP1) and water harvesting practices (CP2) have often been abandoned because of rural-to-urban emigration and local economy changes, which have reduced workforce and collective work. With increased water scarcity challenges in the mountains and lowlands, public and private institutions are now investing in reviving ancestral systems for improving water supply during the dry season. This constitutes a latent

AS from the current ecosystem states whose value is revealed for adaptation. Institutions also foster the co-production of this AS through wetland conservation and restoration, because this multi-functional management provides multiple co-benefits for AS: wetlands produce drought-resilient fodder or medicinal plants and store large amounts of carbon.

(b) Pro-active management for ecosystem transformation

The value of ecosystem ability to transform for supporting adaptation has only been recognized recently by considering the possibility that rates and magnitude of ecosystem change may exceed social incremental adaptive capacity [4,47,62], and that novel ecosystems (i.e. novel species assemblages and functioning, sometimes under non-analogue sets of environmental conditions [63]) could support multiple ES and socio-ecological resilience [64]. However, current management can be locked into resisting transformation owing to the community or institutional path-dependency and lack of reflexivity ([65], p. 27). For example, climate-driven changes in fire regimes may require facilitating resprouting tree species over seeders currently favoured by forest managers and conservationists [24,66].

Encouraging landscape or regional functional diversity that underpins ecological transformation ability [25] can trade off with the persistence of current ES provided by single species or functional groups. This may be the case in intensive crop, fodder or timber production systems, fisheries or aquaculture. For this, new production systems [51,67–69], or rekindling traditional management [56], with skills and technology for management (CP1) and harvest (CP2) across diversified, mosaic land/seascapes are needed, along with managing market expectations and creating novel supply chains (CP3). There may also be a trade-off with cultural values of climate-sensitive species, requiring the adaptation of values for appreciating new landscapes [24,28]. As several of these co-production elements overlap with those presented above for ecosystem resilience, latent and novel ES, we expect positive feedbacks with transformation ability.

Managing connectivity for species migration is essential for fostering transformation ability [4]. Realizing the multiple associated gains in ES provided by mobile organisms (pollination, crop pest control, seed dispersal [70]) requires that managers and planners have legitimate mandate and relevant knowledge for conserving, restoring or creating corridors and matrix connectivity, while limiting spread of novel climate-related weeds, pests and diseases with impacts on biodiversity and ES, and thus costs to adaptation [71,72]. The direct benefits for the transformation of increased connectivity [69] and the associated ES risks and co-benefits need to be understood and distributed to diverse stakeholders [73]. As a special case, green corridors in climate-smart landscapes can benefit climate mitigation through carbon sequestration [74]. This co-benefit is increased by knowledge for tree species selection and by knowledge, manpower and financing for hedgerow and forest management (thinning, deadwood) [75]. These can be enhanced through financial support from multi-objective subsidies or payments for multiple ES [76].

While this is an outstanding future challenge, current evidence of pro-active management for transformation is limited. In our case studies, stakeholders derive benefits from ecosystem transformation capacity but have largely not yet acknowledged it as a resource for the co-production of benefits, hence a lack of co-production factors. Nevertheless, in the Riverina, since the 1980s graziers have developed new grazing systems on floodplains that were transformed from floodplain woodlands to saline chenopod shrublands following vegetation clearing in the nineteenth century, and are subject to repeated, prolonged drought. The development of new grazing systems was a response to anthropogenic transformation to a salty, drought-prone, low-productivity ecosystem. Although not designed as pro-active adaptation to climate change, new grazing systems are highly resilient to rainfall variability and drought. Co-benefits for adaptation have been realized via holistic landscape management. This includes initial revegetation of riparian zones for water quality and availability, and planting shrubs to lower saline water tables below the root zone. Subsequently, salt-tolerant grasslands supporting biodiversity and regulating services establish or are restored, and are enhanced by moderate grazing. These approaches have been extended to other saline lands in Australia, with the recognition that sheep grazing can assist in their sustainable management by enhancing biodiversity and ES and by making it commercially viable to rehabilitate degraded land. A constant, dynamic trade-off exists between the need to adjust stocking rates to ensure profitability as landscape carrying capacity changes, while maintaining and enhancing biodiversity and regulating services. This trade-off is mitigated in part by synergies between grazing benefits and biodiversity benefits.

In Java, as a response to rainfall variability, rain-fed croplands were abandoned and reforested with teak and mahogany plantations by farmers facing crop failure. This pro-active management for ecosystem transformation led to improved water regulation, a latent AS with increased value for adapting to droughts. Co-benefits included increased biodiversity, carbon and forest products, whereas trade-offs with crop production were limited given that previous harvests were uncertain.

(c) Co-producing novel ecosystem services

The co-production of novel (and latent) ES may require different and new co-production factors than current and sustained ES. Once novel ES are recognized as an option, they are often co-produced by new single-purpose management actions (CP1), which can lead to trade-offs with other AS for several reasons. First, competition for land (or aquatic/marine areas) and/or manpower (especially skilled) are risks common with any novel activity. Conversely, novel ES may be co-produced and used first by marginalized/vulnerable people, people facing a crisis or people in need of new livelihoods because of their lack of access to other ES or other capitals [30,77]. Secondly, novel ES co-production can favour specialization and land/sea management practices with new knowledge and technology limited to a single production system, and that do not incorporate environmental impacts or impacts on other ES and AS [78]. Thirdly, novel activities may attract preferential allocation of loans or subsidies [79], as opposed to the maintenance of traditional management. Overall, novel ES co-production can shift power relationships through generating and applying new knowledge gained from learning by doing.

In Mali, when a lake dried out and an invasive tree species spread into the former lake bed, novel ES appeared from the new forest. Women from the group with the lowest social status started to harvest wood (CP2) and produce charcoal for trade (CP3), as a strategy for adapting to environmental changes. These women developed new co-production factors such as skills for harvesting (CP2) and processing (CP3) but faced barriers such as the lack of transportation for marketing (CP3). In addition to the charcoal used by women, the novel forest could provide many more AS to more groups of people if other co-production factors (CP2–3) existed, for example, fuelwood to other community members or fodder and shade to livestock herders. In the observed adaptation strategies, AS co-production did not include management (CP1): the novel forest was not managed (e.g. no thinning or back cutting of fringes), so the AS was at risk of not being available or accessible in the long term.

Responding to recent demand in the French Alps, new, intensively managed crops displace extensive grassland/woodland with trade-offs for some regulating ES (regulation of water quality) or latent services of erosion control and carbon sequestration. However, social capital requirements overlap largely with those for the resilience of fodder production and associated AS: collective land allocation (CP1), solidarity and ability to work together (CP1, CP2). Maintenance of access to parcels is also a shared requirement. These shared co-production elements are likely to mitigate trade-offs from competition for land. Technology and innovation for maintaining/upgrading terraces may also benefit both. Direct income from sales may be common: novel products (vegetables, berries, medicinal plants, other…) will be sold to locals and tourists along with more traditional livestock products (meat, cheese) in new shared retail infrastructure (CP3).

The co-production of novel ES through multi-functional land or landscape management is less likely to create trade-offs than co-production through specialized management. For example, in the Riverina, the new grazing system on transformed chenopod shrubland generates novel products and markets and is synergistic with salinity control. The development of sustainable, low-input grazing systems (CP2) supports sustainable wool production and a high-value saltbush sheep and goat meat industry. Within these production systems, graziers have also revegetated salt-affected land with saltland pasture species (CP1). Graziers, with the support of extension services, researchers and government agencies developed knowledge by experimentation and practice of sheep production systems, and knowledge on how to revegetate successfully. These activities are supported by government grants and subsidies. The national Land, Water and Wool Sustainable Grazing on Saline Lands initiative fostered the co-production of new knowledge or novel production systems and acts as a focal group for the coordination of activities (CP1-3).

(d) Multi-stakeholder and collective co-production

Power relationships among actors involved in the management and mobilization of different AS can result in limitation of options and induce trade-offs. This situation may, in particular, apply to latent and novel ES, with the incoming of new players. With this, new social trade-offs and power relationships may create mismatches between the scales at which governance operates and the scales at which AS are produced (CP2) and at which people benefit (CP3) [80]. Trade-offs can be mitigated by adaptive, polycentric governance arrangements that coordinate across scales, strengthen decision-making autonomy and adaptively re-distribute power across scales according to circumstances and issues of concern [81].

For example, in the Riverina, low land values of saline floodplains were a major disincentive to landscape restoration and realization of AS therefrom. However, empowering graziers to produce new knowledge from learning by doing resulted in stronger ownership of ideas and greater adoption of new grazing systems. Graziers were able to make their own decisions about how the research was used rather than rely on scientists and extension officers. This approach led to improved ecosystem management and restoration (CP1) and the ownership and implementation of new ideas and practices (CP2) that provide benefits and are highly adaptive under climate variability and change (CP3).

In Peru, increasing water challenges have reinforced the values of water regulation by upstream ecosystems, an AS provided to local communities and cities downstream. Upstream communities, which co-produce the AS by managing ecosystems (CP1), control the benefits received by other stakeholders and the way downstream actors can co-produce AS, for example, through water capture and use (CP2, CP3). As a result, the flows of the water regulation AS create new interdependencies and affect power relationships between stakeholders. As upstream communities have the power to manage trade-offs between AS (for example, improving water regulation by reducing food or fodder production), their role is now better recognized by the national water sector, but this recognition does not automatically translate into community empowerment. Despite the consensus on the need to involve upstream and downstream actors into co-producing the AS (e.g. through financial compensations paid by downstream cities and water utilities to upstream communities), downstream powerful actors often apply a top-down non-participatory approach to watershed management.

As with current ES, interactions and negotiation among multiple stakeholders for management and mobilization are expected to reduce trade-offs and increase synergies and co-benefits among AS and ES [82]. In mountains, an adaptation of traditional grassland use strongly based on collective land allocation, management (e.g. mowing and grazing dates) and governance supported by strong extension services is essential for facing increasing climatic uncertainty [83,84].

In the French Alps, regulation and sharing (e.g. manpower, equipment) by farmer collectives of management (CP1) and harvest (CP2) support multiple AS: resilient fodder production, latent erosion control and novel tourism appreciative of flower diversity. They also regulate trade-offs with land allocation and water demand for irrigating novel crops (see above). Terrace restoration or upgrading for novel crops, and tree planting for increasing shade for the stock will also require collective land allocation. Lastly, collaboration and financing by non-farming residents and the tourism sector will probably be essential for supporting novel activities and essential access to infrastructure, and for marketing and selling infrastructure (CP3).

In Kalimantan, in villages affected by extreme rainfall fluctuations, leading to floods or drought, village leaders introduced communal rules to protect forests and their water regulation services (AS). The community-enforced rules like the prohibition of tree cutting along rivers, or a deforestation ban in hill forests, with the possibility of limited selective logging and collection of non-timber forest products for local uses. According to village leaders, this collective co-production

(CP1) aimed deliberately at conserving multiple AS: forest goods and reducing the impacts of intense floods and hot weather for the next generation.

(e) Feedbacks from appropriation, appreciation and access (CP3) to management (CP1) and mobilization (CP2)

Although for simplicity, we have so far analysed co-production mechanisms as sequential, co-production dynamics entail multiple feedbacks across its three stages [33]. Development of processing skills, establishment of markets and infrastructure for multiple novel products (and latent services) feedback financial, manufactured and also human and social capital for managing and mobilizing multiple other AS. Better understanding these feedbacks and activating them is critical for adaptation which can often be limited by, e.g. financial resources or (skilled) manpower. By creating synergies across adaptation actions, they decrease external dependency, a critical component of sustainability—whereas reliance on subsidies or development aid increases vulnerability [85].

In the Riverina, the development and adoption of a novel grazing system (CP1, CP2) has led to the creation of new markets and supply chain for saltbush-fed lamb and improved the profitability of grazing operations (CP3). This has encouraged and enabled graziers to develop and extend novel grazing systems and salinity management on-farm (CP1, CP2). For example, planting native trees and shrubs as shelterbelts for lambing reduces mortality and improves live weight gain, while also lowering the water table and improving water quality.

In the French Alps, new forms of tourism and local demand (CP3) support and motivate the development of novel agricultural production and enable the persistence of livestock farming (CP1, CP2). While financial flows are most evident for escaping dependency on national subsidies (up to 80% of farm income), increasing technical (e.g. digital) knowledge and commercial skills, and strengthening collaborative governance and economy also facilitate all economic activities. Conversely intensive tourism development and summer grazing by large external companies without motivation for better land management through attachment and appreciation can foster a negative feedback.

4. Discussion

(a) Value and limits of the co-production framework for understanding adaptation services trade-offs and co-benefits

Our analysis highlighted five broad mechanisms through which co-production factors can create or mitigate trade-offs or enhance co-benefits among AS. These mechanisms are largely common with those involved in the co-production of current ES and were prevalent across our five case studies, which represent a variety of terrestrial socio-ecosystems at a global scale. While their generic nature would need to be confirmed by a systematic synthesis across NBS case studies, specific additional mechanisms may be revealed for other socio-ecological contexts, such as in intensive agriculture, forestry and urban systems with strong external flows and teleconnections, or in aquatic and coastal systems with interacting local and distant managers and governance. We now reflect on the benefits of adaptation of this analytical approach.

First, many current adaptation responses through multi-level co-production, including in our case studies, react to land use or other direct human pressures resulting or not from climate impacts, rather than anticipating adaptation to severe climate change [62]. To a large extent, it is reassuring that climate adaptation can activate co-production mechanisms already applicable to current ES, meaning that learning and social processes now can support future adaptation [86]. Our case studies illustrated how traditional and multi-functional management that promote resilience and multiple services, or multi-actor and collective governance for decreasing trade-offs among beneficiaries, can be activated for decreasing trade-offs and increasing co-benefits among AS, and with other ES. Also, mechanistic analysis of current co-production can inform on hard trade-offs that will need to be taken into account for adaptation. There are some hard ecological trade-offs like organisms' functional strategies that constrain bundles of ES [87] and future AS management options [23]. Promoting transformation through landscape connectivity can facilitate the spread of weeds, pests and pathogens [72] with negative contributions to adaptation. Hard social trade-offs exist where there are entrenched conflicts in values and interests between actors, or where institutional decision-making systems and governance systems are path-dependent and limit the development of new options for adaptation ([65], p. 27 *et seq.*).

Secondly, our case studies provide mostly evidence for reactive responses to ongoing change, providing insights only into the subset of potential mechanisms and actions for pro-active adaptation. In particular, while this is an outstanding future challenge, current evidence of pro-active co-production for ecosystem transformation is limited. We observed that stakeholders derive benefits from ecosystem transformability but have not yet acknowledged it as a resource for co-production of new benefits. On the other hand, there is ample evidence for pro-active management for maintaining current ES, and for changing governance, learning and knowledge transfer, which fosters collective learning for enabling capabilities for adaptation with ecosystem transformation.

Lastly, our analyses showed how co-production actions in adaptation to current pressures facilitate or impede the co-production of AS in the future through various forms of human-derived capital. This demonstrates the dynamic nature of co-benefits for adaptation over time. Its recognition by actors is essential for building up agency along adaptation pathways, as discussed below.

(b) Values, rules and knowledge underpinning co-production of trade-offs and co-benefits for adaptation

Choices and actions for adaptation are made by decision makers based on what they regard as credible, legitimate and important. Decision makers draw upon personal and societal values, institutional rules and the body of knowledge available to them in order to prioritize possible options. Values, rules and knowledge (VRK) determine the context under which options are assessed and decisions are made [88,89]. Thus, VRK that are excluded from the decision-making process may exclude or limit some options that may be important for ecosystem-based adaptation.

Allowing novel uses of AS may require overcoming such constraints by changing the VRK that shape the existing decision context. Changing the decision context by changing the VRK then enables the co-production of AS and the reduction of their trade-offs. For example, in the Riverina, the development of new grazing systems would normally be done by scientists and extension officers. Re-writing the rules for how research could be done by graziers led to new knowledge, empowerment of the graziers and ownership of that knowledge. This enabled the mobilization of AS along with shifts in values over land management and restoration [45].

The co-production of novel and latent ES may face many barriers to adoption, management and use. This issue arises where ES are linked to cultural identity and where ecosystem transformation requires the transformation of livelihoods. This was the case in Mali where farming and fishing households had little option but to develop livelihoods based on forests and charcoal production (novel and latent ES) [30].

Thus the co-production of novel and latent ES is likely to require changes in decision contexts and the VRK that shape these. Change can be achieved in part by creating new markets, supply chains and benefits from novel ES which then incentivizes adaptation for the broader community. In many cases, novel and latent ES may be perceived as second-best options. Accordingly, increasing co-production and use of novel and latent ES is an indicator of changes in decision contexts and VRK. In the French Alps, changes in VRK for the appreciation of local produce have fed back to developing renewed forms of management and mobilization of novel crops and traditional livestock products [18].

Novel and latent ES may be hard to mobilize because capabilities for co-production have to be developed *de novo*. System locked into past co-production processes may be hard to change and may slow down the transformation. Abandonment of land for extended periods may be one outcome, as in the Riverina after the land became salinized owing to tree clearing in the nineteenth century and before novel grazing systems were developed 70–100 years later [3].

(c) Managing landscapes to co-produce more benefits and decrease trade-offs along adaptation pathways

A means of promoting adaptation is via structured, sequenced, iterative implementation of adaptation actions within an adaptation pathway approach [5]. We expect that the sequence of co-production of multiple AS and ES is a positive component of adaptation, while trade-offs need to be navigated during windows of agency—critical periods where agency plays out to inflect the socio-ecological trajectory towards a positive future [18].

Adaptation pathways may involve gradual substitution from AS provided by persisting ecosystems to novel AS from transformed ecosystems, representing a temporal trade-off [13]. This challenges adaptation as synergies and co-benefits among ES co-produced through traditional management and multi-actor governance may need to be renounced, and trade-offs with AS acknowledged and accepted during social transformation. However, in the French Alps, we observed AS building up over time rather than substitution [18]. This was largely conditioned by actors' ability to collectively negotiate land allocation including novel uses and forms of multifunctionality, and by community support and engagement. Actors perceived that tipping points may occur in the future, when co-production capability could break down. This could incur with the loss of local traditional values or depletion of financial and human capital for livestock farming. These tipping points would lead to less desired futures, strong social and ecological trade-offs, and fewer ES for fewer beneficiaries (e.g. extensive grazing by external enterprises or rewilding for distant urban beneficiaries).

Along pathways, legacies of past landscape management and adaptation may make future adaptation more likely by generating present capabilities and benefits—or may impede it. Such legacies can operate as feedbacks within individual co-production steps or across them. More generally, spatial and temporal scales of AS trade-offs and co-benefits and associated co-production mechanisms need to be considered along pathways. Among these, the integration of landscape processes is crucial as agency and governance for adaptation develop within lived landscapes [90]. Several of the co-production mechanisms we have highlighted directly concern landscape processes. This applies especially to multifunctionality for which the landscape-scale offers multiple options [54]. Likewise, landscape-level biodiversity and spatial connectivity underpin trade-offs and co-benefits in the co-production of novel services. Knowledge of such co-production mechanisms is expected to support adaptation pathways that build on co-benefits, take into account hard ecological trade-offs and use windows of agencies for negotiating AS trade-offs and increasing co-benefits. However, a change in knowledge is only part of the issue. Constraints imposed by values may often be the most difficult to address, whereas those based on rules or knowledge may prove more tangible [69]. Governance systems involving participative learning and deliberation provide a basis for changing such interactions of values, knowledge and rules [47] to enhance co-benefits and minimize trade-offs of AS.

5. Conclusion

Adaptation requires navigating trade-offs and increasing synergies and co-benefits among AS along structured, sequenced, iterative implementation of adaptation actions within adaptation pathways. The five broad mechanisms that underpin AS co-production and their trade-offs or synergies are largely co-production mechanisms already in place for current ES. Further systematic analyses are needed to assess their prevalence and effectiveness depending on biophysical, social and political contexts. Additional specific mechanisms may also prevail in other socio-ecological contexts, such as intensive agriculture, forestry and urban systems, or aquatic systems. The proposed analytical framework, which teases apart trade-offs and co-benefits according to different human-derived capitals along the three steps of co-production, offers the means to produce such knowledge. This analytical perspective is essential because understanding AS co-production helps stakeholders avoid failures or restriction of adaptation options owing to trade-offs, and provides agency to activate new synergies and co-benefits. By focusing on co-production mechanisms, it enables actors and decision-makers to target critical interventions and overcome barriers to adoption, management and use of AS. First, fundamental ecological mechanisms of resilience and transformability and hard ecological trade-offs need to be acknowledged as constraints in ecosystem-based adaptation strategies. Second, the roles of collective governance and power relationships among current and new actors in using this knowledge for reducing trade-offs and increasing co-benefits need to be fully acknowledged by governments and funders. Third, profound shifts in values are required for smart and fair ecosystem-based adaptation. Fourth, agents involved in adaptation pathways approaches need to acknowledge that the co-production of AS entails multiple feedbacks which can amplify or buffer trade-offs and co-benefits. Without integrating these four points into adaptation, it is unlikely that ambitions such as the Sustainable Development Goals will be realized under climate change.

Data accessibility. This article has no additional data.

Authors' contributions. S.L. designed the research, produced data for the French Alps case study and wrote the paper. B.L. participated in concept development, produced data for the Mali, Peru and Indonesia case studies, produced figure 1 and wrote the paper. M.J.C. participated in concept development, produced data for the Riverina case study and wrote the paper. E.B. participated in concept development, produced data for the French Alps case study and wrote the paper.

Competing interests. We declare we have no competing interests.

Funding. S.L. acknowledges French Agence Nationale pour la Recherche MtnPaths (ANR-16-CE93-0008-01) and Investissements d'Avenir CDP Trajectories (ANR-15-IDEX-02). B.L. was supported by the European Union's H2020 research and innovation programme (SINCERE Project) and the CGIAR Research Program on Forests, Trees and Agroforestry (CRP-FTA) with financial support from the CGIAR fund.

Acknowledgements. This paper is a contribution from the Transformative Adaptation Research Alliance (TARA, https//research.csiro.au/tara/), an international network of researchers and practitioners dedicated to the development and implementation of novel approaches to transformative adaptation to global change.

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