Journal of Cleaner Production 501 (2025) 145262

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

# Exploring outcome-driven policymaking on protected areas with an endogenous institutional model

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ARTICLE INFO

Handling editor: Giovanni Baiocchi

*Keywords:*
Endogenous institutions
Protected areas (PAs)
Land use system
Policy modelling
Agent-based modelling

ABSTRACT

Covering over 16 % of the global land surface, nearly 300,000 Protected Areas (PAs) play a pivotal role in conservation efforts worldwide. The allocation and management of these areas vary widely, reflecting the dynamism and complexity of the land use system. Understanding the impacts of PA-related policy mixes on ecosystem service outcomes and the wider land system is essential but challenging. In this research, we employ an endogenous institutional model coupled with an agent-based land use model to examine the processes and feedbacks from PA implementation and land system changes under multiple policies. We focus on modelled PA policy targets that aim to reach conservation outcomes by increasing a proxy for habitat diversity. Alongside other policies with different targets in the land system, PA policies generate dynamic patterns that are challenging to discern through an exogenous, non-systemic lens. Findings reveal that 1) Neither subsidies nor PAs in isolation effectively enhance habitat diversity in the model; however, their synergic implementation effectively increases it. 2) Increasing PA extent to 30 % of the land area does not harm modelled agricultural output in the long term, due to the land system's resilience and adaptability in providing ecosystem services. 3) When the geographic extent of PAs is predetermined, radical expansion proves more beneficial than gradual expansion, as the latter causes prolonged disruptions to existing land uses while accruing fewer cumulative sustainability benefits over time. These insights highlight the importance of a systemic, integrated approach to PA management for sustainable conservation outcomes.

## 1. Introduction

Protected Areas (PAs) currently cover 16.1 % of the global land and inland water area (UNEP-WCMC, 2024). In the context of the global biodiversity crisis (Davis et al., 2018), PAs have been identified as an essential policy tool for tackling ecosystem degradation and safeguarding habitats and species (Gray et al., 2016; Mu et al., 2024; Yang et al., 2023). In line with Target 1 of the Convention on Biological Diversity, the EU's Biodiversity Strategy aims to restore biodiversity within Europe through various measures including expanding current PA coverage to 30 % of the EU's land surface by 2030 (European Commission, 2020). To achieve this ambitious goal, the rate of current expansion needs to be doubled (European Environment Agency, 2023).

However, it is important that public policy institutions do not see the PA 30 % target as the ultimate goal, but instead focus on biodiversity outcomes. Understanding where best to allocate and implement additional PAs to achieve this underlying goal is not trivial, and is likely to require cyclical monitoring of impacts (e.g., on biodiversity) and modification of design (Li et al., 2022; Ma and Pan, 2024; Zhao et al., 2024). PAs face additional challenges relating to their net effect on the broader land system (Leverington et al., 2010; Scheffer et al., 2015; Watson et al., 2014). A lack of 'biodiversity mainstreaming' means that PAs are often standalone measures that conflict with other land uses and policies, and so encounter direct or indirect opposition. PAs can also cause trade-offs in ecosystem service provision, such as by restricting food production and causing indirect land use change under growing global food demand (Meng et al., 2023). For all of these reasons, protected area policy is rarely static over the long term, but instead adapts

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https://doi.org/10.1016/j.jclepro.2025.145262
Received 25 June 2024; Received in revised form 24 February 2025; Accepted 8 March 2025
Available online 10 March 2025

in response to perceived impacts, opportunities, and pressures (Dearden et al., 2005; Geldmann et al., 2015).

The process by which outcome-based, adaptive policy interventions are made, and their inter-policy impact on land use changes, require a distinct approach in simulation models. At present, studies that analyse PA targets prescribe the 30 % target and then explore its consequences for, for example, biodiversity and food security (Staccione et al., 2023). This is often related to model design, with common optimization approaches in particular providing valuable information about trade-offs and synergies but little information on timescales and sub-optimal outcomes that characterise real-world change (e.g. Brown et al., 2021). Gradual policy implementation and associated changes over time are usually neglected, along with the critical dynamics of conflicting sectoral policies that do so much to determine PA effectiveness in reality. As a result, exploratory research has been largely unable to assess the likelihood of successful policy implementation that avoids counterproductive clashes with socio-economic requirements now and in the future (Oldekop et al., 2016). This leaves an important research gap in understanding PA expansion as an integrated component of land system policy under rapid global change.

One way to address this gap is to integrate public policy institutions endogenously within models of the land system, so that varied emergent pathways and impacts, embedded in the wider system, can be explored. Modelled institutions can be given different policy targets, policy instruments to achieve these targets, and the ability to evaluate and modify their policies. Endogenising the policy process also enables exploration of the interactions with other policy sectors such as agriculture, accounting for the respective power dynamics between them. Nevertheless, there is a scarcity of literature that considers endogenous institutional processes in land systems (Holzhauer et al., 2019). Agent-based models (ABMs) are conceptually suited to this task and have been used to explore institutional dynamics (e.g., Balke et al., 2013; Brown et al., 2017; Ghorbani, 2022), but with few applications to large-scale policy implementation across entire land systems. This approach has therefore the potential to provide new insights into the complexities and interdependencies of PA policies and their broader impacts on society and the environment, as well as the social processes underpinning sustainable transitions (Davidson et al., 2024).

The aim of this research is to explore outcome-based PA policy development, by modelling endogenous institutional interventions and their interactions across PA and other land-based policy areas. By coupling an endogenous institutional modelling framework developed by Zeng et al. (2025) with the CRAFTY agent-based land use model (Murray-Rust et al., 2014), we investigate the dynamics of the feedback loop between land users and PA-related policies. This allows examination of the effects of PA policies within a broader socio-economic and environmental context, which can help to capture meaningful, stylized system behaviours.

## 2. Methods

Fig. 1 illustrates the operational procedures of the endogenous institutional modelling framework (Zeng et al., 2025) coupled with a land system model, CRAFTY-Europe (Murray-Rust et al., 2014). The figure categorizes the model procedures into three parts: a) institutions, b) land use, and c) both, which refer to the endogenous institutional model, the land use change model, and the overlap between these two, respectively. The overlap indicates the policy implementation procedure, a customizable intersection of the other two parts. This section describes these modelled procedures and the experimental settings of the numerical experiments, including the 11 steps indicated in Fig. 1.

### 2.1. *The endogenous institutional model (steps 2 to 9)*

A detailed description of the endogenous institutional model can be found in (Zeng et al., 2025). The operational steps within an

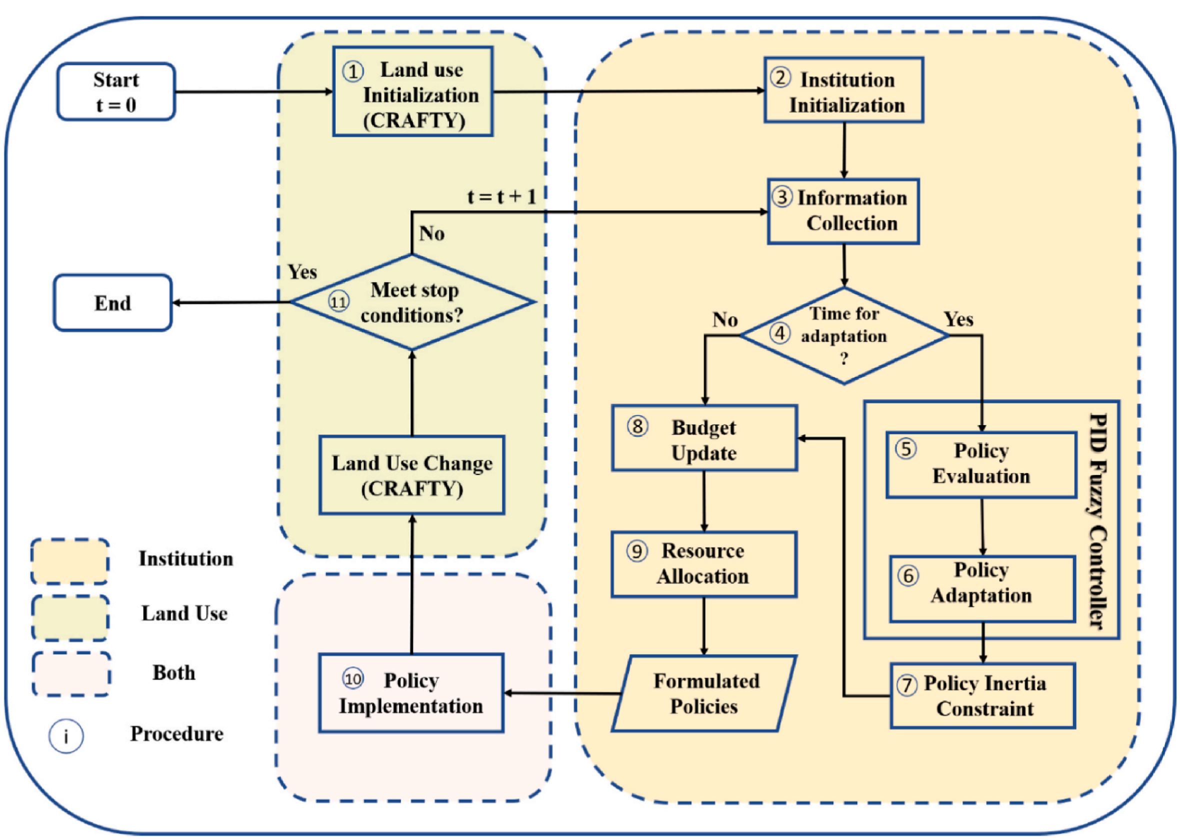


**Fig. 1.** The operational procedures of the institutional model when embedded in a land use modelling framework (Zeng et al., 2025).

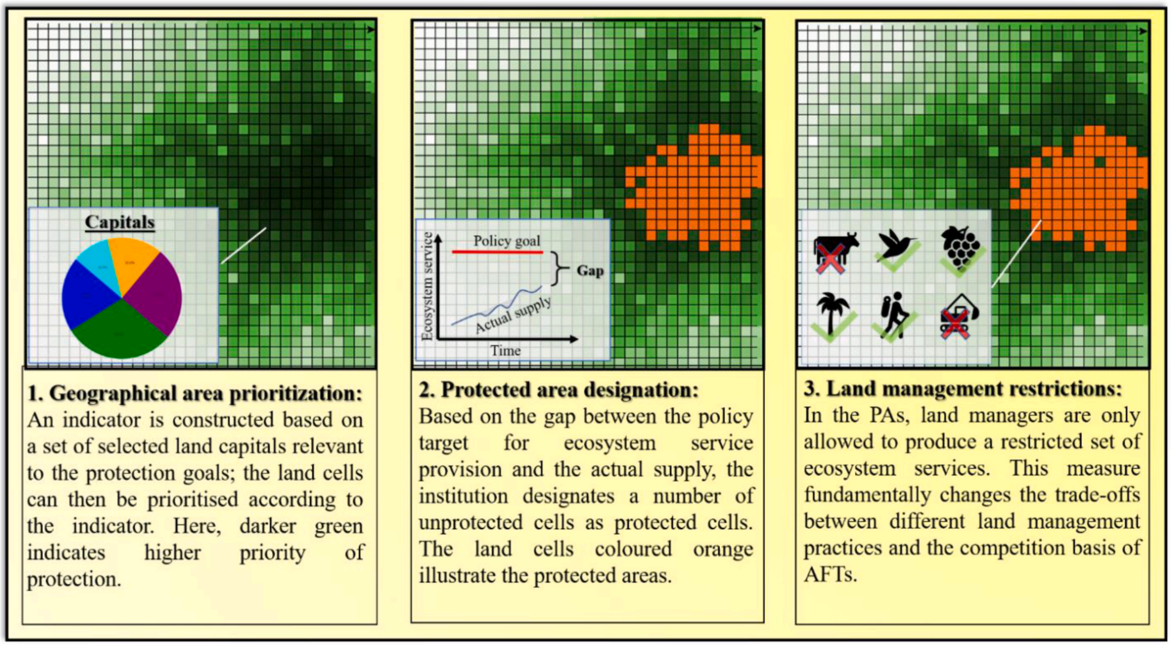


**Fig. 2.** Core steps of PA policy implementation in this study.

institutional agent are depicted in Table A1 in Appendix A. Here, we present a brief overview of the institutional model.

The outline framework of the endogenous institution model is a closed-loop control system where institutional agents can observe and adjust the behaviour of land users to reach specific policy goals. The institutional agents can collect information about land user types, land system conditions, and ecosystem service production. Based on this information, institutional agents evaluate and adapt policies using a PID (Proportional-Integral-Derivative) fuzzy controller mechanism, which offers a parsimonious yet systematic approach to mimic a policymaker's evaluation and adaptation processes. Meanwhile, this controller can be calibrated with experts' knowledge in an IF-THEN form. On the microscopic level, the endogenous institutional model reflects the heuristic feature of human decision-making in complex environments and bounded rationality in general. Macroscopically, the institutional agents' behaviour aligns with the theory of incrementalism, suggesting that institutional agents prefer incremental policy changes over transformative changes (Zeng et al., 2025). The extent of a single policy change is boundedly adjustable. This is achieved by changing the value of the policy inertia constraint, a variable that influences how much a policy intervention is allowed to vary in one adaptation. The policies issued by the same institution are also constrained by the institution's budget, which can be solved as a convex optimization problem.

### 2.2. The CRAFTY land use model

The CRAFTY land use model offers an environment within which the institutional agents can work. Initializing CRAFTY is the first step (step 1, Fig. 1), followed by the initialization of the institutional agents. In addition, CRAFTY is responsible for simulating land use changes in response to institutional interventions.

Specifically, CRAFTY is an agent-based land use model that was developed to model large-scale land use changes (Blanco et al., 2017; Brown et al., 2018; Murray-Rust et al., 2014). At the microscopic level within CRAFTY, numerous heterogeneous land user agents leverage land capitals to produce a variety of ecosystem services. The land users are categorized into discrete Agent Functional Types (AFTs) (Arneth et al., 2014), each with a different set of sensitivities in terms of land capital, indicating their diverse capabilities for producing ecosystem service portfolios. These AFTs span land use sectors (forestry, agriculture, conservation etc.) and so allow exploration of multiple policy sectors. A significant driver of CRAFTY's dynamics is a set of demands for different ecosystem services, which together with ecosystem service supply contributes to the utility perceived by the land users. The perceived utility forms the basis of the land user agents' competition for land. Institutional agents can utilize policy instruments to directly or indirectly influence the land users' perceived utility, and thus change their relative advantages in competition. Due to CRAFTY's ability to systematically factor in land user utility, land capitals, and ecosystem outcomes within the land system, it offers a convenient testbed for examining outcome-based PA policies. The basic CRAFTY framework is depicted in Brown et al. (2018). Here, we use an emulator of the CRAFTY-EU model (Brown et al., 2019b, 2021) allowing for rapid adaptation to facilitate this exploratory study.

### 2.3. Policy implementation

According to the International Union for Conservation of Nature (IUCN)'s definition, a protected area is "a clearly defined geographical space, recognised, dedicated and managed, through legal or other

**Table 1**
The capitals, ecosystem services and relevant vectors.

| Capital | Crop productivity | Forest Productivity | Grassland productivity | Financial capital | Human capital | Social capital | Manufactured capital | Urban capital |
|---|---|---|---|---|---|---|---|---|
| ***d*** | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| **Ecosystem service** | Meat | Crops | Habitat diversity | Timber | Carbon | Urban | Recreation | |
| ***w*** | 0 | 0 | 1 | 0 | 0 | 0 | 0 | |

**Table 2**
Institutions and Policies in the four modelled experiments. Policy-SD indicates "**S**ubsidizing habitat **D**iversity"; Policy-PD indicates "**P**rotecting habitat **D**iversity"; Policy-TM means "**T**axing **M**eat production"; Policy-SC represents "**S**ubsidizing **C**rops".

| Experiments | Institutions and Policies | Purpose and Explanation |
|---|---|---|
| **Experiment 1:** One institution, one policy. | Nature Institution: *Policy-SD* | Examining the impact of Policy-SD in isolation on ecosystem service supply. Policy-SD aims to increase habitat diversity using subsidies. The policy goal of Policy-SD is the experimental variable. Detailed parameterization is given in Table A2. |
| **Experiment 2:** One institution, one policy. | Nature Institution: *Policy-PD* | Examine the influence of Policy-PD in isolation on ecosystem service supply. Policy-PD aims to increase habitat diversity by establishing protected areas. The maximum geographical area Policy-PD is planned to protect is the experimental variable. Detailed parameterization is given in Table A2. |
| **Experiment 3:** One institution, two policies. | Nature Institution: *Policy-SD* and *Policy-PD* | Exploring the joint impact of Policy-SD and Policy-PD in contrast with their separate impact on the change of habitat diversity. The policy goal of Policy-SD and the maximum PA Policy-PD covers are experimental variables and are changed simultaneously. Detailed parameterization is given in Table A3. |
| **Experiment 4:** Two institutions, two policies. | Nature Institution: *Policy-SD* and *Policy-PD* Agriculture Institution: *Policy-TM* and *Policy-SC* | Involving two institutions with four policies in total to explore the compound influence of multiple policies. Specifically, the policy inertia constraint of Policy-PD is the experimental variable that is changed to investigate the impact of drastic versus gradual PA expansion on ecosystem services. Detailed parameterization is given in Table A4. Policy-TM taxes meat production. Policy-SC subsidizes crop production. |

effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values" (Dudley, 2008). When the institutional model is embedded in the CRAFTY framework, policies, including those related to Protected Areas, can be implemented in step 10 (Fig. 1). In general, we can structure the implementation of PAs into three major steps: geographical area prioritization, protected area designation, and land management restrictions, as detailed below and illustrated in Fig. 2.

Area prioritization means sorting the geographic areas according to their importance to a set of specific conservation purposes, and so relies on indicators that measure this importance. Constructing an accurate indicator, in silico as in reality, requires clear objectives, system understanding, robust metrics and high-quality data. The practical consequence is that PA decisions are often made on the basis of imperfect information, which we here represent with a single, simple proxy representing habitat diversity. This approach does not allow comparison of different designation methods, but does provide a stylized representation of prevalent area-based PA management (Maxwell et al., 2020), serving as proof of concept for future studies with more realism. For each land cell with multiple capitals, we construct an indicator $PRTC_{xy}$ by calculating the dot product of these capitals and a vector of weights $\boldsymbol{d}$ reflecting each capital's importance to diversity:

$$PRTC_{xy} = \boldsymbol{d} \cdot \boldsymbol{CAPT}_{xy} \tag{1}$$

where $\boldsymbol{CAPT}_{xy}$ is a vector representing the richness of the capitals in the land cell at $(x, y)$.

Using the area prioritization results, institutions designate PAs. An institutional agent can either adjust the area allocation threshold of *PRTC* or select *N* unprotected land cells with the highest *PRTC* to adaptively expand protected areas in every iteration. Because the modelled institutions are outcome-oriented, they evaluate the need for newly established PAs based on the gap between the policy goal of increased habitat diversity and its actual provision. Both the threshold and *N* can be changed according to pre-defined decision rules embedded within a fuzzy logic controller (Zeng et al., 2025). In the current implementation, the second method (using *N*, number of cells) is selected to gain more control precision because the threshold approach might cause a drastic expansion if many land cells have similar *PRTC*.

Within the designated PAs, land management practices are restricted, affecting the ecosystem services produced from the full set possible in CRAFTY. A straightforward way to represent the land management restrictions is to use a vector $\boldsymbol{w}$, whose elements are weights that indicate which ecosystem services are allowed to be produced and to which levels. Hence, an AFT's competitiveness at land cell $(x, y)$ can be calculated using:

$$c_{xy} = \sum_S \left( w_S p_S \left( \sum_i V_{t+1}^{i,S} + m_S \right) \right) \tag{2}$$

where $w_S$ represents an element in $\boldsymbol{w}$; $c_{xy}$ denotes the competitiveness of a land use agent at the land cell whose coordinates are $(x, y)$; $S$ is the ecosystem service the land user produces. $p_S$ denotes the production level of ecosystem service S. $V_{t+1}^{iS}$ is the institution $i$'s economic policy that targets ecosystem service $S$; $m_S$ is marginal utility brought by ecosystem service $S$.

The integration of the institutional model with the CRAFTY land use model creates a closed-loop control system. In this system, institutional agents act as controllers, guiding the land use system towards specific policy goals. The institutional model is endogenous and dynamic because the policies it generates result from the agents' adaptive responses to changes in land use. Policy goals are predefined, and the decision rules can be developed based on inputs from stakeholders and experts, or hypothesized by the model's users. Institutional agents assess actual ecosystem outcomes — such as the production of meat, crops, and habitat diversity — against these policy goals, identifying any discrepancies.

To address these discrepancies, the agents adjust policies to alter the competitiveness of various land users. This competitiveness is calculated using Equation (2), where $w_S$ can be set as a binary indicator (set to 1 or 0) to determine whether ecosystem service S is permitted on a land parcel at coordinates (x, y), which differentiates protected areas from the unprotected. The term $V_{t+1}^{i,S}$ represents monetary incentives that directly modify the perceived utility of a land user. Both $w_S$ and $V_{t+1}^{i,S}$ stem from the policy adaptation processes of the institutional agents. Through Equation (2), policy adjustments to protected areas and economic incentives influence the competitiveness of land users, driving key processes, such as land turnover and ecosystem service provision within the model. The resultant time-dependent policy adjustments regarding protected areas and economic incentives emerge as endogenous policy implementation pathways.

### 2.4. Experimental settings

The institutional model was coupled with the CRAFTY emulator, which is set up according to the CRAFTY-EU land use model (Brown et al., 2019b) and parametrized with data for the RCP2.6-SSP1 climatic and socio-economic scenario (Brown et al., 2019b). This scenario is selected as one in which protected area targets are relevant and achievable, given societal pressure for environmental restoration in the scenario narrative. We do not simulate other scenarios here as we focus on interactions between institutional agents and land system change against the scenario background, but note that these dynamics would likely differ in their outcomes under different scenario conditions (Staccione et al., 2023).

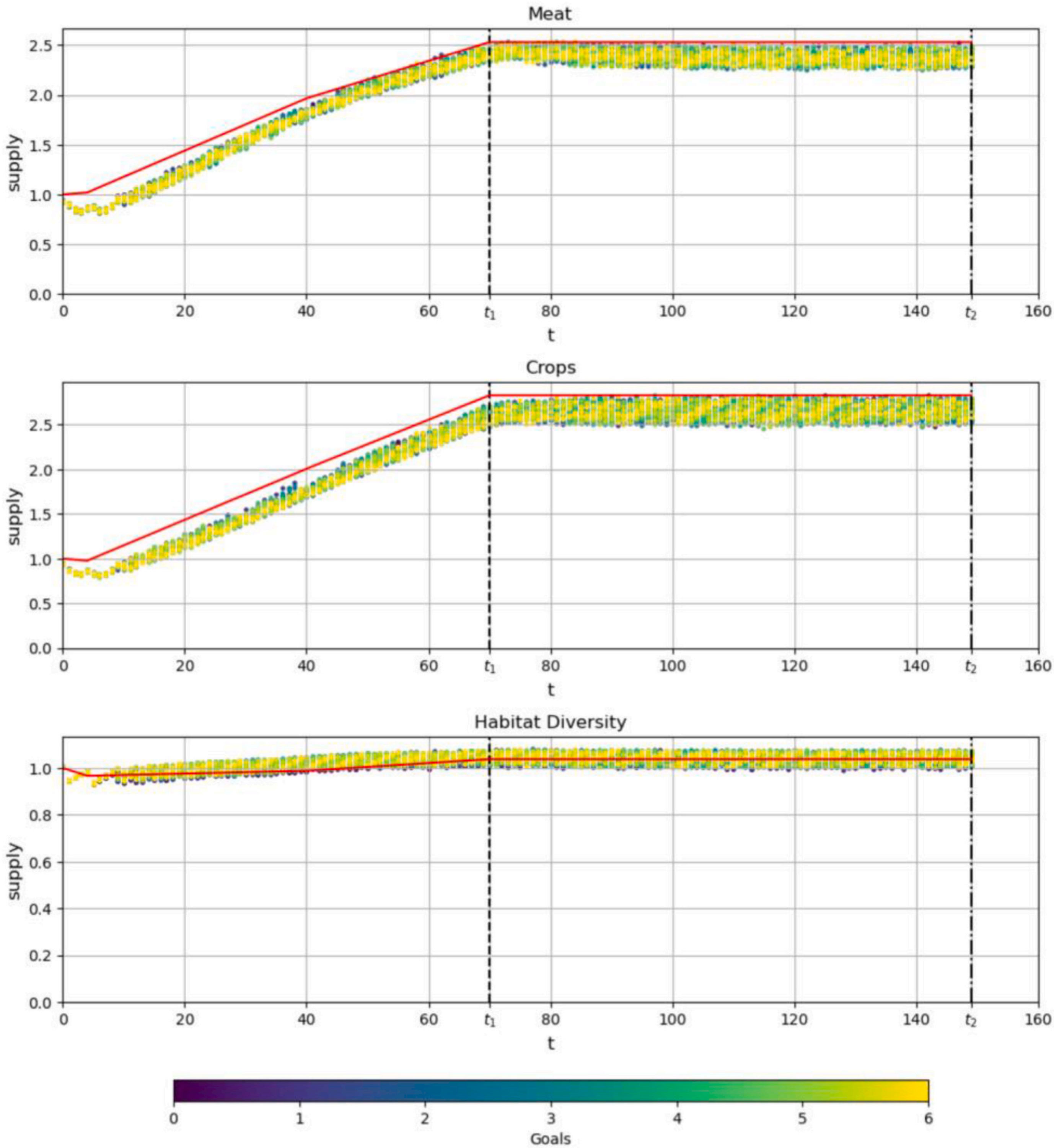


**Fig. 3.** Ecosystem service supplies under the impact of Policy-SD, in which Nature Institution subsidizes habitat diversity with varying policy goals. Red lines are demands. t is the simulation timestep; Goals and supply are expressed as a proportion of supply at t = 0.

Within the model, each AFT can produce up to seven ecosystem services. The model uses a map of European countries at a 10 arcmin resolution, allowing small-scale changes in protected areas and ecosystem service production to interact with European-level demand for goods and political processes. The map has 23871 land cells, each of which contains eight capitals that describe resources available for ecosystem service production. The names of the AFTs, the initial distribution of the AFTs, and the AFT attributes can be found in Zeng et al. (2025).

The capitals, ecosystem services and relevant vectors required to establish protected areas are shown in Table 1. CRAFTY-EU does not directly model biodiversity, and so a proxy for habitat diversity (labelled in the model as habitat diversity) is used instead; this output is monitored by the modelled institutional agents to inform their decisions. Besides the data availability, targeting a proxy for habitat diversity is appropriate due to several empirical reasons: habitat diversity and

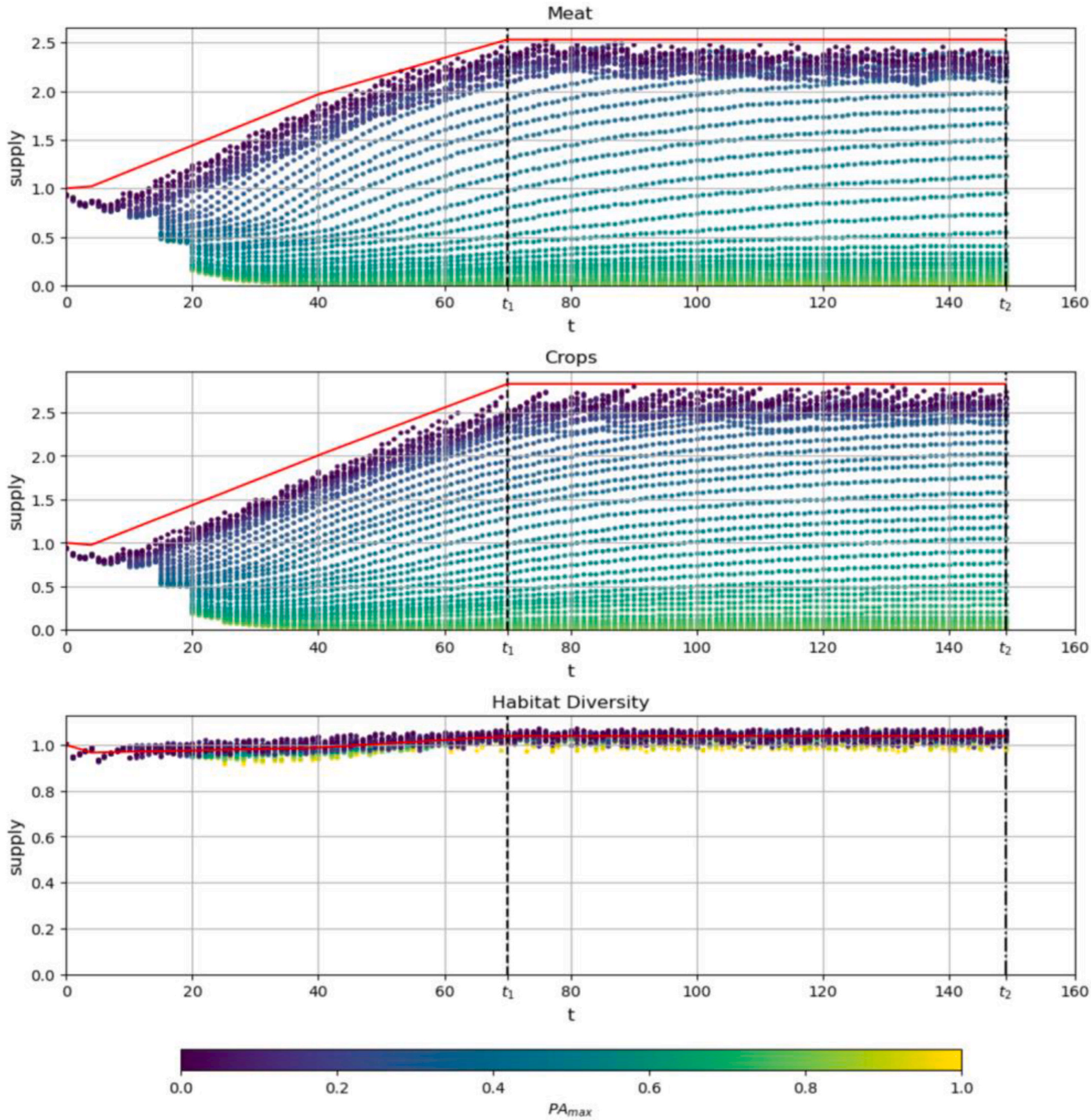


**Fig. 4.** Supply of ecosystem services under the influence of Policy-PD, in which Nature Institution's PA policy targets habitat diversity. Red lines are demands. t is the simulation timestep; supply is expressed as a proportion of supply at t = 0; $PA_{max}$ means the maximum PA coverage expressed as a proportion of PA to the total number of land cells.

biodiversity are profoundly interconnected (Oehri et al., 2020); both are important indicators of sustainable development (Sonko et al., 2021); and protecting habitats is a common function of PAs (Dudley, 2008).

We also utilised two types of natural capital within the CRAFTY model to build into the PA indicator: forest productivity and grassland productivity, on the assumption that metrics like this would be used to estimate the scope for improvements in habitat diversity. As above, better-suited data for building a PA prioritization index may exist in reality, but would likely remain approximations.

The extents to which the capitals contribute to habitat diversity are considered in a binary (1 or 0) way. With regard to $\boldsymbol{w}$, a vector of weights reflecting the restrictiveness of PA policies imposed on ecosystem service production, the most restrictive case is applied here: land users are allowed to contribute to habitat diversity only.

This research adopted a progressive experimental process to gradually increase the number of policies involved in the experiments. Four experiments represent scenarios ranging from a single institution with a single policy to two institutions with four policies (see Table 2). These institutions and policies are all outcome-oriented and dedicated to achieving their policy goals of changing target ecosystem service

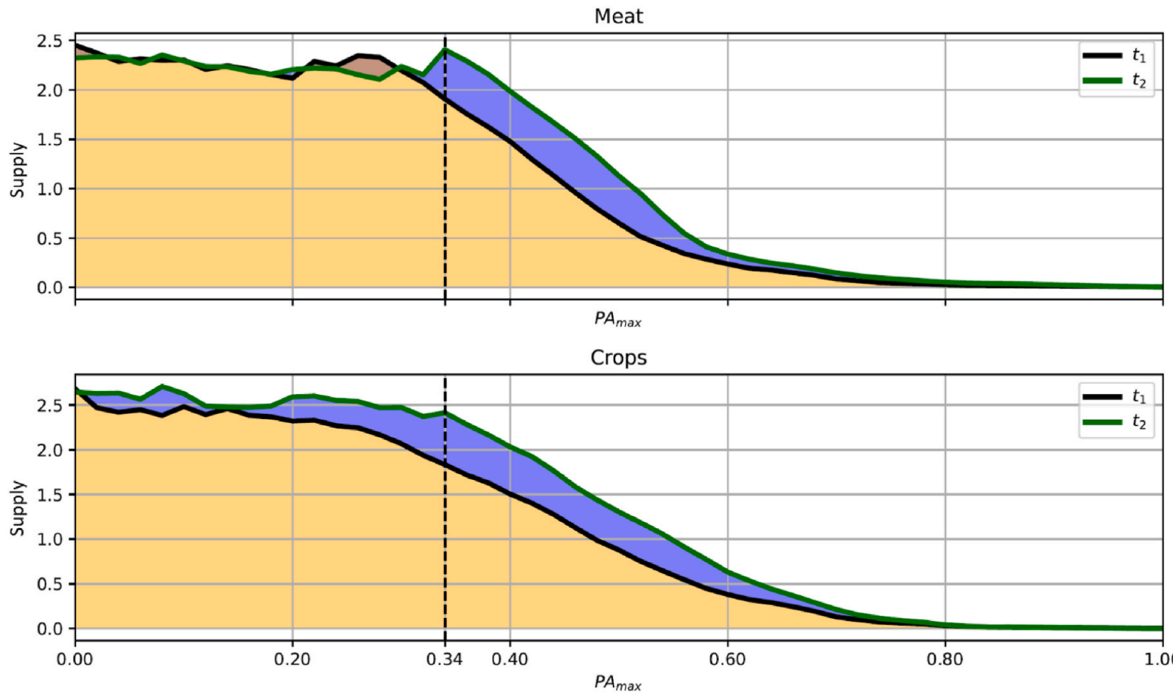


**Fig. 5.** Meat and crop supply with different $PA_{max}$ values at $t_1$ and $t_2$. Supply is expressed as a proportion of supply at t = 0; $PA_{max}$ means the maximum PA coverage expressed as a proportion of PA to the total number of land cells.

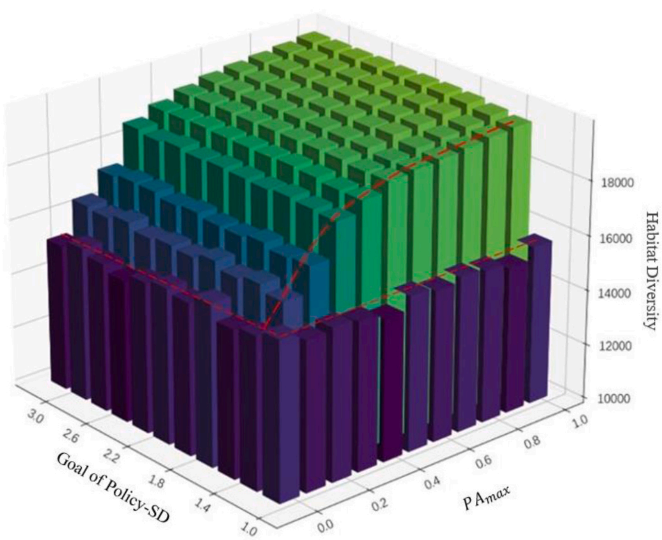


**Fig. 6.** The joint impact of Policy-SD (subsidizing diversity) and Policy-PD (expanding $PA_{max}$) on the supply of habitat diversity. Goal of Policy-SD is expressed as a proportion of the initial supply of habitat diversity; $PA_{max}$ means the maximum PA coverage expressed as a proportion of PA to the total number of land cells.

supplies.

The institutions can use three sets of decision rules labelled Subsidy, Tax, and Protection respectively indicating how the institutions utilize subsidies, taxes, and protected areas in response to land use changes. All the decision rules are defined in the FLC language. The details of Subsidy and Tax can be found in Zeng et al. (2025), while Protection is given in Table B1.

The following experiments focus on three types of ecosystem services relevant to this study, which are meat, crops and habitat diversity. Each simulation has 150 iterations (from 0th to 149th) with only the first 71 years (from the 0th to 70th iteration) of data to update the annual demands and capitals. After the 70th iteration, the demands and capitals remain constant. This treatment enables us to observe the dynamics of the model with and without the influence of changing input data. In the following experiments, the 70th and 149th year are respectively labelled as $t_1$ and $t_2$ for descriptive convenience.

## 3. Results of the numerical experiments

### 3.1. Experiment 1: the impact of Policy-SD

The resultant supplies of relevant ecosystem services under the influence of Policy-SD with different policy goals are shown in Fig. 3. It can be seen that the changes in the policy goal have almost no effect on the supply of habitat diversity or other ecosystem services. The results are consistent with the scenario without policy intervention depicted in Zeng et al. (2025), where ecosystem service supply generally tends to follow the corresponding demand changes. This can be attributed to the small scale of habitat diversity supply relative to the other services. The land users are assumed to prioritize the ecosystem services with larger profitability, which results in higher dominance of ecosystem services with large demand and supply. Hence, even if the policy goal varied significantly, the demand and supply dynamics for habitat diversity were markedly more muted compared to commodities such as meat and crops. In reality, with the expansion of agricultural land use, both biodiversity and habitat diversity are severely affected. Due to the different economic attractiveness for land users, policy interventions based on pure economic incentives might manifest as ineffective, which, therefore, entails the engagement of administrative regulations such as delimiting protected areas to assist with non-economic purposes.

### 3.2. Experiment 2: the impact of Policy-PD

The geographic extent of PAs is an important factor affecting land use changes. In this experiment, the institution only applies Policy-PD in order to elevate the supply of habitat diversity; the upper bound of the maximum proportion of protected areas (denoted as $PA_{max}$) is changed

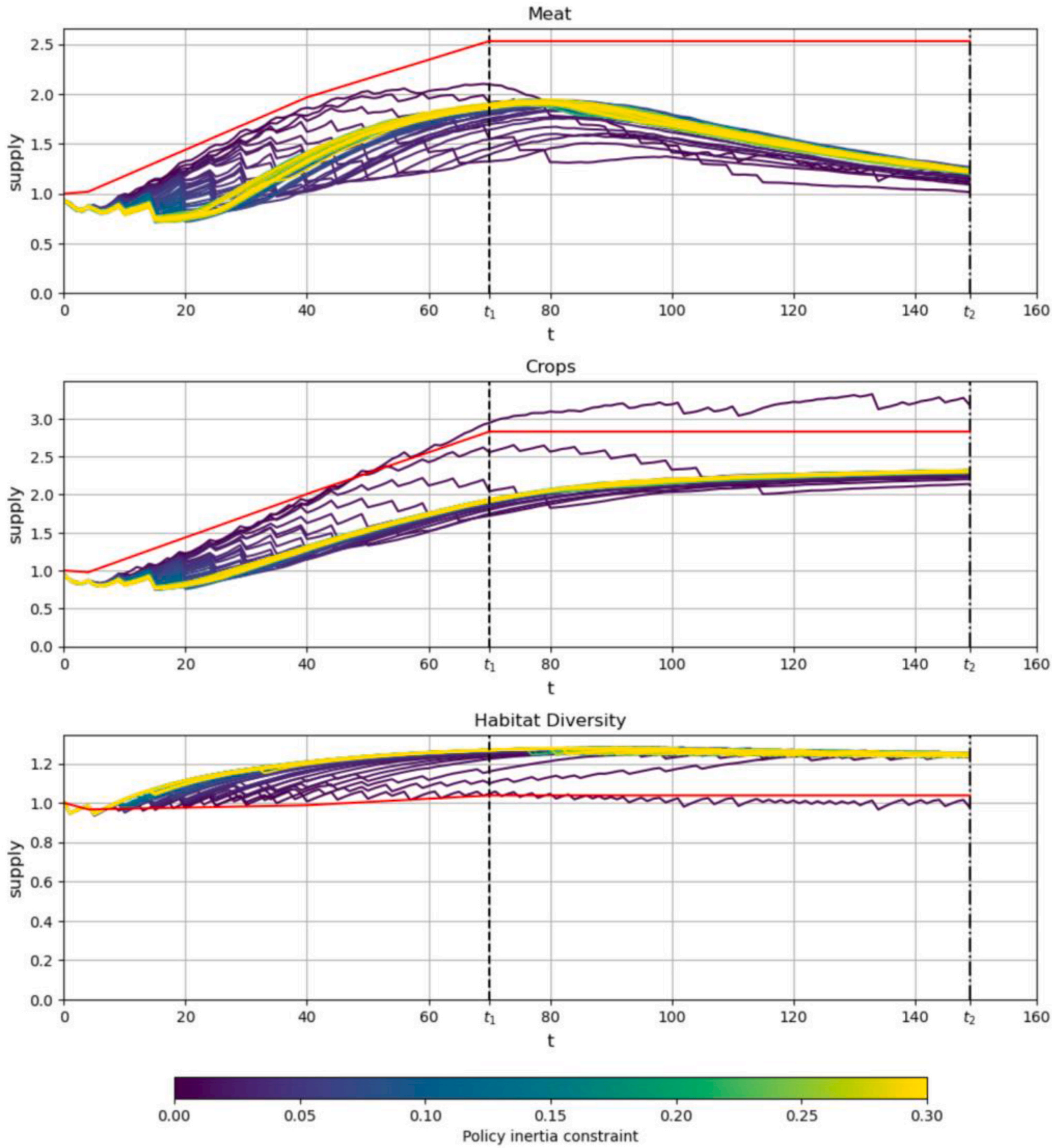


**Fig. 7.** Joint impact of four policies under different policy inertia constraints of Policy-PD. Red lines are demands. Policy inertia is a parameter bounded within [0,1] constraining the maximum number of land cells that can be protected in one iteration. Larger policy inertia constraint values indicate more land cells can be designated as PA in one iteration. t is the simulation timestep; supply is expressed as a proportion of supply at t = 0.

between 0 and 1 gradually across simulations. The results are illustrated in Fig. 4. It can be seen that $PA_{max}$ has a notable impact on multiple ecosystem services including meat and crops. Overall, a higher $PA_{max}$ leads to lower production of these ecosystem services, which is plausible because Policy-PD is very restrictive, and habitat diversity is the only ecosystem service that is allowed to be produced in protected areas. However, the results show habitat diversity supply still remains unchanged. This outcome might appear to be counter-intuitive, but is explainable. Because the supply of habitat diversity is driven by demand, the current negligible gap between supply and demand indicates that there is little economic incentive for land users to provide more, so that enforced increases in one area prompt emergent reductions elsewhere. Similar to Policy-SD, Policy-PD alone is incapable of increasing the supply of diversity. Nevertheless, it is useful to test whether these

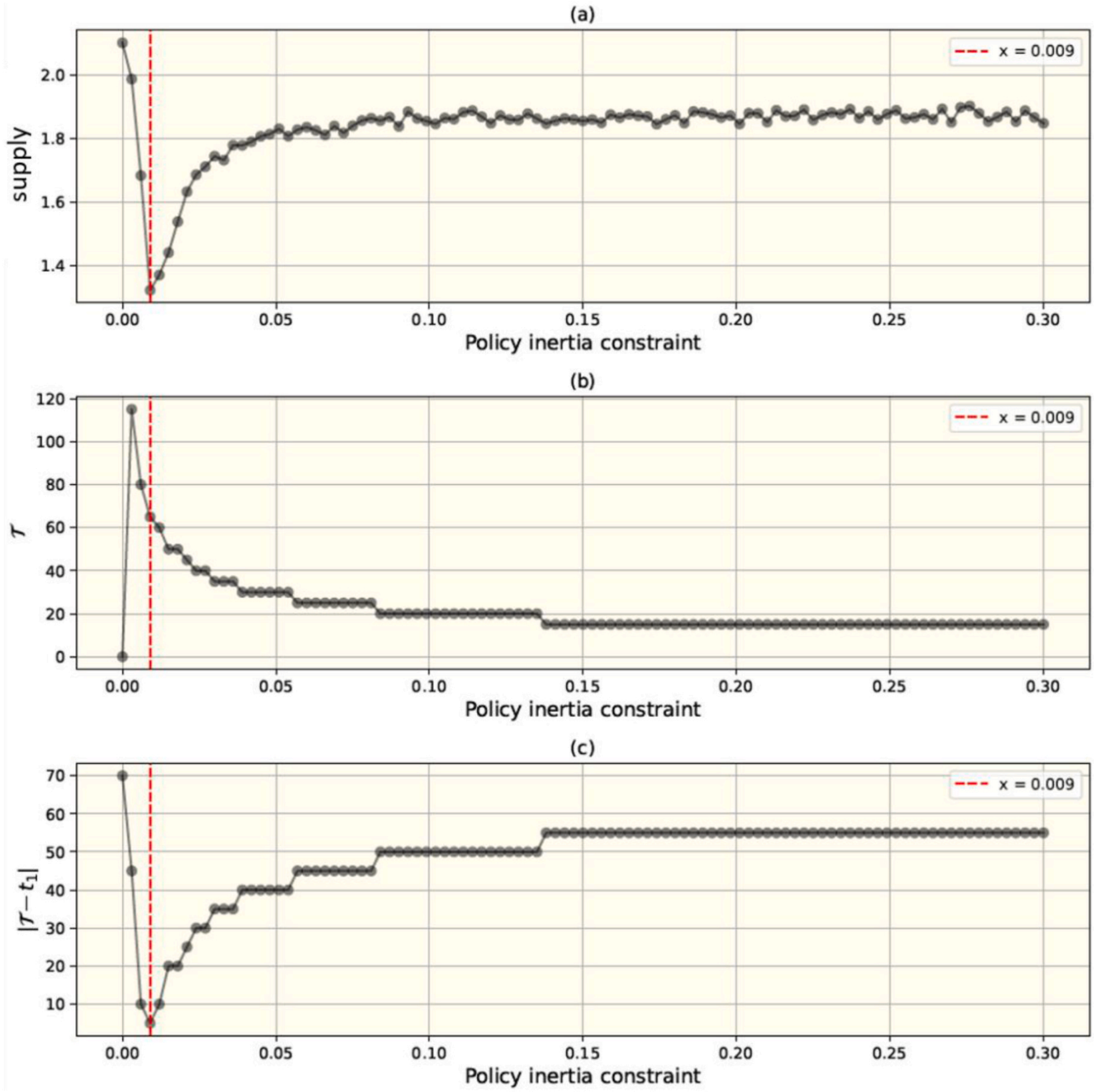


**Fig. 8.** Meat supply at $t_1$ (a), the timing ($\mathcal{T}$) when the protected areas reach the maximum ($PA_{max}$) (b) and the distance between $\mathcal{T}$ and $t_1$ (c) under different policy inertia constraints.

two policies in combination might be effective in promoting the supply of diversity given that their roles are complementary.

Furthermore, Fig. 4 shows that although PAs demonstrate prominent restrictions to the supply of meat and crops, these services can recover to levels close to their demands within a certain range of $PA_{max}$. Fig. 5 illustrates more clearly the production levels that the two ecosystem services can reach under different values of $PA_{max}$. These plots demonstrate some common features. Both the crop and meat supply exhibit an inverted S-shaped curve. The supply of both ecosystem services is flat when $PA_{max}$ is approximately 0–0.34. There is a turning point around $PA_{max} = 0.34$ for crop and meat supply. These patterns imply that the modelled land use system has redundancy in supporting the production of these ecosystem services. As the available areas shrink, "buffer zones" of $PA_{max}$ exist that maintain the production of some ecosystem services at the same level.

### 3.3. Experiment 3: the joint impact of Policy-SD and Policy-PD

Fig. 6 shows that combining Policy-SD and Policy-PD can make a difference in habitat diversity provision. A noticeable trend is that habitat diversity supply increases as $PA_{max}$ increases, but the rate of increase decreases, whilst adjusting the goal of Policy-SD has little effect. However, the contrast between the peripheral short bars in dark colours and the higher bars surrounded by them indicate that both the policy goal of Policy-SD and $PA_{max}$ controlled by Policy-PD are indispensable to achieve a higher level of habitat diversity, which confirms the previous speculation about the joint impact of both economic incentives and PAs.

### 3.4. Experiment 4: the impact of inertia constraints of Policy-PD

In this experiment, the Nature Institution and Agriculture Institution are involved simultaneously. The inertia constraints of Policy-PD are changed to see if gradually expanding protected areas is better at meeting the policy goals than radical expansion. A larger value of policy inertia constraint indicates that the Nature Institution can expand PAs more radically within a single iteration. The results (Fig. 7) do not show a smooth spectrum of variations as the policy inertia constraint gradually increases. Instead, there are a multitude of supply curves overlapping one another when the policy inertia constraint is relaxed. In

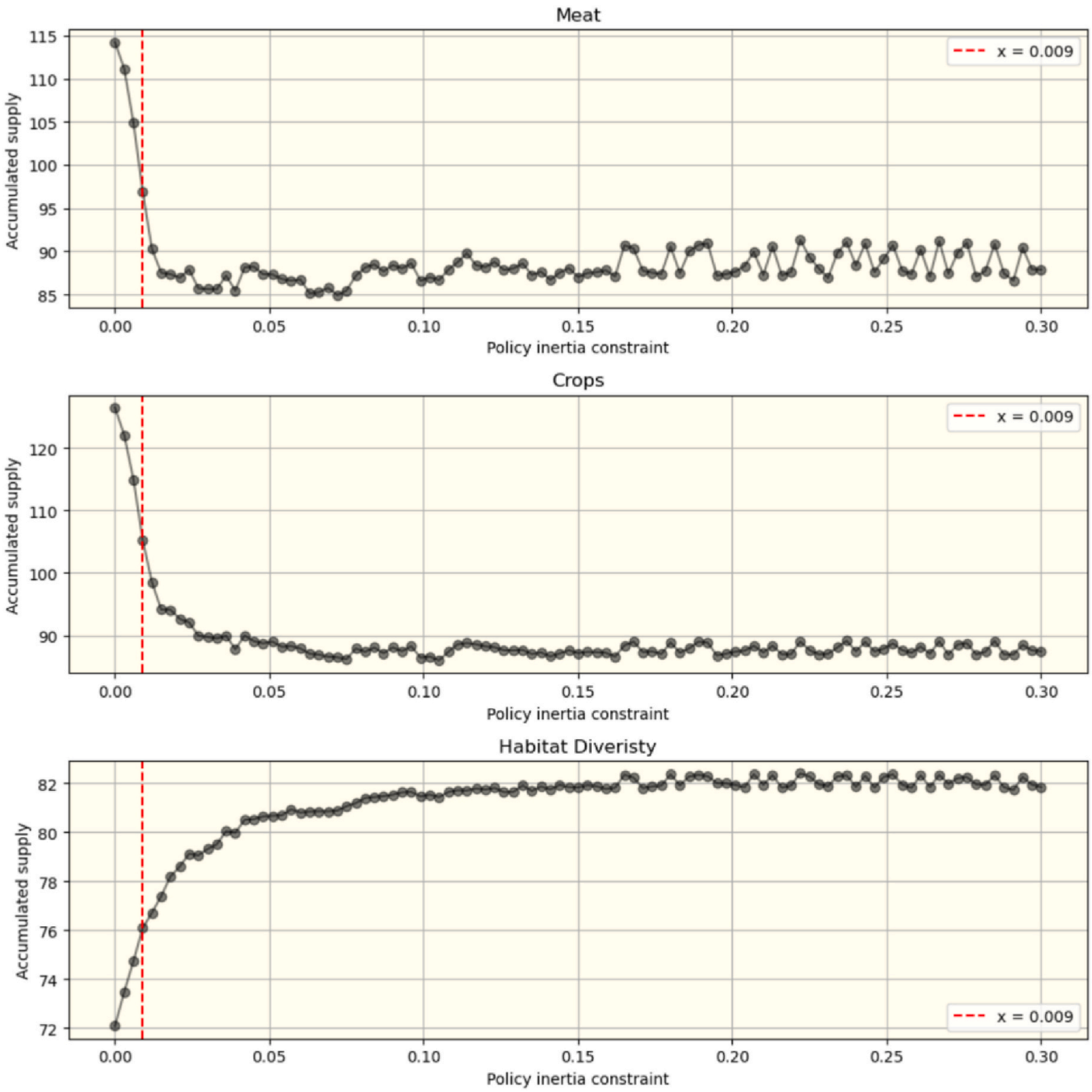


**Fig. 9.** Accumulated ecosystem service supply under different policy inertia constraints of Policy-PD. Accumulated supply indicates the sum of relative supply that is expressed as the proportion of supply at timestep 0.

contrast, when the policy inertia constraint is tight, supply curves do not show a consistent trend, which is particularly prominent in meat production as the supply curves in dark colours behave differently within $t_1$ years. Particularly for meat supply, there is a great contrast between supply in the low policy inertia scenarios (dark-coloured curves). The inconsistency in the supply trend when policy inertia is high is counter-intuitive.

To visualize this inconsistency more clearly, the meat supplies at $t_1$ are plotted with their corresponding policy inertia constraints of Policy-PD in Fig. 8 (a). Meat supply starts from a high level (2.0 times the initial supply) and drops rapidly before the policy inertia constraint reaches 0.009. The meat supply then increases gradually before eventually plateauing. Fig. 8 (a) shows the inconsistency of meat supply when the policy inertia constraint is extremely low and the convergence of meat supply in most cases when the policy inertia constraint is comparatively high.

The results demonstrate that if the institutions attempt to use PAs to aid Policy-TM in lowering meat production at $t_1$, there exists an optimal policy inertia constraint to expand PAs. However, if the institutions expect to enlarge the PAs while avoiding a drastic impact on meat production at $t_1$, it is safer to set the policy inertia constraint to a high value, which implies that prescribing all protected areas at the beginning of the simulation is most effective. A plausible reason why such a pattern emerges is that extremely low policy inertia constraint (less than 0.009) might not enable Nature Institution to expand the PAs to $PA_{max}$ within $t_1$, and therefore leaves more land available for meat production; while a high policy inertia (e.g., greater than 0.05) lets the land use system reach $PA_{max}$ early, and thus avoid continually interrupting meat production. If this hypothesis is valid, one might expect that the policy inertia constraint of 0.009 would enable protected areas to reach the maximum while using the longest time within $t_1$ years.

To examine this hypothesis, the timing (denoted as $\mathscr{T}$) when the proportion of PAs reaches $PA_{max}$ under different policy inertia constraints is depicted in Fig. 8 (b). It can be seen that with different policy inertia constraints $PA_{max}$ is reached in different years. This figure can be further converted to visualize the absolute distance of $\mathscr{T}$ from $t_1$, as shown in Fig. 8 (c). When the policy inertia constraint equals 0.009, the distance is shortest, indicating the land use system uses the longest time within $t_1$ to expand the PAs to $PA_{max}$ and corresponds precisely to the curve in Fig. 8 (c). Therefore, the hypothesis is confirmed.

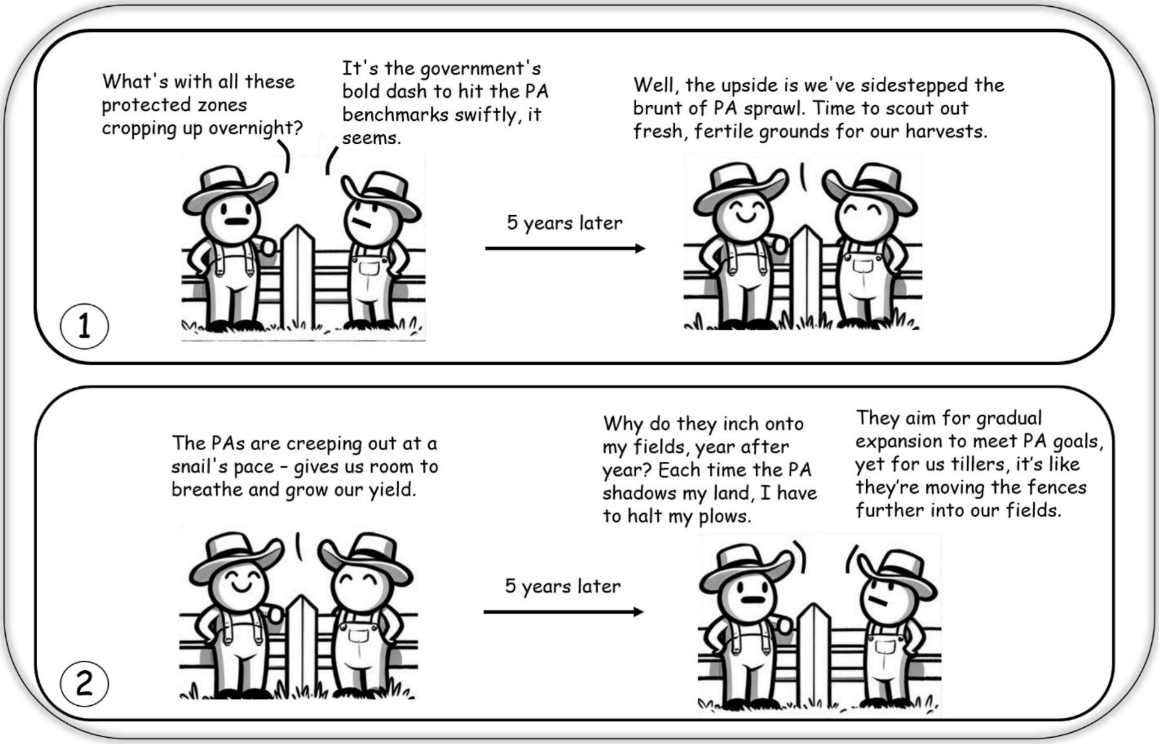


**Fig. 10.** Imagined conversations between two land user agents from the modelled land system to illustrate the impacts of radical and gradual PA expansion on land users' activities. The simulation results exhibit some advantages of radical PA expansion, which probably has not yet been sufficiently discussed.

It seems that gradually expanding protected areas is also helpful for Policy-TM in lowering meat production (Fig. 8 (a)). However, it is noteworthy that hitting a low level of meat production at $t_1$ does not necessarily mean obtaining a low level of accumulated quantity over time. Fig. 9 exhibits the accumulated production of different ecosystem services from $t = 0$ to $t = t_1$ under different policy inertia constraints. A very tight policy inertia constraint is neither beneficial for reducing meat production nor for boosting habitat diversity. Contrarily, loose policy inertia constraints are conducive to both targets.

Based on the analysis above, we find that gradually expanding protected areas can lower meat production at a specific point in time. Gradual expansion works because it imposes unremitting interruption on the ongoing meat production activities, which can be regarded as a "goalpost-moving strategy". However, gradual expansion does not perform well in reducing accumulated meat production nor in increasing habitat diversity supply. In contrast, radical expansion helps the land use system delimit the protected areas in the early stage and thus results in better accumulative performance over time. In addition, radical expansion leaves the land users more freedom to manifest economically reasonable behaviours without being interfered with by frequent administrative disturbances, which is beneficial for the land use system to respond to market demand.

## 4. Discussion

### 4.1. Gradual versus radical PA expansion

This study examines the dynamic interactions between land use policies and their impacts, focusing specifically on how protected areas influence habitat diversity and agricultural production. These factors are modelled alongside other policies implemented by endogenous institutions aiming to balance habitat conservation with agricultural needs. The experiments capture multiple meaningful patterns that align with the model's mechanisms and resonate with existing literature. As illustrated in Table C1, this model effectively captures various patterns and has potential as a systematic framework for analyzing policy and land-use dynamics.

There is limited previous literature discussing the effects of protected area expansion at different rates. Our experiment with joint impacts of two institutions, with four policies in total, was an exploration of rapid versus gradual policy implementation. The results illustrate that slow PA expansion leads the land use system towards minimum levels of meat production. It exhibits synergies with Policy-TM, which aimed to reduce meat production at $t_1$ in the experiments. However, in-depth analysis shows that the meat reduction associated with gradual PA expansion is actually achieved through continual disruption to existing land users. In contrast, radical PA expansions perform better in reducing accumulated meat production across years while allowing meat production to respond to demand changes, and also enable PA expansion to achieve the planned geographical policy goal sooner, benefitting habitat diversity. In other words, if all PAs can be established very early, land managers can avoid utilising and relying on areas that will be protected in the future.

This finding is notably dependent on our assumption that PAs function effectively upon their establishment (and that they are therefore worth expanding, rather than consolidating). This is not always the case in reality (e.g., Adams et al., 2019; Kuempel et al., 2018; Le Saout et al., 2013), and evidence from countries that have undergone rapid expansion of PAs suggests that their environmental and wider land use impacts take time to develop as political, social and practical responses play out, often gradually (Amkieltiela et al., 2022; Gardner et al., 2018). While this could blur the distinction we observe between rapid and gradual change in PA extent, there is some evidence to support effective and rapid PA expansion that also limits undesired indirect effects, including via participatory processes that account for local land use and socio-economic and political contexts (e.g., Bruner et al., 2004; Pitman et al., 2021; Pringle, 2017). Given the urgent need to increase protection, as embedded in the Kunming-Montreal framework (CBD, 2022), developing these approaches further is a clear priority.

These results highlight the significance of regulatory predictability (Masur and Nash, 2022; World Bank, 2019). As Masur and Nash (2022) pointed out "It is essential for environmental protection that private actors be able to anticipate government regulation". Fig. 10 gives a vivid illustration to help comprehend this micro process by fabricating conversations between two farmers from the modelled land use system. Although, in the real world, radical PA expansion is likely to be more challenging due to high resistance and indirect negative impacts not modelled here, the findings agree with literature that emphasizes the importance of a participatory PA policymaking process to reduce interruptions and conflicts in PA management (Li and Han, 2023).

### 4.2. The confusion of 30 % PA as policy target

The comparison of gradual versus rapid PA expansion poses more questions about setting policy goals. In general, a clearly stated policy goal is tied to a specific time for achievement. For instance, the EU biodiversity strategy for 2030 sets out a target of protecting at least 30 % of EU land by 2030. This policy goal seems to confuse policy measures with policy goals. Establishing PAs is a policy measure, through which targets related to biodiversity can be achieved. This offers important insights into both institutional modelling and sustainability practices. It is also crucial to distinguish between the policy goals to be reached at a time point and those accumulated across a period of time. As demonstrated here, the policy indirectly reduced meat production at $t_1$, but does not necessarily reduce meat production accumulatively. Factors such as the time, protected area sizes, and ecosystem service production, should be seen as a manifestation of structural change in land use rather than a superficial numerical indicator to be achieved. Otherwise, substantial effort might be in vain because underlying policy goals are neglected and missed.

### 4.3. Further modelling effort

Modelling improvements are also likely to prove valuable. The simulations here represent a first step towards endogenising PA-related policy-making process, including some of its key imperfections (such as abstract targets, lack of information, and fragmented policy aims). Future developments could usefully include better representation of biodiversity as a principal outcome of PA policy, the broader policy context including other objectives that compete with environmental goals, and more accurate forms of protection within PAs. In particular, our findings relating to consequences for other European land uses and food production are strongly dependent on the immediate and strict control of land use change within PAs, which does not reflect current practice in many European countries (e.g., Jones-Walters and Čivić, 2013). Higher-resolution modelling of natural and social processes will also be advantageous in better demonstrating land managers' responses to changing policy and impacts on ecosystem services (Hummel et al., 2017; Jones et al., 2022). In addition, exploring alternative approaches to enhance the representation of policymakers might also lead to new insights, such as using large language models (Zeng et al., 2024a, 2024b) or optimization-based algorithms (Zeng et al., 2024c). These developments should provide greater understanding of the effects of different long-term policy pathways on a variety of specific outcomes that span environmental and socio-economic sectors.

## 5. Conclusion

This research examined the complex interplay between protected area (PA) policies and land use changes through an innovative application of the CRAFTY model, coupled with an endogenous institutional model, within a hypothetical scenario involving two key institutions: The Nature institution and the Agriculture institution. By exploring the conflicts and synergies between their varying policy objectives, this study has highlighted critical insights into policy and land-use dynamics, suggesting that a more outcome-focused approach could enhance the effectiveness of environmental policies.

## CRediT authorship contribution statement

**Yongchao Zeng:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Conceptualization. **Joanna Raymond:** Writing – review & editing, Validation, Methodology, Conceptualization. **Calum Brown:** Writing – review & editing, Writing – original draft, Validation, Project administration, Conceptualization. **Mark Rounsevell:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgements

This work was supported by the Helmholtz Excellence Recruiting Initiative, Climate Mitigation and Bioeconomy Pathways for Sustainable Forestry (CLIMB-FOREST; grant no. 101059888) and Co-designing Holistic Forest-based Policy Pathways for Climate Change Mitigation (grant no. 101056755) projects. We acknowledge support by the Karlsruhe Institute of Technology (KIT) Publication Fund.

## Appendix A

**Table A1**
Operational steps within an institutional agent.

| |
|---|
| **Step 2:** The institutional agent initializes policy targets, policy instruments, and other parameters needed for the institutional model. |
| **Step 3:** The institutional agent then collects information from the land use system. For instance, the production of ecosystem services, the AFT distributions, the capital distributions, the locations of the protected areas, etc. |
| **Step 4:** After data collection, the institutional agents determine if it is time to adapt the policy. This reflects time lags in policy interventions (Brown et al., 2019a). |
| **Step 5:** The model implements a PID (Proportional-Integral-Derivative) control mechanism to evaluate previous policy interventions. PID here represents three types of errors indicating the gaps between policy targets and actual policy outcomes. P means the proportional error; I represents the integral errors; D represents the derivative errors. |
| **Step 6:** A fuzzy logic controller is applied to adapt the current policies. The fuzzy logic controller allows to integrate experts' knowledge as IF-THEN rules within the institutional model. The coupled PID-fuzzy logic controller serves as a function that maps the target-outcome discrepancies onto policy adjustments. |
| **Step 7:** The adjusted policies are constrained by the policy inertia constraint mirroring the non-monetary resistance to policy changes. |
| **Step 8:** The policies are also constrained by the budget limitation. The model introduced a procedure to allocate the institution's budgets across all the policies that belong to the institution. **Step 9:** After all these procedures, policies for the new iteration are formulated and ready to be implemented in the land use model. |

**Table A2**
Parameterization of Nature Institution, Policy-SD, and Policy-PD for Experiment 1 and Experiment 2. Experimental variables are highlighted in bold.

| Nature Institution | | |
|---|---|---|
| **Institution parameter** | **Value** | |
| Unique ID | Nature | |
| Policies | Policy-SD, Policy-PD | |
| Information | Diversity supply, diversity demand, land capitals, protected areas | |
| Uncertainties | Null | |
| Budget | Unlimited | |
| Decision rules | Subsidy, Protection | |
| **Policy parameter** | **First policy** | **Second policy** |
| Unique ID | Policy-SD | Policy-PD |
| Target service | Diversity | Diversity |
| Policy Type | Subsidy | PA |
| Initial guess | 10000 | 10000 |
| Inertia constraint | 0.2 | 0.2 |
| Policy goal | **0–6** | **4 with $PA_{max}$ changing from 0.0 to 1.0** |
| Intervention | 0.0 | 0.0 |
| Intervention modifier | 0.0 | 0.0 |
| Evaluation result | 0.0 | 0.0 |
| Time lag | 5 | 5 |
| Timer | Equal to Time lag | Equal to Time lag |
| Adapting | False | False |

**Table A3**
Parameterization of Nature Institution, Policy-SD, and Policy-PD for Experient 3. Experimental variables are highlighted in bold.

| Nature Institution | | |
|---|---|---|
| **Institution parameter** | **Value** | |
| Unique ID | Nature | |
| Policies | Policy-SD, Policy-PD | |
| Information | Diversity supply, diversity demand, land capitals, protected areas | |
| Uncertainties | Null | |
| Budget | Unlimited | |
| Decision rules | Subsidy, Protection | |
| **Policy parameter** | **First policy** | **Second policy** |
| Unique ID | Policy-SD | Policy-PD |
| Target service | Diversity | Diversity |
| Policy Type | Subsidy | Protected areas |
| Initial guess | 10000 | 10000 |
| Inertia constraint | 0.2 | 0.2 |
| Policy goal | **1.0–3.0** | **Same as Policy-SD's goal but with $PA_{max}$ from 0.0 to 1.0** |
| Intervention | 0.0 | 0.0 |

(continued on next page)

**Table A3** (*continued*)

| Nature Institution | | |
|---|---|---|
| Intervention modifier | 0.0 | 0.0 |
| Evaluation result | 0.0 | 0.0 |
| Time lag | 5 | 5 |
| Timer | Equal to Time lag | Equal to Time lag |
| Adapting | False | False |

**Table A4**
Parameterization of Agriculture Institution, Policy-TM, Policy-SC, Nature Institution, Policy-SD, and Policy-PD for Experient 4. Experimental variables are highlighted in bold.

| Agriculture Institution | | |
|---|---|---|
| **Institution parameter** | **Value** | |
| Unique ID | Agriculture | |
| Policies | Policy-TM, Policy-SC | |
| Information | Crop supply, crop demand, meat supply, meat demand | |
| Uncertainties | Null | |
| Budget | Unlimited | |
| Decision rules | Tax, Subsidies | |
| **Policy parameter** | **First policy** | **Second policy** |
| Unique ID | Policy-TM | Policy-SC |
| Target service | Meat | Crops |
| Policy Type | Tax | Subsidy |
| Initial guess | 1000000 | 1000000 |
| Inertia constraint | 0.2 | 0.2 |
| Policy goal | 1.0 | 4.0 |
| Intervention | 0.0 | 0.0 |
| Intervention modifier | 0.0 | 0.0 |
| Evaluation result | 0.0 | 0.0 |
| Time lag | 5 | 5 |
| Timer | Equal to Time lag | Equal to Time lag |
| Adapting | False | False |
| **Nature Institution** | | |
| **Institution parameter** | **Value** | |
| Unique ID | Nature | |
| Policies | Policy-SD, Policy-PD | |
| Information | Diversity supply, cell capitals | |
| Uncertainties | Null | |
| Budget | Unlimited | |
| Decision rules | Subsidy, Protection | |
| **Policy parameter** | **First policy** | **Second policy** |
| Unique ID | Policy-SD | Policy-PD |
| Target service | Diversity | Diversity |
| Policy Type | Subsidy | Protected areas |
| Initial guess | 10000 | 10000 |
| Inertia constraint | 0.2 | **0.0–0.3** |
| Policy goal | 3.0 | Same as Policy-SD's goal but with $PA_{max} = 0.36$ |
| Intervention | 0.0 | 0.0 |
| Intervention modifier | 0.0 | 0.0 |
| Evaluation result | 0.0 | 0.0 |
| Time lag | 5 | 5 |
| Timer | Equal to Time lag | Equal to Time lag |
| Adapting | False | False |

## Appendix B

**Table B1**
Parameterization of Decision Rule labelled as "Protection"

```
FUNCTION_BLOCK Protection
VAR_INPUT
  gap: REAL;
END_VAR
VAR_OUTPUT
  intervention: REAL;
END_VAR
FUZZIFY gap
  TERM plow:= (0,1) (0.15,0);
  TERM plight:= (0.025, 0) (0.175, 1) (0.325,0);
  TERM pmild:= (0.175,0) (0.325,1) (0.45,0);
  TERM phigh:= (0.325, 0) (0.45, 1);
END_FUZZIFY
DEFUZZIFY intervention
  TERM neutral:= (0,1) (0.075,0);
  TERM plight:= (0.025,0) (0.075,1) (0.125,0);
  TERM pmild:= (0.075,0) (0.125,1) (0.175,0);
  TERM phigh:= (0.125,0) (0.2,1);
  METHOD: COG;
  DEFAULT = 0;
END_DEFUZZIFY
RULEBLOCK No1
  AND: MIN;
  ACT: MIN;
  ACCU: MAX;
  RULE 0: IF gap IS plow THEN intervention IS neutral;
  RULE 1: IF gap IS plight THEN intervention IS plight;
  RULE 2: IF gap IS pmild THEN intervention IS pmild;
  RULE 3: IF gap IS phigh THEN intervention IS phigh;
END_RULEBLOCK
END_FUNCTION_BLOCK
```

## Appendix C

**Table C1**
Key results, interpretation, and their connection with existing literature

| Experimental Policies | Key resultant patterns | Explanation by model mechanisms | Related literature |
|---|---|---|---|
| **Experiment 1:** Policy-SD | Negligible impact of subsidies on habitat diversity. | All land users produce mixed services and compete based on total utility, with habitat diversity offering lower benefits compared to crops and meat. | Nature conservation measures may yield too little profit relative to agricultural production, and hence not effective in boosting sustainable land use management (Crook and Clapp, 1998); Income from carbon and biodiversity services does not cover the expected agricultural losses from land-use changes (Baral et al., 2014). |
| **Experiment 2:** Policy-PD | Negative impact of PA establishment on meat and crop production; | Protected areas reduce land available for agricultural production; stable demand for habitat diversity does not incentivize land users to increase habitat diversity. | Trade-off exists between biodiversity and food security (Vijay and Armsworth, 2021). Protecting natural areas from agricultural expansion (Schmitz et al., 2023). |
| | PAs alone have no notable impact on habitat diversity. | Since low economic incentives are not enough to increase habitat diversity, it is plausible that protected areas with no economic incentives are not able to drive land users to improve habitat diversity. | Literature (e.g., Baral et al. (2014) and Crook and Clapp (1998)) that highlights the lack of profitability in terms of nature conservation activities also applies here. |
| **Experiment 3:** Policy-SD, Policy-PD | Subsidies together with PA are more effective in enhancing habitat diversity. | Synergistic effect of protected areas and subsidies on increasing habitat diversity, which filters out the influence of other ecosystem services on total utility while offering economic incentives. | Policies that bring economic incentives show effectiveness in natural conservation in the studied PAs (Lu et al., 2006); Socio-economic incentives contribute significantly to the studied rehabilitated areas (Chami, 2016); Economic incentives are promising for biodiversity conservation within the studied protected areas (Muchapondwa et al., 2012). |

(*continued on next page*)

**Table C1** (*continued*)

| Experimental Policies | Key resultant patterns | Explanation by model mechanisms | Related literature |
|---|---|---|---|
| **Experiment 4:** Policy-SD, Policy-PD, Policy-TM, Policy-SC | Long-term recoverability of meat and crop production; | Land user agents are motivated to adapt by moving to more suitable land in the long run and able to maintain the desired agricultural production level. | Agricultural production is becoming concentrated in more suitable areas, while marginal agriculture areas and extensive grazing decrease (Izquierdo and Grau, 2009); Increasing the extent or protection level of PAs generally did not undermine the EU-wide supply of ecosystem services (Staccione et al., 2023). |
| | Radical PA expansion is more effective in reducing meat production if the target of PA expansion is prescribed. | Radical expansion achieves maximum coverage quickly while avoiding frequent disruption to land user adaptation. | Literature on the expansion rate of PAs is limited. Further studies are needed to examine this finding further. More discussion on this can be found in Section 4.1. |

## Data availability

Datasets for this research are available at https://osf.io/3thsm/. The code used in this study can be accessed at https://github.com/YcZen/CRAFTYMason.git.

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