Introducing wetland offset markets under development-restoration conflicts: The role of public offset credit supply

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Abstract: Wetland offset markets (WOMs) are increasingly applied worldwide as powerful tools for mitigating conflicts between wetland development and restoration. Reducing benefit uncertainty is key to promoting private restoration and introducing WOMs, which necessitates sufficient and stable price signals. Given that governments are important suppliers in WOMs, this article aims to explore the role of public offset credit (OC) supply in delivering and adjusting price signals during WOM formation and evolution. A general spatial agent-based wetland offset market model is built to simulate landowners' behavior, price dynamics, and WOM evolution under different public OC supply schemes. The results show that the spontaneous formation of WOMs is a time-consuming process. Price signals of public OCs reduce price fluctuations at the early stage of WOMs. This price stabilizing effect can cause a long-term reduction in benefit uncertainty perceived by landowners. Therefore, public OCs can facilitate WOM formation either through the supply side with high supply prices or through the demand side with low supply prices. During the entire WOM evolution process, due to landowners' readaptation, cheap public OCs can cause significant market fluctuations following the ceasing of cheap public supplies. The impacts of public OC on wetland development and restoration might change over time, and the suitability of public OC supplies under different long-term wetland management preferences was analyzed. These findings can further the understanding of the process of introducing a new market mechanism, such as WOMs, and the role of the government as a supplier. The research results provide insights for WOM practices, public restoration and OC supply scheme design, and wetland development-restoration conflict coordination.

Keywords: Wetland offset market; Public offset credit supply; Wetland development-restoration conflict; Agent-based model; Price signal

1. Introduction

Wetlands play a significant role in providing critical ecosystem services such as climate regulation (UN Water, 2018; Zou et al., 2018). However, worldwide wetland areas are notably decreasing due to human activities (Davidson, 2014; Gardner and Finlayson, 2018; UN Water, 2018), especially in developing countries with high development demands. (Bruner et al., 2004; Failler et al., 2019; Lynch et al., 2016; Wang et al., 2022). Effective management and coordination of the mounting conflicts between wetland development and restoration are of paramount importance for attaining sustainable development goals.

For a long time, wetland restoration has been dominated by the public sector, such as national reserved areas (Bonneuil, 2015; Hahn et al., 2015; Kangas and Ollikainen, 2019; Wissel and Wätzold, 2010). However, limited fiscal budgets greatly constrain wetland restoration (Bruner et al., 2004; Failler et al., 2019; Lynch et al., 2016; Wang et al., 2022). Moreover, within government-led restoration mechanisms, the responsibility for addressing wetland degradation shifts from developers to governments. This shift disrupts the nexus between development and restoration and thereby increases the difficulty in synchronizing wetland restoration efforts with the pace of economic growth. In this context, wetland offset markets (WOMs) are increasingly gaining focus worldwide (Bennett et al., 2017; Bernasconi et al., 2016; Salès et al., 2023; Villarroya et al., 2014).

WOMs are practices of tradable permits in the field of biodiversity offset and are also called mitigation banking (Salvesen et al., 2013), conservation banking (Bruggeman et al., 2009), conservation offset (Drechsler, 2022), ecosystem offset markets (Ungaro et al., 2022), etc. Offset credits (OCs) are used in WOMs to quantify the ecosystem losses/gains caused by development/restoration activities. Developers can buy ecologically equivalent OCs from restorers to offset their negative development impacts on wetlands (BenDor et al., 2011; Koh et al., 2019; Needham et al., 2019). Therefore, WOMs hold the potential, in theory, to achieve a "no net loss" of wetlands while simultaneously achieving economic growth (Alvarado-Quesada et al., 2014; McKenney and Kiesecker, 2010; Simpson et al., 2022).

Specifically, based on OC and OC prices, the process of environmental cost internalization can strengthen value connections between wetlands and individual behavior. Differences in individual costs create opportunities for mutually beneficial transactions between developers and restorers (Koh et al., 2019; Wissel and Wätzold, 2010), which can motivate developers to minimize ecological impacts and attract more private restoration endeavors (Boisvert et al., 2013; Coralie et al., 2015; Needham et al., 2019; Taherzadeh and Howley, 2018). Consequently, WOMs can effectively supplement the limited government funding for wetland restoration, and the primary question for WOM practices lies in how to introduce WOMs.

One of the main challenges in introducing WOMs is how to motivate the private OC supply. First, well-functioning WOMs rely on a sufficient scale of supply and demand (Needham et al., 2019; van Teeffelen et al., 2014). Demands in WOMs are generated mainly from regulations and economic development (BenDor et al., 2011; Vaissière and Levrel, 2015), and how to drive private sectors to restore wetlands and become OC suppliers is a key problem for WOMs. However, the high upfront cost of restoration and the lagging return due to restoration duration cause great benefit uncertainty for OC suppliers (Alvarado-Quesada et al., 2014; Bonneuil, 2015). In addition, the inherent uncertainty in wetland restoration due to the complexity of ecosystems might lead to poor restoration results and reduce the amount of OCs that restorers can obtain (BenDor et al., 2011; Bull and Strange, 2018; van Teeffelen et al., 2014). Private sector businesses are unable to fully understand the possible gains from WOMs due to the above factors, which discourages them from becoming OC suppliers (Alvarado-Quesada et al., 2014; Bonneuil, 2015). Therefore, sufficient and stable price signals might be keys to introducing WOMs, and external support is important for price signal formation during this process.

Public OC supplies play an important role in WOMs (Bonneuil, 2015; Froger et al., 2015; Vaissière and Levrel, 2015). In the United States, it was the collaboration between the government and private firms that facilitated the emergence of the first OC supplier, thereby driving the development of WOMs (Bonneuil, 2015). As previously mentioned, wetland restoration is led mainly by the public sector, indicating that the government might be the initial OC supplier during the introduction of WOMs. Therefore, the public OC supply can be a critical instrument in shaping sufficient and stable price signals when introducing WOMs.

Although there are an increasing number of WOM studies, most of them are based on the postformation stage of WOM practices to explore institutional nature (Boisvert, 2015; Koh et al., 2019; Vaissière and Levrel, 2015), required institutional conditions(Alvarado-Quesada et al., 2014; Maron et al., 2012; McKenney and Kiesecker, 2010), key WOM mechanism design and impacts (Simpson et al., 2021, 2022; Doyle and Yates, 2010; Drechsler, 2022; Kangas and Ollikainen, 2019), and market performance(Bennett et al., 2017; Simpson et al., 2021). There is a lack of studies that focus on problems in the introduction of a new environment market mechanism, such as WOMs, especially on price signal formation and evolution. In addition, although some scholars have noted the importance of government intervention in regulating market failure, they have focused mainly on monitoring and regulatory institutions (BenDor et al., 2011; Levrel et al., 2017; van Teeffelen et al., 2014), and very few studies have explored the role of governments play as suppliers when implementing public restoration programs. Limited studies have noted the possible extrusion effects of public OC supply on private supply (Bennett et al., 2017; Salvesen et al., 2013), while the price delivery and adjustment functions of public OC supply are still underexplored.

Therefore, this study attempts to explore the role of public OC supply in WOM introduction and evolution processes. A spatial agent-based model (ABM) was built to simulate price signal transfer, WOM evolution and land use dynamics under different public OC supply scenarios. Specifically, this study attempts to explore four questions: (1) what is the spontaneous formation process of WOM? (2) what is the role of public OC supply in WOM formation? (3) what are the impacts of public OC supply on WOM evolution over time? and (4) what are the suitable public OC supply schemes under different wetland management preferences?

This research has the following contributions. First, this study provides a general spatial agent-based model that can be used to analyze the introduction process of a new market mechanism. Second, from the perspective of price signals, our findings add more understanding to WOM formation and the functions of public restoration and OC supply schemes. Third, the study provides a simulation instrument and implications for the formation of other environmental markets (e.g., the carbon market).

2. Methodology

2.1. Theoretical analysis

Given the effects of motivating private restorers and coordinating wetland development-restoration conflicts, WOMs are being increasingly applied worldwide. However, the presence of benefit uncertainty in wetland restoration significantly impacts private restoration, thus influencing the formation and development of WOM. Consequently, reducing benefit uncertainty in restoration is essential for introducing WOMs.

Sufficient and stable price signals play a crucial role in mitigating benefit uncertainty (Boisvert, 2015; Ribaudo et al., 2010). On the one hand, the price signal should be adequate to cover the costs incurred by wetland restoration, including the restoration cost and opportunity cost. However, given the substantial demand for development in most regions, the price signal should not be too high to discourage local development (Wissel and Wätzold, 2010). On the other hand, significant price fluctuations can exacerbate benefit uncertainty (Wissel and Wätzold, 2010), implying the importance of maintaining a stable price signal.

Price signals may be released from various sources, including the market (e.g., transaction price), market participants (e.g., willingness to pay), and the government (e.g., government guidance price). The introduction of WOM is a market creation process (Boisvert, 2015; Bonneuil, 2015). During this process, environmental costs are internalized with OCs, which requires the transition of private sectors from a state where environmental costs are disregarded to one where these expenditures are factored into their financial considerations. The latter state is often referred to as the "developer pays" rule (Koh et al., 2017). Before WOMs are created, the private sector faces difficulties in ascertaining transaction prices and lacks price benchmarks from comparable products. Moreover, the information asymmetry causes barriers for individuals in accurately obtaining price signals from other market participants. Given the insufficient price signals originating from the market and its participants, the price signal provided by the government plays a significant role in the WOM formation process. In this context, this study intends to explore the role of public OC supply in delivering and adjusting price signals during WOM formation and evolution.

The price, quantity, and duration of public OC supply are the main focuses of this study. The price of the public OC supply can directly influence the OC price perceived by the private sector, while the quantity of public OC supply can indirectly adjust transaction prices by affecting the OC supply-demand relationship. Furthermore, the duration of public OC supply changes the functioning period of public price signals. To simplify the problem, public OCs are supplied at a fixed quantity and uniform price: the government provides a consistent quantity of public OCs every year throughout the supply duration, with the supply price remaining constant during a transaction period (one year in this study) albeit subject to periodic adjustments.

The role of public OC supply is analyzed by comparing WOM evolution results without and with public OC supply. The price signal is considered the primary driver of WOM formation, and the level of the price signal is measured by the ratio of the transaction price to the average cost per OC. This metric is employed to assess the role of public OC supply in delivering and adjusting price signals.

WOM formation and evolution results are used for evaluating the effects of public OC supply. The market appearance time, price variation and benefit uncertainty perceived by landowners are used to analyze the role of public OC supply in facilitating WOM formation. Specifically, the market appearance time is measured by the time that the first OC transaction appears, which reflects the time needed for WOM formation.

The regional ecological and economic results are considered when analyzing WOM evolution. Regional economic outcomes are assessed through the development scale (i.e., the proportion of economic parcels). In addition to assessing the restoration scale (i.e., the proportion of restored parcels), we consider the ecological clustering of restoration to be a crucial metric for evaluating ecological outcomes, given its importance for species survival and wetland recovery. Additionally, the total ecological value was analyzed to compare the impacts of restoration scale and clustering and to reflect the ultimate ecological results.

According to the evolution of the first WOM in the United States, developers were initially mandated to offset development impacts themselves (Bonneuil, 2015), and the cost difference between private sectors gradually facilitates transactions between developers and restorers. Therefore, we assume that the negative ecological impacts of development (i.e., development impacts) can be mitigated through self-offsetting or purchasing OCs within WOMs.

2.2. Spatial agent-based wetland offset market model

2.2.1. Model overview

The spatial agent-based wetland offset market model developed in this study is used to simulate the initiating process of a WOM and examine the role of public OC supply. The model operates on a yearly time step, and this section provides an overview of the model. The model consists of four types of agents: (1) spatial agents, (2) landowner agents, (3) the government agent, and (4) the WOM agent. A flowchart depicting the spatial agent-based wetland offset market model is presented in Fig. 1.

The model simulates an L×W coastal region. Each spatial agent represents a land parcel, and all spatial agents compose the geographical landscape of the model. Based on their land use status, spatial agents are categorized into economic parcels, original ecological (OE) parcels, restored ecological (RE) parcels, spare parcels, and sea areas. The economic, OE and RE parcels have associated landowners. Spare parcels represent abandoned regions to be restored, and these parcels have no owners but can be bought by landowners for restoration and for generating OCs. Sea areas represent the sea and coastal line, which have no landowners. For simplification, public parcels used for generating public OCs are not considered in the model.

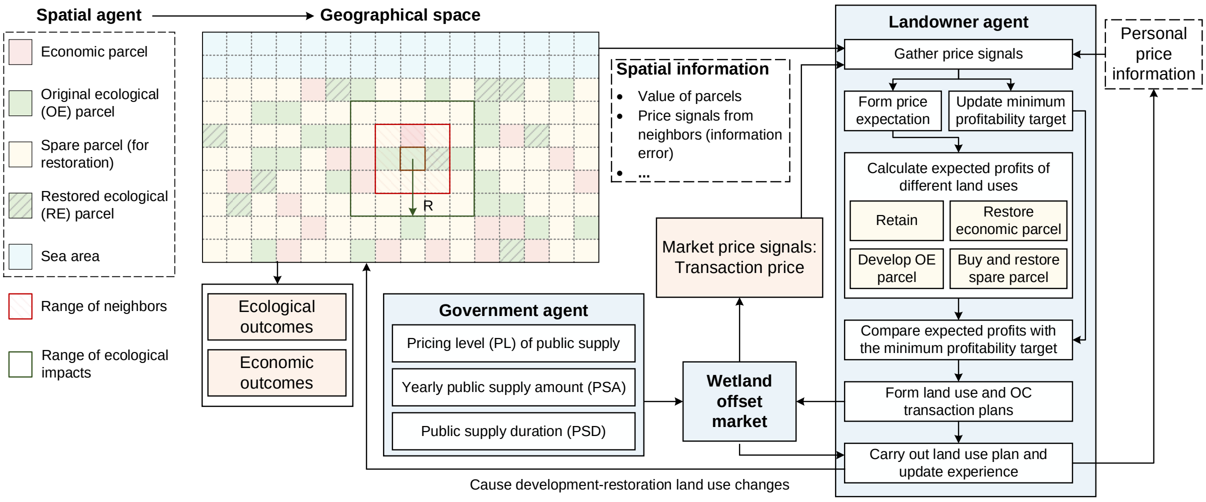

Fig. 1. Flowchart of the spatial agent-based wetland offset market model.

Each spatial agent has both economic value and ecological value. The economic value is determined according to the distance to the sea and macroeconomic growth. The ecological value of spatial agents is the basis for accounting and releasing OC. The ecological value correlation between spatial agents is considered in the model and is used to reflect the ecological spatial agglomeration effects.

NLO landowner agents are randomly distributed within the space and make decisions regarding land use and OC trading. Each landowner agent initially owns one spatial agent, which could be an economic or OE parcel. According to the status of the originally owned parcels, landowner agents are categorized into economic parcel owners, OE parcel owners, and RE parcel owners. Landowner agents gather price signals, form minimum profitability targets and expected OC prices, calculate expected gains from different land use plans, and subsequently make decisions regarding land use and OC transactions.

The government agent formulates the public OC supply scheme, participates in WOM, and releases OCs to private landowners. A practical OC release mechanism typically combines advanced release and scheduled release to alleviate economic pressures on restorers and mitigate the risk of substandard restoration, due to issues such as fraud and uncertainty (BenDor et al., 2011). In the advanced release mechanism, restorers can obtain partial OCs at the beginning of restoration; in the scheduled release mechanism, OCs are allocated according to the restoration progress. For simplification, the advanced release approach is applied in the model, in which restorers can obtain partial OCs at the beginning of restoration and obtain the remaining OCs at the end of restoration.

The WOM agent gathers OC transaction plans from landowner agents and matches buyers and sellers. The model utilizes a discriminatory auction mechanism for transactions. Under this mechanism, sellers' bids and buyers' bids are sorted in ascending and descending order based on the bid price, and the clearing price of each successful match is set at the average of matched bidders' bid prices. Within each transaction period (one year in the model), the auction is repeated until no OC supply or demand remains. The WOM agent publishes the average transaction price of all successful matches at the end of each transaction year.

We assume that the government agent provides restoration schemes and relevant information, and that landowner agents know their restoration costs and the ecological value of their lands. However, landowner agents lack clear information about current and future credit prices. To simplify the problem, landowners are assumed to strictly adhere to the restoration scheme when they decide to restore their parcels or spare parcels. Consequently, the benefit uncertainty in restoration primarily arises from OC prices in the model.

Three types of price signals are considered in the model: individual experiences, price information from neighbors, and transaction prices (including public OC prices). At the beginning of the simulation, no OC transactions happened before. In the absence of public OCs, potential developers (i.e., OE parcel owners) first form OC price expectations by deciding whether to buy and restore spare parcels for development, which acts as the initial price signal. When public OCs are introduced, the transaction price (i.e., the public supply price) between new developers and the government acts as the initial price signal. Specifically, when public OCs are provided, potential developers first attempt to purchase OCs from the government if the public supply price is lower than their price expectations. OE parcel owners with higher economic outcomes have priority when buying public OCs.

To maintain model dynamics and align with the actual policy process, which often involves multiple stages and varying scopes, as described in the studies of Brown et al., (2018) and Kandiah et al., (2019), the spatial range for implementing WOM is assumed to gradually expand throughout the entire geographical space. Therefore, according to the study of Kandiah et al., (2019), landowner agents at different locations are progressively activated over time. Only activated landowner agents can make decisions related to land use and OC transactions within the model.

OC transactions between developers and restorers typically require ecological equivalence. In practice, the trading ratio, i.e., the ratio of OCs a developer needs to offset to the OCs it consumes, is applied to address ecological risks stemming from spatial and temporal disparities between development and restoration. For example, when the trading ratio is 1:1.4, development activity consumes 1 unit of OC, while the developer needs to purchase 1.4 units of OC to offset the development impact. Therefore, the trading ratio can affect the supply-demand relationship and transaction price of OCs. Given that this study mainly focuses on the role of public supply, the trading ratio is treated as a constant in the model.

2.2.2. Submodel of spatial agents

Spatial agents have both economic value and ecological value. The economic value of the development of the *i*-th parcel $v_{i,t}^{\text{develop}}$ in the *t*-th year is assumed to decrease with the increasing distance to the sea d_i. The economic growth rate of the *i*-th spatial agent is r_i, $r_i \sim U(r_{\min}, r_{\max})$, and $v_{i,t}^{\text{develop}}$ can be obtained by Eq. (1).

$$v_{i,t}^{\text{develop}} = (a_{i,t} - \frac{\alpha d_i}{d_{\max}})(1+r_i)^t \tag{1}$$

$a_{i,t}$ is the basic development value of the *i*-th spatial agent at the *t*-th time step, and $a_{i,t} \sim U(a_{\min}, a_{\max})$. $d_{\max}$ is the maximum distance to the sea in the model, and α is the decreasing degree of the development value with the distance to the sea. $v_{i,t}^{\text{develop}}$ is also the annual gain of economic parcels.

According to Drechsler and Wätzold (2009), the ecological value of spatial agents consists of two parts: inherent value and locational value. The latter reflects the ecological impacts of neighboring parcels. The ecological value is assumed to be immediately lost as the parcel is developed. The inherent value of the original ecological parcels is b_i, and the original ecological value $v_{i,t}^{\text{ecology-o}}$ can be obtained by Eq. (2).

$$v_{i,t}^{\text{ecology-o}} = b_i + \lambda \sum_{k=0}^{NE(t,R)} b_k \tag{2}$$

λ represents the ecological impacts of nearby ecological parcels, including OE and RE parcels. $NE(t,R)$ is the number of nearby ecological parcels within radius R at time t. Therefore, the ecological value of each spatial agent increases with the number of nearby ecological parcels. The original ecological value is used as the restoration goal, and the development impacts need to be offset. This means that the OCs that developers need to obtain and the OCs that restorers can obtain increase with the number of nearby ecological parcels.

The restoration results might be lower than the parcel's original ecological value due to factors such as ecosystem complexity and restorer ability. Given the perfectly compliant landowners assumed in the model, the final restored level of spatial agents, including economic and spare parcels, depends on the restoration ability δ_j of the *j*-th landowner agent (see the Supplementary File) and the random restoration risk ε. Hence, the parcel's ecological value after restoration $v_{i,t}^{\text{ecology-r}}$ can be obtained by Eq. (3).

$$v_{i,t}^{\text{ecology-r}} = b_i \bullet \min(1, \delta_i + \varepsilon) + \lambda \sum_{k=0}^{NE(t,R)} b_k \tag{3}$$

Spare parcels can be bought only by landowners for restoration. For simplification, the land market for spare parcels is not considered in the model, and all spare parcels are set at the same price. The price of spare parcels p_t^{parcel} is the net present value obtained with the average economic value of economic parcels $\bar{v}_t^{\text{economy}}$ and the regional average economic growth rate $\bar{r}$.

$$p_t^{\text{parcel}} = \sum_{k=0}^{\infty} \bar{v}_t^{\text{economy}} (1+\bar{r})^k \tag{4}$$

2.2.3. Submodel of offset credit accounting and release

Assuming that the ecological value corresponding to one OC is u_{ev} , the number of OCs $n_{i,t}^{\text{OC}}$ corresponding to each parcel's original ecological value $v_{i,t}^{\text{ecology-o}}$ can be obtained by Eq. (5). The trading ratio (i.e., the ratio of OCs a developer needs to offset to OCs it consumes) is set as φ , and the number of OCs needed to be offset by developing an OE parcel is $\varphi n_{i,t}^{\text{OC}}$:

$$n_{i,t}^{\text{OC}} = \frac{v_{i,t}^{\text{ecology-o}}}{u_{\text{ev}}} \tag{5}$$

Suppose that the government agent does not know about landowner agents' restoration ability and calculates the OCs generated by restoration according to the parcel's original ecological value $v_{i,t}^{\text{ecology-o}}$ (i.e., $n_{i,t}^{\text{OC}}$). The advanced release ratio is ρ (see Section 2.2.1); therefore, the number of OCs n_t^{r0} that the restorer can obtain at the beginning of the restoration is equal to $\rho n_{i,t}^{\text{OC}}$. The remaining OCs that the restorer can obtain at the end of the restoration are calculated and released according to the actual restoration results. Therefore, the OCs that the restorer can obtain at the end of the restoration n_t^{r1} can be obtained by Eq. (6).

$$n_t^{\text{r1}} = \frac{v_{i,t}^{\text{ecology-r}}}{u_{\text{ev}}} - \rho n_{i,t}^{\text{OC}} \tag{6}$$

2.2.4. Submodel of the government agent

Public OCs are generated from restoring public lands by the government, e.g., the national reserved area. To simplify our problem, the process of restoring public lands is not included in the model.

The amount of public OCs supplied each year is PSA, and the duration of public OC supply is PSD , which corresponds to the duration of the public restoration program. The price of public OCs is p_t^{gov} in the t-th year, and p_t^{gov} is fixed within the same transaction year. The government agent is assumed to have full information on the gains from economic parcels. Given that landowners can buy and restore spare parcels to offset their development impacts, the cost of buying and restoring spare parcels constitutes the landowners' opportunity cost of buying OCs. Therefore, the price of spare parcels and the restoration cost are used as references for calculating the public OC supply price p_t^{gov} .

$$p_t^{\text{gov}} = \frac{PL(p_t^{\text{parcel}} + C_r)}{\overline{n}^{\text{OC}}} \tag{7}$$

C_r is the total restoration cost per parcel, which is provided by the government agent and is set at the same value for all parcels. $PL > 0$ is the pricing level of public OC. Because p_t^{parcel} measures the average economic value of economic parcels, $\frac{p_t^{\text{parcel}} + C_r}{\overline{n}^{\text{OC}}}$ actually represents the average cost per OC. Therefore, $PL < 1$ means that the public supply price is lower than the average cost per OC, $PL = 1$ means that the public supply price is equal to the average cost per OC, and $PL > 1$ means that the public supply price is higher than the average cost per OC.

2.2.5. Submodel of landowner agents

Landowner agents aim to maximize their profits through their land use decisions. Specifically, the potential developers, or OC buyers, are OE parcel owners. All kinds of landowners can be potential restorers (OC sellers), because they can restore economic parcels or buy and restore spare parcels. A brief description of the decision process is provided in this section, and detailed descriptions of the price signal gathering, price expectation formation, and land use and transaction decisions can be found in the Supplementary File.

For simplification, we assume that each landowner agent can only buy one spare parcel during each time step. Potential developers prefer to buy spare parcels that align with their OC requirements, while potential restorers tend to buy nearby parcels due to the ecological spatial agglomeration effects embedded within the model. Individuals with more restoration experience might have greater restoration ability and less restoration uncertainty. Therefore, when a spare parcel attracts multiple prospective buyers, landowners with more restoration experience are given greater priority.

The decision-making process of landowner agents unfolds in several steps. First, landowner agents gather price signals from individual experience, the market and their neighbors. The neighbors are defined as being spatially connected via an 8-cell Moore neighborhood. Information transmission errors between landowner agents and their neighbors are considered. Second, landowner agents formulate minimum profitability targets and expected OC prices. The price fluctuation is used to calculate the minimum profitability goal, which can reflect landowners' perception of benefit uncertainty.

Third, with expected OC prices, landowner agents make choices regarding land use and OC transactions that maximize their profits while adhering to their minimum profitability targets. Economic parcel owners decide whether to retain current land use, restore owned economic parcels, or buy and restore spare parcels while keeping current land use. OE parcel owners decide whether to retain current land use, develop owned OE parcels, or buy and restore spare parcels while keeping current land use. Redevelopment of RE parcels is not allowed in the model, and RE parcel owners can choose whether to buy and restore spare parcels.

2.3. Simulation design

The geographical space of the model consists of N=110×32 spatial agents, with each representing a 0.3 km × 0.3 km parcel. The uppermost 110 × 2 spatial agents are set as sea areas. Half of the spatial agents, excluding those in sea areas, serve as spare parcels, and the number of landowner agents is equivalent to half the count of nonsea spatial agents. At the beginning of the simulation, 50% of the landowner agents are OE parcel owners, while the remainder are initial economic parcel owners. The leftmost 12 × 32 spatial agents constitute the initial spatial range for implementing WOM. This range gradually expands to the right with 2×32 spatial agents each year, which reflects the gradual spread of policy. The code was written in Python 3.8.

The Yellow River Delta, China, is chosen as the reference area for deciding on the economic data of the model. Specifically, parcel economic values and the upper bound of the growth rate are determined according to the economic output data from the *Dongying Statistic Yearbook*, and restoration investment is obtained from *The Overall Plan for the Yellow River Estuary National Park*. The main parameters and their values for the simulations are listed in Table S2. The Latin hypercube sampling method is employed to generate parameter samples for simulation.

Two experiments were designed to explore the role of public OC supply (Table 1). Specifically, in the Baseline experiment, which was operated without public OC supply, and the initial price signal is generated from potential developers buying and restoring spare parcels. The POCS experiment explores different combinations of public OC supply strategies, including different pricing levels (*PLs*), public supply amounts (*PSAs*) and public supply durations (*PSDs*).

The simulation period is 50 years, and each scenario is executed 50 times to obtain average results. Specifically, the ratio of average transaction prices to average cost per OC is applied to analyze the extent of the price signal. The average cost per OC is obtained with the spare parcel price, restoration costs, and average OC amounts that can be generated from restoring one parcel. To analyze the degree to how many restored parcels cluster to ecological parcels, the ecological clustering index ECI_t was applied in this study, which was adapted from the study of Drechsler et al. (2022). ECI_t is measured by the average proportion of nearby ecological parcels within the ecological impact range of RE parcels:

$$ECI_t = \frac{\frac{1}{N(R)}\sum_{i=1}^{N_P} L_i NE(t,R)}{\sum_{i=1}^{N_P} L_i} \tag{8}$$

where $N(R)$ represents the number of nearby parcels within the ecological impact radius R. L_i represents the land use status of the parcel, $L_i = 1$ represents the RE parcel, and $L_i = 0$ represents other parcels. N_{P} is the number of spatial agents.

Table 1. WOM simulation scenarios to analyze the role of government supply.

Experiment	Pricing level of public supply (*PL*)	Yearly public supply amount (*PSA*)	Public supply duration (*PSD*)
Baseline	/	/	/
POCS	0.5-1.5, 0.1 as the interval	2/10	5/10/20 years

3. Results

3.1. Price and WOM dynamics

The impacts of public OC supply on the formation and development of WOM are analyzed in this section. The Baseline experiment required approximately four years for the emergence of WOM (Table 2). In the POCS experiment, the WOM emerges immediately when the pricing level (*PL*) of public OCs is less than 1.2. However, when the *PL* exceeds 1.2 and is coupled with a higher public supply amount (*PSA*), more time is needed for WOM to emerge. This is because such a price exceeds the cost of buying and restoring spare parcels, and potential developers prefer to generate OCs themselves to offset the development impact rather than buying OCs, postponing the emergence of the market. The time needed for WOM emergence was not affected by the public supply duration (*PSD*) in the POCS experiment because *PSD* is significantly longer than the WOM emergence process. Overall, the appearance of the market in the POCS experiment is significantly faster than that in the Baseline experiment, indicating that the price signal provided by public OCs can reduce transaction uncertainty and facilitate the formation of WOM.

Table 2. Market appearance time

Experiment		Market appearance time (years) [mean, (standard deviation)]
Baseline		4.367 (1.224)
POCS	*PL*<1.2, *PSA*=2 & *PSA*=10	0.000 (0.000)
	PL=1.2, *PSA*=2	0.060 (0.369)
	PL=1.2, *PSA*=10	0.120 (0.461)
	PL=1.3, *PSA*=2	0.173 (0.574)
	PL=1.3, *PSA*=10	0.193 (0.650)
	PL=1.4, *PSA*=2	0.653 (1.119)
	PL=1.4, *PSA*=10	0.574 (1.037)
	PL=1.5, *PSA*=2	1.000 (1.200)
	PL=1.5, *PSA*=10	1.047 (1.353)

Price fluctuations are examined through the standard deviation of transaction prices over 5-year intervals

(Fig. 2). Fig. 3 provides a comparison of yearly private OC supply, the minimum profitability target, and the level of the price signal (i.e., average transaction price divided by average cost per OC). In the Baseline experiment, considerable price fluctuations are evident during the early formation phase of the WOM (1-5 years). This is because a price signal exceeding 1.3 times the average cost per OC is necessary to trigger WOM formation (Fig. 3g). An abrupt increase in the price signal induces significant price fluctuations during the first five years, leading to an increase in landowners' minimum profitability target (Fig. 3d), indicating a greater benefit uncertainty perception of landowner agents.

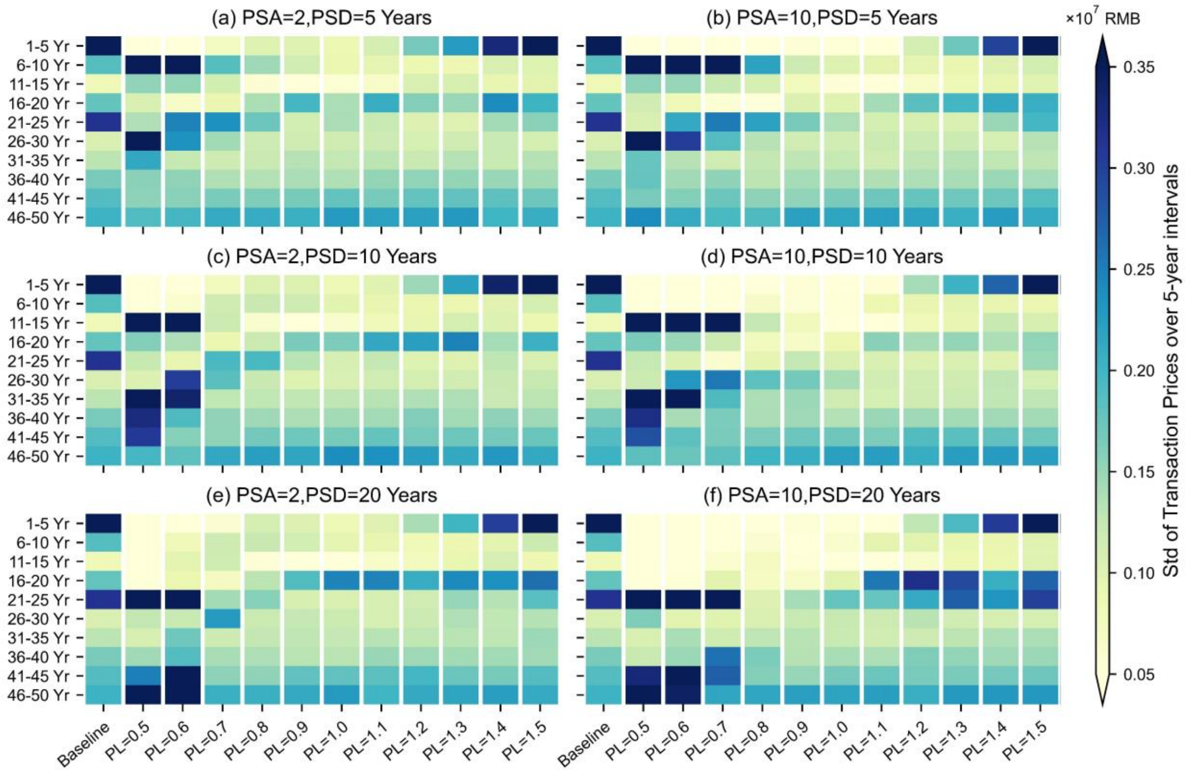

Fig. 2. Standard deviation of transaction price over five-year intervals (plotted with the mean of 50 runs; *PL* = pricing level of public OCs, *PSA* is yearly supplied amount of public OC, and *PSD* means duration of public OC supply, same below).

Transaction prices tend to be stable as WOM develops between the 6th and 15th years. The high price signal generated during market emergence quickly attracted increasing restoration activities, leading to a significant increase in the yearly private supply (Fig. 3a). In addition, affected by the restoration period and the transfer time of price signals, a time lag was observed between the highest price signals and the highest yearly private supply level. The time lag further intensifies the herding of restoration activities. Therefore, the pullback of transaction prices to the average cost per OC significantly reduces the price fluctuation between the 6th and 15th years. A gradually normalized market causes a significant decrease in the benefit uncertainty perceived by landowner agents, leading to a reduction in the average minimum profitability target in the Baseline experiment (Fig. 3d). Restoration activities and yearly private supply decrease as the transaction price continue to decrease in the baseline experiment, and this requires potential developers to release higher price signals to motivate restorers again. Therefore, in the Baseline experiment, transaction prices increase again starting from the 16th year (Fig. 3g).

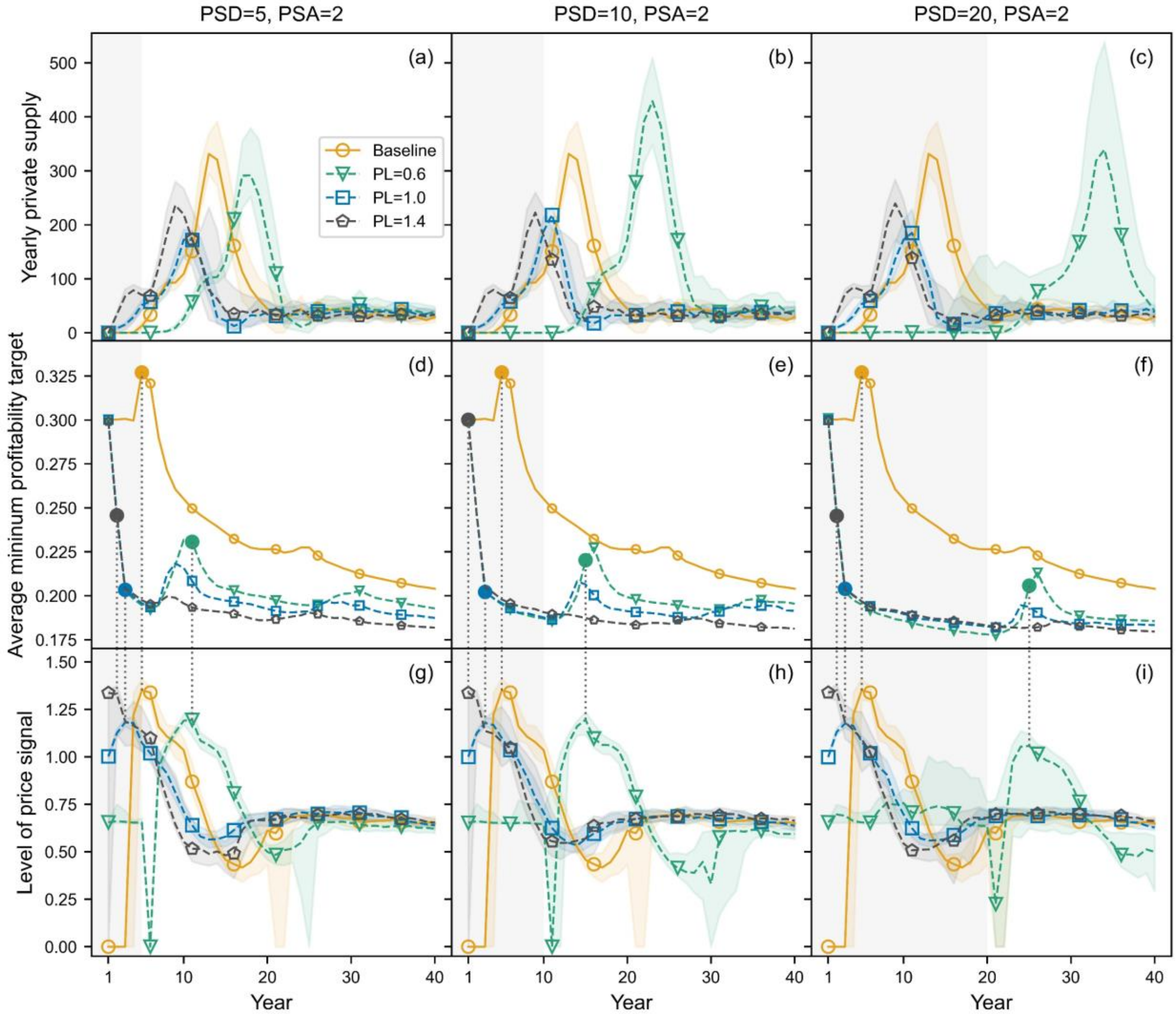

Fig. 3. Yearly private offset credit supply, average minimum profitability target, and level of price signal (the level of the price signal is equal to the average transaction price divided by the average cost per OC; the light grey area represents the public supply period; Fig. 3d-Fig. 3f are plotted with the mean of 50 runs; Fig. 3a-Fig.3c and Fig. 3g-Fig. 3i are plotted with the median, lower and upper quantile of 50 runs).

The above landowners' self-adaptation process causes the second price fluctuation in the Baseline experiment between the 16th and 25th years (Fig. 2). Because the minimum profitability target in this study is calculated by all historical price signals, the second price fluctuation greatly offsets the impact of the first price fluctuation, leading to a continuous decrease in the minimum profitability target in the Baseline experiment after the first price fluctuation (Fig. 3d). After two large adaptation processes, landowner agents gradually adapt to market dynamics, and the wetland offset market enters a relatively steady state. Therefore, the price signal in the Baseline experiment gradually stabilizes at approximately 0.6 times the average cost per OC (Fig. 3g), and the gradually increasing price fluctuations after the 26th year (Fig. 2) primarily stem from economic growth. A gradually stabilized transaction price greatly reduces the uncertainty experienced by landowner agents, and the average minimum profitability goal gradually decreases to approximately 0.2 in the Baseline experiment.

The price signal from the public OC can significantly mitigate price fluctuations during the WOM formation phase (Fig. 2). The benefit uncertainty perceived by landowner agents is significantly mitigated by the price stabilizing effect of public OCs, leading to lower average minimum profitability targets in the POCS experiment than in the Baseline experiment (Fig. 3d-Fig. 3f). Specifically, the early positive impacts of public OCs on uncertainty reduction exhibit long-term influence. Although the price signals of both the Baseline and POCS experiments gradually stabilized at approximately 0.6 in the long term, the landowner agents in the POCS experiment perceived significantly less benefit uncertainty and had lower minimum profitability targets than in the Baseline experiment.

The reduction in price fluctuations from the 1st to the 5th year is more significant in scenarios with higher *PSAs* and lower *PLs*. This is because large amounts of public OCs with low supply prices significantly extrude private supply (Fig. 3a-Fig. 3c), while increasing OC demands (Fig. S2). In this context, transactions between new developers and the government grow significantly, and a stable public supply price serves as a potent dampener that reduces price fluctuations. However, in the scenarios with *PL* ≤0.7, large price fluctuations were observed after the public OC supply ceased (Fig. 2 and Fig. 3g-Fig. 3i). This is caused by the severely extruded private supply, and potential developers need to readapt to WOM dynamics after the government ceases to offer cheap public OCs, thereby generating enough price signals to stimulate private OC supplies (Fig. 3g-Fig. 3i). Private supply increases significantly due to these high price signals and landowners' reduced uncertainty perception.

In scenarios with *PL*≥1.0, the price signals provided by public OCs exceed the average cost per OC, leading to more active restoration and a higher private supply in the early stage of WOM (Fig. 3a-Fig. 3c). However, due to the price stabilizing effect of public OCs, increases in price signals appear to be lower in the POCS experiment than in the Baseline experiment (Fig. 3g-Fig.3i). For example, when *PSA*=2, the highest price levels in the POCS experiment are 1.337 under *PL*=1.4 and 1.178 under *PL*=1.0, while the highest price level in the Baseline experiment is 1.350. The limited increase in price signals caused by the price stabilizing effect of public OCs (especially those with a *PL* close to 1.0) can alleviate the herding of restoration, leading to a lower maximum yearly private supply. Therefore, public OC supply with *PL*≥1.0

can reduce the extent and duration of price fluctuations during the entire WOM evolution process. Consequently, public OCs can facilitate WOM formation by motivating restorers from the supply side with high *PLs*, or through attracting developers from the demand side with low *PLs*.

PSD mainly changes the timing of landowners' readaptation in scenarios with extremely low *PLs*. In addition, the readaptation process is similar to the self-adaptation process of landowner agents in the Baseline experiment. Therefore, the second price fluctuation in the Baseline experiment (16-25 years) is also postponed in the POCS experiment with extremely low *PL* (*PL* ≤0.7) and long *PSD* (Fig. 2).

3.2. Regional economic and ecological outcomes at different time scales

This section analyses the impacts of public OC supply on regional economic and ecological outcomes at different time scales. Fig. 4 shows the regional development scale in the 5th and 50th years. It is evident that the public OC supply has similar impacts on the development scale in the short term and long term: public OCs with lower *PLs*, higher *PSAs* and longer *PSDs* can generate higher development scales. This phenomenon occurs for two reasons. First, more development demands can be satisfied with a larger amount of cheap public OCs. This is especially important in the short term because of the extrusion effect of cheap public OCs on the private OC supply. Second, as illustrated before, in the POCS experiment with low *PL*, the landowner readaptation process after public supply ceases can induce a significant increase in private supply, which leads to a decrease in the transaction price. The increased cheap private OCs in the POCS experiment with low *PL* play a significant role in generating a higher development scale in the long term.

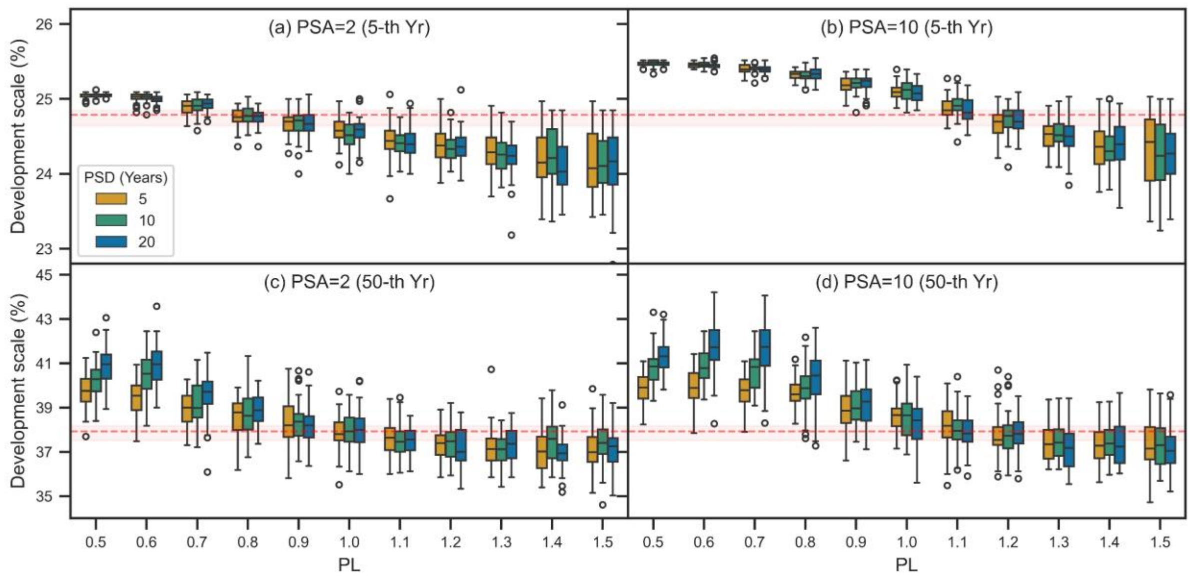

Fig. 4. Development scale in the 5th and 50th years (the red dashed line and the error range are plotted with the median, lower and upper quantile of the development scale in the Baseline experiment).

Regional ecological outcomes were analyzed by examining the private restoration scale, the ecological cluster index, and changes in total ecological value. In the short term (5th year), scenarios with higher *PL*, particularly when *PL*≥1.0, can motivate more private restoration activities. This finding is consistent with the former findings that price signals provided by public OCs can attract more private restoration in the early stage of WOM. However, the extrusion effect of public OCs on private restoration is observed when *PSA*=2 increases to *PSA*=10 (Fig. 5a and Fig. 5b). This might be because an increase in public OC can change the supply-demand ratio of OCs, and lower price signals were observed in scenarios with *PSA*=10 than in those with *PSA*=2 (Fig. S1). This phenomenon aligns with our theoretical analysis and indicates that the public OC supply amount can change the price signal and affect private restoration activity.

The effects of public OC supply on private restoration differ in the long term (Fig. 5c and Fig. 5d): private restoration can be extruded with *PL*≥0.8, especially as *PL* approaches 1.0 and *PSD* increases. A lower *PL* and *PSA* are more effective at increasing the scale of private restoration. This finding aligns with the findings in the previous section that the price stabilizing effects of public OCs with higher *PLs* can alleviate the herding of restoration. However, due to landowner agents' readaptation process, scenarios with extremely low *PLs* (≤0.7) can cause intensive herding of private restoration after public OC supply ceases, leading to a greater restoration scale in the long term.

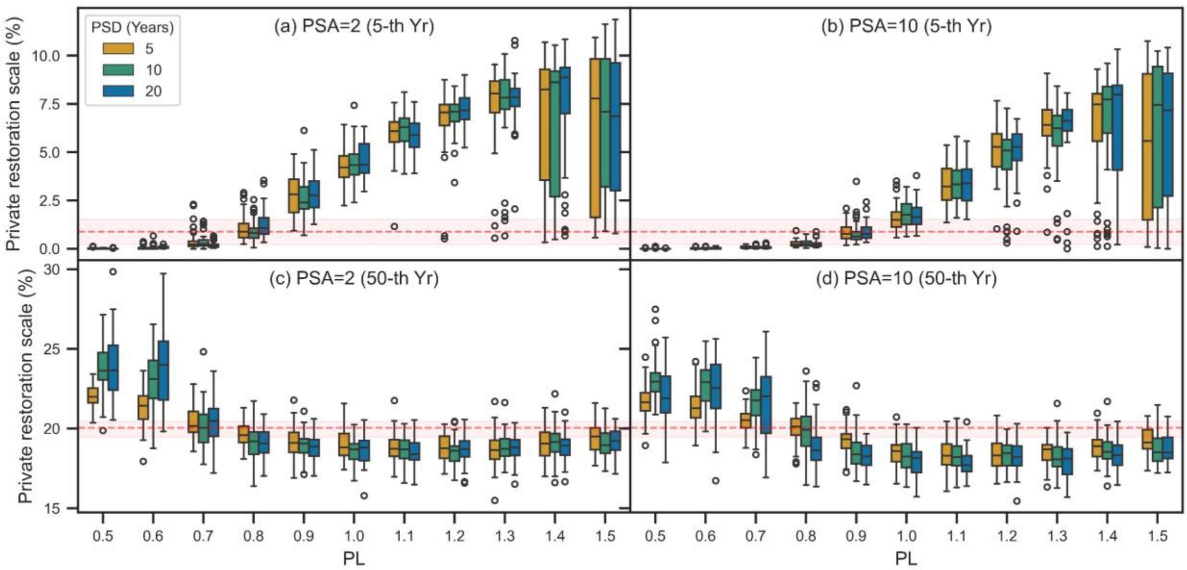

Fig. 5. Private restoration scale in the 5th and 50th years (the red dashed line and the error range are plotted with the median, lower and upper quantile of the private restoration scale in the Baseline experiment).

The impact of *PSD* is not significant when *PL*≥0.8. However, for *PL*≤0.7, differences became evident in private restorations with varying *PSDs*. Specifically, a public OC supply with *PSD*=10 leads to a higher private restoration scale when *PSA*=10, while a public OC supply with *PSD*=20 has better performance when *PSA*=2. As shown in Fig. 3, *PSD* can affect the timing of landowners' readaptation processes, subsequently altering the alignment between the minimum profitability target and the price signals generated during the readaptation process, thus impacting private restoration activity.

Public OC supply has similar short- and long-term impacts on ecological clustering (Fig. 6): higher *PL* performs better at promoting ecological clustering. A higher ecological clustering index in the short term was caused by greater restoration scale (Fig. 5a and Fig. 5b) and a lower development scale (Fig. 4a and Fig. 4b). Nevertheless, the long-term impacts of public OC supply on ecological clustering differ from its long-term impacts on the private restoration scale (Fig. 5c, Fig. 5d, Fig. 6c and Fig. 6d): in scenarios with lower *PL*, the private restoration scale increases, while the ecological cluster index decreases. This phenomenon may result from the significantly increased development scale under such cheap public OC supply schemes (Fig. 4c and Fig. 4d), and active development activities cause the fragmentation of ecological parcels.

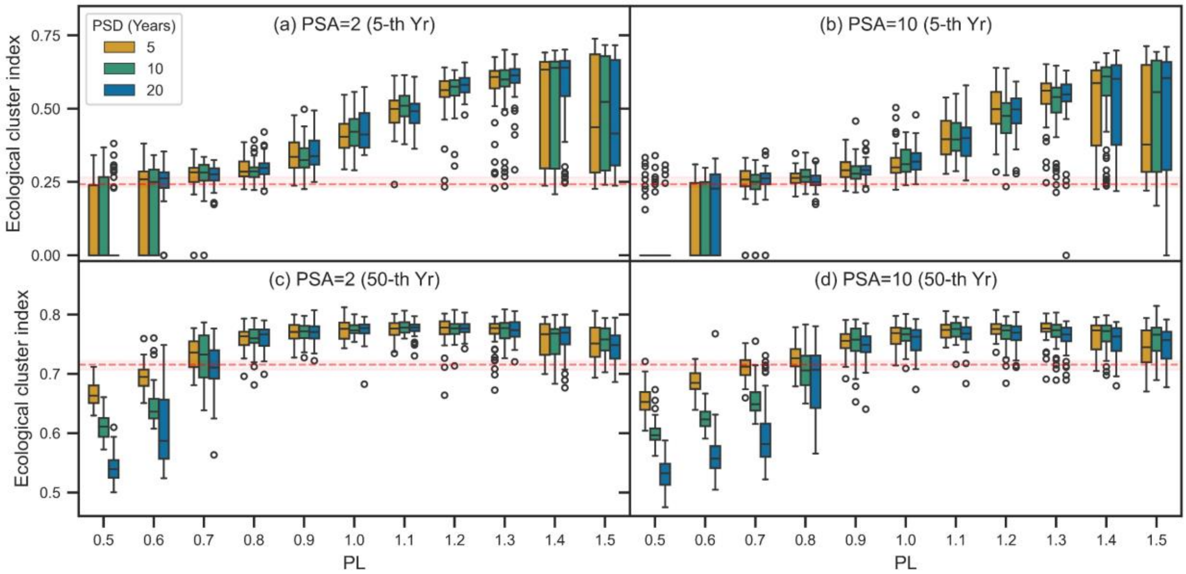

Fig. 6. Ecological cluster index in the 5th and 50th years (the red dashed line and the error range are plotted with the median, lower and upper quantile of the ecological cluster index in the Baseline experiment).

The initial total ecological value ranged from 9425.18 to 9529.00. Fig. 7 depicts the changes in ecological value compared to the initial total ecological value. In the short term, the low private restoration scale caused a decrease in the total ecological value (Fig. 5b and Fig. 7b). This is because the ecological value created by public restoration activity is not considered. In the long term, despite having a greater development scale than the private restoration scale (Fig.4 and Fig. 5), the total ecological value in the 50th year was significantly greater than the initial total ecological value, indicating that WOM can simultaneously promote wetland restoration and regional economic development. The reason for the development scale surpassing the private restoration scale under the growth of total ecological value might be the exclusion of the public restoration programme and the consideration of spatial agglomeration effects. Therefore, the OCs generated by restoring a parcel in an ecological agglomeration area can offset the impacts of developing more than one parcel in a nonecological agglomeration area.

Furthermore, the impacts of public OC supply on total ecological value are similar to the impacts on the private restoration scale (Fig. 7). However, affected by development activities, only the total ecological value under conditions of *PL*≤0.6 and *PSA*=2 as well as *PL*≤0.6 and *PSA*=10 exceeded that of the Baseline experiment in the long term (Fig. 7c and Fig. 7d). The impact of ecological clustering on the total ecological value was not significant. This may be because, in most scenarios, the ecological cluster index reaches 0.7 (indicating that, on average, 70% of the lands around the restored parcel are ecological parcels), which already represents a high level of spatial clustering.

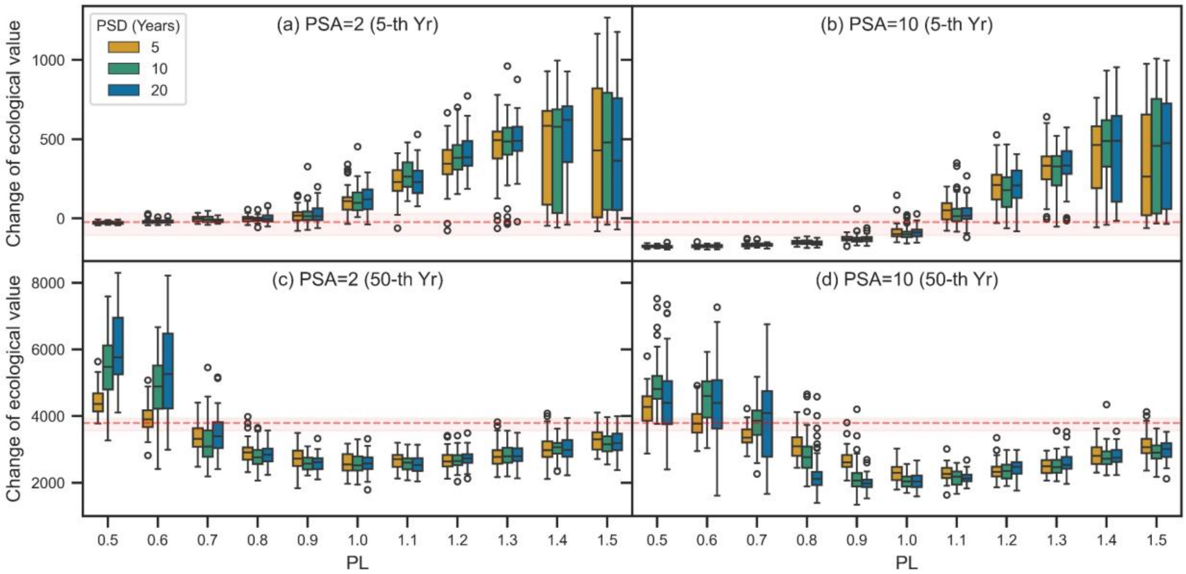

Fig. 7. Ecological value changes at the 5th and 50th year compared to the initial ecological value (the red dashed line and the error range are plotted with the median, lower and upper quantile of the ecological value change in the Baseline experiment).

4. Discussion

4.1. Role of public OC supply in WOM formation and evolution

Combining the simulation results, this section discusses: (1) the spontaneous formation of wetland offset markets (WOMs), (2) the role of public offset credit (OC) supply in WOM formation, (3) the impacts of public OC on WOM evolution, and (4) the suitability of the public OC supply under different wetland management preferences.

Our results showed that the spontaneous emergence of WOM requires price signals that are at least 1.3 times higher than the average cost per OC. It may take more than four years to form such high price signals. In the absence of public OCs, it takes more than 20 years for price signals in WOM to become stable. These findings are based on our theoretical model, and the complexity of practical situations might cause WOM formation to take even longer.

In the formation stage of the WOM, the price signal provided by public OCs can significantly reduce price fluctuations, especially with lower pricing levels. Landowners' perception of benefit uncertainty can be long-term reduced by this price stabilizing effect, which contributes to WOM formation. Besides, during WOM formation, public OCs can facilitate WOM emergence through the supply side with high pricing levels, or from the demand side with low price levels. This indicates that apart from monitoring and regulating (BenDor et al., 2011; Levrel et al., 2017; van Teeffelen et al., 2014), the price adjusting function of governments as suppliers is also important for WOM establishment.

From the perspective of the entire WOM evolution process, shorter adaptation time is needed for landowners under public OCs with prices close to or higher than the average cost per OC, leading to fewer market fluctuations. When public OCs are priced below average cost per OC, the cessation of such public supply can cause huge market fluctuations. This is because, cheap public OCs can severely extrude private supply during the public supply period, and landowners need to readapt to the WOM after the cheap public OC supply ceases, thereby generating enough price signals to motivate private restorers. During the readaptation period, private supply will increase significantly due to the combination of high price signals and reduced uncertainty perception of landowners.

In addition, higher public supply amounts generally exhibit a more significant price stabling effect and greater severe extrusion on private supply. The extrusion of public OCs on private OCs is also observed in WOM practices (Bennett et al., 2017; Salvesen et al., 2013). The duration of public OC supply mainly changes the timing of landowners' readaptation process under low public supply prices.

With respect to the impacts on wetland development-restoration outcomes under WOM evolution, public OCs have similar economic impacts but exhibit different ecological impacts over time. For economic outcomes, more active development activities occur under a cheap public OC supply with a larger supply amount and longer supply duration, both in the short and long term. For ecological outcomes, in the short term, public OCs with higher pricing levels, combined with reduced benefit uncertainty perceived by landowner agents, can attract more private restoration and promote ecological clustering. In the long term, public OCs with higher pricing levels can result in less private restoration compared to the Baseline, although greater ecological clustering still appears under such a public supply. On the one hand, the price stabilizing effect of such public supply will lead to lower price signals and less private restoration. On the other hand, ecological fragmentation is greatly alleviated by less development activity under public OCs with higher prices. In contrast, affected by the readaptation process mentioned before, scenarios with lower public OC prices can achieve a greater restoration scale in the long term, while severe ecological fragmentation occurs due to active development activities.

The above findings indicate that governments may face different development-restoration challenges over time. In the short term, major challenges might be tradeoffs between restoration scale and development as well as tradeoffs between ecological clustering and development. In the long term, major challenges change to tradeoffs between ecological clustering and restoration scale (Drechsler, 2023) as well as tradeoffs between ecological clustering and development. This phenomenon might be the result of the ecological equivalence required between development and restoration in WOMs

The complete recovery of wetlands can be a long-term process, and public OC supply schemes should be designed according to long-term wetland management preferences. If the restoration scale is the main focus of local wetland recovery, then public OC supplies with lower pricing levels and supply amounts might be more suitable. Specifically, economic interests can also be guaranteed under such public supply schemes, although this might occur at the expense of ecological clustering. However, if ecological clustering has higher priority in local wetland or other ecosystem protection, then public OC supplies with higher pricing levels might be more suitable, while this might sacrifice more economic interest.

4.2. Implications for WOM practices and ecological conservation

Our findings might contribute to WOM practices and wetland development-restoration conflict alleviation in developing countries in the following aspects.

First, price fluctuations are generally considered harmful to markets (Wissel and Wätzold, 2010), and this is proven by the increased uncertainty perception of landowners and decreased private supply in the WOM early stage in this study. However, price fluctuations might also have positive meanings because more private restorers can be attracted by significantly increased price signals. This positive impact is caused mainly by the time lag of price signals and restorers' herd behavior. However, this study only analyzes WOM performance from the perspective of regional outcomes, while individual restorers might suffer great losses due to their herd behavior (Klein, 2013) as the OC price can decrease sharply. Therefore, public wetland restoration and OC supply schemes might face tradeoffs between pursuing higher public interest (i.e., a greater restoration scale) and protecting individual benefits, and future studies can further explore the impacts of WOM and public OC supply on individual welfare.

Second, our results reveal that landowners' self-adaptation process is better at generating higher price signals, while public OC supply plays a significant role in achieving long-term reductions in landowners' uncertainty perceptions. This implies that the main focus of public OC supply schemes might be on curtailing restoration uncertainties via its price stabilizing effect. Furthermore, public OC supply should be implemented as early as possible, because early curtailment of uncertainty can cause a long-term reduction in the uncertainty perceived by landowner agents. This indicates the necessity of controlling risks at the beginning of the WOM introduction process, and clear price signals might be the key in this aspect. This approach might be especially important for new environmental market mechanisms such as WOMs due to the lack of price benchmarks from comparable products. Future studies can further analyze and compare the risk control effects of other wetland policies that involve price signals (e.g., taxes, payments and public procurement).

Third, the finding of changing development-restoration tradeoffs implies that long-term wetland management goals and private sector reactions should be the keys to the pricing of public OCs rather than the cost of public restoration programs. For simplification, the changing pricing of public OCs is not simulated in this study; rather, this change can be analyzed in the future by designing a changing public OC supply that is equipped for both short- and long-term interests.

Fourth, our analysis of WOM initiation and the role of public OC supply can also provide advice for other environmental markets, especially for carbon markets. On the one hand, carbon markets and other environmental markets are increasingly applied worldwide, and governments are also the main suppliers in these markets due to the large scale of publicly funded environmental conservation projects. The agent-based model developed in this study can be adapted to analyze the introduction of other environmental markets, such as carbon markets, and our findings about the effects of public supply can also provide guidance for public carbon sink programs and public carbon credit pricing. On the other hand, wetlands are important carbon sinks. For simplification, the economic profits of restored wetlands that will not cause wetland losses are not considered in this study. However, increasingly active carbon markets might be important sources of income for restored wetlands, thereby changing the cost-benefit structure of wetland restoration programs. Therefore, we call for future studies that focus on combinations of carbon markets and wetland offset markets.

Due to the research scope, this study might have the following limitations. First, this study primarily focuses on governments' role in WOM initiation and development, and the regional economic growth path and ecological evolution are greatly simplified in the model. Second, other key mechanisms in WOM (such as the advanced-releasing ratio and transaction ratio) are not discussed in this study. Therefore, to facilitate the understanding of WOM and the design of more practical wetland policies, future studies can extend our model with more complex real-world processes and detailed empirical data.

5. Conclusions

Wetland offset markets (WOMs) are receiving increasing attention worldwide due to growing conflicts between wetland development and restoration, and understanding how to facilitate the introduction of WOMs is critical. Given the insufficient price signals faced by WOM development, this study focuses on governments' role as offset credit (OC) suppliers in delivering and adjusting price signals and analyses the impacts of public OC supply on WOM formation and evolution over time. Specifically, a general spatial agent-based wetland offset market model was built in this study to simulate WOM evolution and wetland development-restoration dynamics under different public OC supply schemes.

The results show that spontaneous WOM formation can be more time-consuming. In the formation stage of WOM, public OCs can reduce price fluctuations, leading to a long-term reduction in landowners' benefit uncertainty perception. In addition, WOM formation can be facilitated by public OCs either from the supply side with high supply prices or from the demand side with low supply prices.

According to the entire WOM evolution process, public OCs with prices close to or higher than the average cost per OC can reduce market fluctuations. However, due to landowners' readaptation process, public OCs with prices lower than the average cost per OC can cause significant market fluctuations after the cheap public supply ends. In addition, changing development-restoration tradeoffs over time were found in this study. Specifically, in the long term, governments might face tradeoffs between ecological clustering and restoration scale and between ecological clustering and economic growth. Given the time-consuming nature of complete wetland recovery, long-term wetland management goals should be specified before implementing public OC supply schemes. In the long term, public OC supplies with lower pricing levels perform better at achieving higher restoration scales and development scales, and public OC supplies with higher pricing levels are superior at promoting ecological clustering.

The above findings can further the understanding of the process of introducing a new market mechanism such as WOMs and the price adjusting role of governments as OC suppliers. Our results can also provide guidance for the implementation of public restoration and OC supply schemes and for the coordination of development and wetland conservation. The general model developed in this study can be extended with detailed ecological and economic processes, which can be used to analyze other important key mechanisms in WOM or explore the introduction process of other environmental markets.

Credit author statement

Yeqing Duan: Conceptualization, Formal Analysis, Methodology. **Shenbei Zhou:** Conceptualization, Writing – review & editing. **Jing Ning:** Writing – review & editing. **Martin Drechsler:** Methodology, Writing – review & editing.

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References

Alvarado-Quesada, I., Hein, L., Weikard, H.-P., 2014. Market-based mechanisms for biodiversity conservation: a review of existing schemes and an outline for a global mechanism. Biodivers Conserv 23, 1–21. https://doi.org/10.1007/s10531-013-0598-x

BenDor, T.K., Riggsbee, J.A., Doyle, M., 2011. Risk and Markets for Ecosystem Services. Environ. Sci. Technol. 45, 10322–10330. https://doi.org/10.1021/es203201n

Bennett, G., Gallant, M., Ten Kate, K., 2017. State of biodiversity mitigation 2017: Markets and compensation for global infrastructure development. Washington, DC: Forest Trends Ecosystem Marketplace.

Bernasconi, P., Blumentrath, S., Barton, D.N., Rusch, G.M., Romeiro, A.R., 2016. Constraining Forest Certificate's Market to Improve Cost-Effectiveness of Biodiversity Conservation in São Paulo State, Brazil. PLOS ONE 11, e0164850. https://doi.org/10.1371/journal.pone.0164850

Boisvert, V., 2015. Conservation banking mechanisms and the economization of nature: An institutional analysis. Ecosystem Services 15, 134–142. https://doi.org/10.1016/j.ecoser.2015.02.004

Boisvert, V., Méral, P., Froger, G., 2013. Market-Based Instruments for Ecosystem Services: Institutional Innovation or Renovation? Society & Natural Resources 26, 1122–1136. https://doi.org/10.1080/08941920.2013.820815

Bonneuil, C., 2015. Tell me where you come from, I will tell you who you are: A genealogy of biodiversity offsetting mechanisms in historical context. Biological Conservation 192, 485–491. https://doi.org/10.1016/j.biocon.2015.09.022

Brown, C., Alexander, P., Rounsevell, M., 2018. Empirical evidence for the diffusion of knowledge in land use change. Journal of Land Use Science 13, 269–283. https://doi.org/10.1080/1747423X.2018.1515995

Bruggeman, D.J., Jones, M.L., Scribner, K., Lupi, F., 2009. Relating tradable credits for biodiversity to sustainability criteria in a dynamic landscape. Landscape Ecol 24, 775–790. https://doi.org/10.1007/s10980-009-9351-y

Bruner, A.G., Gullison, R.E., Balmford, A., 2004. Financial Costs and Shortfalls of Managing and Expanding Protected-Area Systems in Developing Countries. BioScience 54, 1119–1126. https://doi.org/10.1641/0006-3568(2004)054[1119:FCASOM]2.0.CO;2

Bull, J.W., Strange, N., 2018. The global extent of biodiversity offset implementation under no net loss policies. Nat Sustain 1, 790–798. https://doi.org/10.1038/s41893-018-0176-z

Coralie, C., Guillaume, O., Claude, N., 2015. Tracking the origins and development of biodiversity offsetting in academic research and its implications for conservation: A review. Biological Conservation 192, 492–503. https://doi.org/10.1016/j.biocon.2015.08.036

Davidson, N.C., 2014. How much wetland has the world lost? Long-term and recent trends in global wetland area. Mar. Freshwater Res. 65, 934. https://doi.org/10.1071/MF14173

Doyle, M.W., Yates, A.J., 2010. Stream ecosystem service markets under no-net-loss regulation. Ecological Economics, Special Section: Coevolutionary Ecological Economics: Theory and Applications 69, 820–827. https://doi.org/10.1016/j.ecolecon.2009.10.006

Drechsler, M., 2023. Ecological and economic trade-offs between amount and spatial aggregation of conservation and the cost-effective design of coordination incentives. Ecological Economics 213, 107948. https://doi.org/10.1016/j.ecolecon.2023.107948

Drechsler, M., 2022. On the Cost-Effective Temporal Allocation of Credits in Conservation Offsets when Habitat Restoration Takes Time and is Uncertain. Environ Resource Econ 82, 437–459. https://doi.org/10.1007/s10640-022-00685-y

Drechsler, M., Wätzold, F., 2009. Applying tradable permits to biodiversity conservation: Effects of space-dependent conservation benefits and cost heterogeneity on habitat allocation. Ecological Economics, Participation and Evaluation for Sustainable River Basin Governance 68, 1083–1092. https://doi.org/10.1016/j.ecolecon.2008.07.019

Drechsler, M., Wätzold, F., Grimm, V., 2022. The hitchhiker's guide to generic ecological-economic modelling of land-use-based biodiversity conservation policies. Ecological Modelling 465, 109861. https://doi.org/10.1016/j.ecolmodel.2021.109861

Failler, P., Touron-Gardic, G., Traore, M.-S., 2019. Is Aichi Target 11 Progress Correctly Measured for Developing Countries? Trends in Ecology & Evolution 34, 875–879. https://doi.org/10.1016/j.tree.2019.07.007

Froger, G., Ménard, S., Méral, P., 2015. Towards a comparative and critical analysis of biodiversity banks. Ecosystem Services 15, 152–161. https://doi.org/10.1016/j.ecoser.2014.11.018

Gardner, R.C., Finlayson, C., 2018. Global wetland outlook: state of the world's wetlands and their services to people, in: Ramsar Convention Secretariat. pp. 2020–5.

Hahn, T., McDermott, C., Ituarte-Lima, C., Schultz, M., Green, T., Tuvendal, M., 2015. Purposes and degrees of commodification: Economic instruments for biodiversity and ecosystem services need not rely on markets or monetary valuation. Ecosystem Services 16, 74–82. https://doi.org/10.1016/j.ecoser.2015.10.012

Kandiah, V.K., Berglund, E.Z., Binder, A.R., 2019. An agent-based modeling approach to project adoption of water reuse and evaluate expansion plans within a sociotechnical water infrastructure system. Sustainable Cities and Society 46, 101412. https://doi.org/10.1016/j.scs.2018.12.040

Kangas, J., Ollikainen, M., 2019. Economic Insights in Ecological Compensations: Market Analysis With an Empirical Application to the Finnish Economy. Ecological Economics 159, 54–67. https://doi.org/10.1016/j.ecolecon.2019.01.003

Klein, A.C., 2013. Time-variations in herding behavior: Evidence from a Markov switching SUR model. Journal of International Financial Markets, Institutions and Money 26, 291–304. https://doi.org/10.1016/j.intfin.2013.06.006

Koh, N.S., Hahn, T., Boonstra, W.J., 2019. How much of a market is involved in a biodiversity offset? A typology of biodiversity offset policies. Journal of Environmental Management 232, 679–691. https://doi.org/10.1016/j.jenvman.2018.11.080

Koh, N.S., Hahn, T., Ituarte-Lima, C., 2017. Safeguards for enhancing ecological compensation in Sweden. Land Use Policy 64, 186–199. https://doi.org/10.1016/j.landusepol.2017.02.035

Levrel, H., Scemama, P., Vaissière, A.-C., 2017. Should We Be Wary of Mitigation Banking? Evidence Regarding the Risks Associated with this Wetland Offset Arrangement in Florida. Ecological Economics 135, 136–149. https://doi.org/10.1016/j.ecolecon.2016.12.025

Lynch, A.J.J., Kalumanga, E., Ospina, G.A., 2016. Socio-ecological aspects of sustaining Ramsar wetlands in three biodiverse developing countries. Mar. Freshwater Res. 67, 850. https://doi.org/10.1071/MF15419

Maron, M., Hobbs, R.J., Moilanen, A., Matthews, J.W., Christie, K., Gardner, T.A., Keith, D.A., Lindenmayer, D.B., McAlpine, C.A., 2012. Faustian bargains? Restoration realities in the context of biodiversity offset policies. Biological Conservation 155, 141–148. https://doi.org/10.1016/j.biocon.2012.06.003

McKenney, B.A., Kiesecker, J.M., 2010. Policy Development for Biodiversity Offsets: A Review of Offset Frameworks. Environmental Management 45, 165–176. https://doi.org/10.1007/s00267-009-9396-3

Needham, K., de Vries, F.P., Armsworth, P.R., Hanley, N., 2019. Designing markets for biodiversity offsets: Lessons from tradable pollution permits. Journal of Applied Ecology 56, 1429–1435. https://doi.org/10.1111/1365-2664.13372

Ribaudo, M., Greene, C., Hansen, L., Hellerstein, D., 2010. Ecosystem services from agriculture: Steps for expanding markets. Ecological Economics, Special Section - Payments for Ecosystem Services: From Local to Global 69, 2085–2092. https://doi.org/10.1016/j.ecolecon.2010.02.004

Salès, K., Frascaria-Lacoste, N., Marty, P., 2023. The place of spatialized ecological information in defining and implementing biodiversity offsets policies. A comparative study of Colombia and France. Environmental Science & Policy 147, 279–291. https://doi.org/10.1016/j.envsci.2023.06.014

Salvesen, D., Marsh, L.L., Porter, D.R., 2013. Mitigation Banking: Theory And Practice. Island Press.

Simpson, K.H., de Vries, F.P., Dallimer, M., Armsworth, P.R., Hanley, N., 2022. Ecological and economic implications of alternative metrics in biodiversity offset markets. Conservation Biology 36. https://doi.org/10.1111/cobi.13906

Simpson, K.H., Vries, F. de, Dallimer, M., Armsworth, P.R., Hanley, N., 2021. Understanding the Performance of Biodiversity Offset Markets: Evidence from An Integrated Ecological - Economic Model. Land Economics. https://doi.org/10.3368/le.97.4.030420-0032R

Taherzadeh, O., Howley, P., 2018. No net loss of what, for whom?: stakeholder perspectives to Biodiversity Offsetting in England. Environ Dev Sustain 20, 1807–1830. https://doi.org/10.1007/s10668-017-9967-z

UN Water, 2018. 2018 UN World Water Development Report, Nature-based Solutions for Water.

Ungaro, M., BenDor, T.K., Riggsbee, J.A., 2022. Prioritizing streams: The impacts of in-kind mitigation rules on an ecosystem offset market. Environmental Science & Policy 132, 131–141. https://doi.org/10.1016/j.envsci.2022.02.005

Vaissière, A.-C., Levrel, H., 2015. Biodiversity offset markets: What are they really? An empirical approach to wetland mitigation banking. Ecological Economics 110, 81–88. https://doi.org/10.1016/j.ecolecon.2015.01.002

van Teeffelen, A.J.A., Opdam, P., Wätzold, F., Hartig, F., Johst, K., Drechsler, M., Vos, C.C., Wissel, S., Quétier, F., 2014. Ecological and economic conditions and associated institutional challenges for conservation banking in dynamic landscapes. Landscape and Urban Planning 130, 64–72. https://doi.org/10.1016/j.landurbplan.2014.06.004

Villarroya, A., Barros, A.C., Kiesecker, J., 2014. Policy Development for Environmental Licensing and Biodiversity Offsets in Latin America. PLOS ONE 9, e107144. https://doi.org/10.1371/journal.pone.0107144

Wang, B., Yan, H., Dong, J., 2022. Rationality and effectiveness of protected areas decrease with the declining development levels of the Belt and Road Initiative Countries. Ecological Engineering 182, 106705. https://doi.org/10.1016/j.ecoleng.2022.106705

Wissel, S., Wätzold, F., 2010. A Conceptual Analysis of the Application of Tradable Permits to Biodiversity Conservation. Conservation Biology 24, 404–411. https://doi.org/10.1111/j.1523-1739.2009.01444.x

Zou, Y., Duan, X., Xue, Z., E, M., Sun, M., Lu, X., Jiang, M., Yu, X., 2018. Water use conflict between wetland and agriculture. Journal of Environmental Management 224, 140–146. https://doi.org/10.1016/j.jenvman.2018.07.052