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Behavioural and Welfare Analysis of an Intermediary in Biodiversity Offset Markets

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Abstract

This paper provides a behavioural and welfare analysis of an intermediary in biodiversity offset markets. These markets are characterised by high information requirements and transaction costs, threatening economic efficiency and even biodiversity outcomes. Specialised intermediaries facilitate trading by providing information and brokering services. By buying, holding and selling offset credits from storage, the intermediary can decrease both financial and ecological risks in the market. As a drawback, the intermediary may exploit market power upstream or downstream due to ecological features of the offset market. Intermediaries decrease the trading parties' transaction costs by offering specialised information, reduce uncertainty, and decrease the costs of offsetting by increasing liquidity in the market and offering certain offset credits. When the intermediary has market power, selling and buying prices deviate from the competitive equilibrium. This welfare loss may be lower than the loss from transaction costs and trade ratios in decentralised trade, even in the case of the intermediary having both monopoly and monopsony power. The intermediary is the most useful when trade ratios are high and when the intermediary stores mature credits, which eliminates ecological uncertainty and thereby offers cost savings for developers, and may result in a higher level of biodiversity.

Keywords Biodiversity offsetting · Ecological compensation · Habitat banking · Intermediary · Market power · Offset market

JEL Classification Q57 · D43 · H41

1 Introduction

Biodiversity is decreasing globally at an alarming rate. The Dasgupta review on the economics of biodiversity highlights the need to both reduce our demand for natural resources and nature and strengthen the supply of natural capital in order to halt biodiversity loss (Dasgupta 2021). Construction, road building, and agriculture, among other human

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activities, degrade natural habitats. Current conservation efforts are not sufficient and the need for new policy tools in biodiversity conservation is urgent to stop the continued decrease in habitats and the abundance of species due to land use. One tool for this purpose is biodiversity offsetting, also called ecological compensations. It requires developers responsible for habitat degradation to compensate for the unavoidable biodiversity losses with commensurate environmental gains following a so-called mitigation hierarchy (avoid, minimise, restore on-site, offset) (ten Kate et al. 2004). The developers must meet their offsetting requirements by taking conservation actions either themselves (one-off offsets) or by buying offset credits from landowners who invest in conservation actions to supply the credits. Such actions include setting up protected areas (averted loss offsets) and/or restoring degraded habitats (Bull and Strange 2018; Maseyk et al. 2021). The common goal of offsetting is to ensure no net loss of biodiversity or, increasingly, net gain (Simmonds et al. 2020; zu Ermgassen et al. 2021). Disincentivising land use change and offsetting unavoidable harmful development impacts thus contribute to maintaining or increasing stocks of natural capital (Dasgupta 2021).

From an economic angle, mandatory offsetting would impose the spoiler pays principle on economic agents harming nature and provide them incentives to minimise their impacts on nature. Thus, it would be a counterpart of the polluter pays principle in biodiversity conservation. Under the spoiler pays principle, developers needing offsets would be willing to pay for credits that landowners supply. This implies that mandatory biodiversity offsetting would create a biodiversity offset market. A majority of current offset projects are driven by public environmental policy, and the share of voluntary projects is small (Bull and Strange 2018). Thus, voluntary demand is not likely to produce an adequately sized market and sufficient trading activity. Regulation and enforced legislation are essential for a well-functioning habitat banking and offset market (Santos et al. 2015).

To be ecologically sound, offsetting must ensure at least full ecological compensation of the damage caused. Thus, the offset market is basically a quantity-based instrument like, for instance, the emissions trading system. However, the quantity requirement, no net loss or net gain, is an individual ecological equivalence between losses and gains on the project-level whereas in emission trading, the cap is for the market as a whole. Determining the ecological equivalence to guarantee no net loss or provision of net benefits requires careful ecological calculations drawing on specific calculation procedures (see e.g., Kangas et al. 2021 for a comparison of alternative biodiversity indexes). Thus, the biodiversity offset market has huge information requirements. Trading rules, such as habitat equivalence and like-for-like requirements, increase the transaction costs (Lapeyre et al. 2015). Lack of expertise and high transaction costs of finding a buyer or a seller of offset credits hinder the development of offset markets. A market solution for this challenge may be provided by intermediaries who offer the required scientific expertise and brokering services, thereby reducing transaction costs and uncertainties (Benassi and Di Minin 2009; Gangadharan 2000; Stavins 1995; Woodward and Kaiser 2002; Woodward et al. 2002). Intermediaries can provide benefits for the offset market. They benefit from economies of scale, which can reduce transaction costs for both buyers and sellers, especially through the provision of information and core offset services that are time-consuming and require a lot of information (negotiation, monitoring and reporting) (Coggan et al. 2013a).

Intermediaries may also be beneficial for biodiversity. They reduce the ecological uncertainty associated with measuring the adequacy of offsets by investing in technology, data and knowledge required (Coggan et al. 2013a). Furthermore, they may decrease not only financial but also ecological risks if they act as a bank by buying, holding and selling offset credits (Coggan et al. 2013a; Stavins 1995). Given the uncertainty on the outcomes of restoration and negative ecological effects of time lags between biodiversity losses and gains, intermediaries can reduce ecological risks by offering mature offset credits. Keeping a storage of mature credits provides immediacy and liquidity and decreases trade ratios for the developers (Kangas and Olllikainen 2019). This feature may distinguish intermediaries in offset markets from conventional brokers: they play a more crucial role than, for instance, in water quality markets, where simply aggregating credits and linking buyers and sellers are the key services provided by the intermediaries or clearinghouses (Selman et al. 2009; Woodard and Kaiser 2002, Shortle et al. 2021). This may be a source of weakness as well, as it may create market power to intermediaries, which causes welfare loss.

Despite the intermediaries' prevalence in existing offsetting programmes (Coggan et al. 2013a; Froger et al. 2015), there are only a few papers that focus on intermediaries in the context of biodiversity offsetting (Coggan et al. 2013a, 2013b). To our knowledge, the only study that introduces the impact of intermediaries in the offset market is by Kangas and Ollikainen (2019). They find, in an offset market equilibrium model, that by keeping a portfolio of mature credits and thus decreasing ecological risks, an intermediary can reduce the costs of offsetting to developers due to lower trade ratios. They did not, however, examine the behaviour of intermediaries. In this paper we examine the role of intermediaries in a biodiversity offset market formally and numerically.

We build on the general economic understanding of intermediaries' role in providing search and bargaining services. Much of this literature has modelled intermediaries both as a monopolist (Gehrig 1993; Spulber 1996b; Wooders 1997) or postulated multiple small intermediaries in the market (e.g., Rubinstein and Wolinsky 1987). An intermediary may exploit monopoly power as it temporarily owns information that is crucial for a transaction (Benassi and Di Minin 2009). A monopolistic intermediary is more likely if there are fixed costs of entry to the intermediation market, for instance, if it is difficult and costly to develop knowledge base to determine a traded good's quality (Biglaiser 1993; Gehrig 1993). An intermediary that has market power buys at a lower buying (bid) price and sells at a higher selling (ask) price, which generates positive revenue (Spulber 1996a). It must, however, account for the possibility of decentralised trade between agents, in which demanders and suppliers match and negotiate prices directly and bear the transaction costs (Gehrig 1993; King and Kuch 2003; Nguyen et al. 2013; Rubinstein and Wolinsky 1987; Shortle 2013). Thus, this possibility restricts the intermediary's use of market power.

We focus on intermediaries in an emerging biodiversity offset market. A natural hypothesis is that intermediaries decrease the trading parties' transaction costs by offering specialised information and knowledge, reduce uncertainty related to offsetting, and decrease the costs of offsetting by increasing liquidity in the market and offering certain offsets (i.e., decreasing trade ratios). The benefits are guaranteed for the case of multiple intermediaries that behave competitively, but they are decreased if intermediaries have market power upstream or downstream. Thus, we need to assess the welfare gains from intermediation against the welfare losses from having market power and examine how severe the welfare loss from having market power is. The use of market power is restricted by the possibility of trading in a decentralised market. If the transaction costs and higher trade ratios due to uncertainties and time delay lead to smaller offsetting costs, demanders and suppliers would not employ intermediaries.[1]

[1] An alternative to an intermediary firm is a governmental intermediary agency, which is the case, e.g., in Germany (OECD 2016).

We develop an economic model to examine how the intermediary behaves in biodiversity offset market when it may have market power both upstream and downstream. As a monopolist, it faces a downward-sloping demand curve and can set either the selling price of offset credits or the quantity, but not both. As a monopsonist, it faces an upward-sloping supply function of offset credits and is able to set either buying price or quantity. Assuming multiple intermediaries work at the market, the price of offsets approaches that of a competitive market. Given the local nature of offset credit production, an intermediary may more likely act as a monopsonist, but the presence of multiple intermediaries may also lead to a solution reflecting perfect competition. We employ data on key Finnish habitats and examine numerically the behaviour and welfare implications of the intermediary under the requirement of no net loss and alternative assumptions on transaction costs and trade ratios. To our knowledge, this paper provides the first systematic treatment of intermediaries and their welfare effects in environmental markets both theoretically and numerically. Our approach can be applied in other environmental contexts, such as water quality trading and voluntary carbon offsetting.

2 Economic Analysis of an Intermediary

2.1 The Intermediary's Behaviour with and Without Market Power

Consider an intermediary that has market power both upstream and downstream. Thus, the intermediary faces a downward-sloping demand curve for restored sites and an upward-sloping supply of these sites. We consider first a case where the demand and supply relate to identical sites (equal amount of loss and gain in the same type of habitat). As a monopolist and a monopsonist, the intermediary chooses the area of sites so as to maximise the difference between bid price of the supplied sites and ask price of the demanded sites. The demand for offset credits is impacted by a trade ratio which determines the size of the compensation area relative to the degraded area. The higher the trade ratio, the larger the offset requirement, i.e., the larger the land area that the developer must acquire as compensation. Thus, a higher ratio shifts the demand function outwards. Let q_i refer to the area of habitat i, the sellers' inverse supply function be $w(q_i)$ and the buyers' inverse demand function be $p(q_i)$. The profits of the intermediary are given by

$$\pi = p(q_i)q_i - w(q_i)q_i. \tag{1}$$

The profit-maximizing area of restored sites bought and sold is determined by

$$\pi_q = \left[p + p'(q_i)q_i\right] - \left[w + w'(q_i)q_i\right] = 0. \tag{2}$$

By Eq. (2), the optimal mediated area to the market is determined at the point where the marginal revenue (MR) from selling sites equals the marginal buyer cost (MBC). For this amount, the bid and ask prices p and w are determined by supply and demand functions. It is easy to extract the cases where market power is restricted on the demand or supply side only. For a constant cost w for offset credits, the optimal monopoly's intermediation is characterised by $\left[p + p'(q_i)q_i\right] - w = 0$, and for a constant credit price, the monopsonistic intermediation to the market is given by $p - \left[w + w'(q_i)q_i\right] = 0$. Interpretation is conventional, entailing that in these cases as well, the market is underserved by the intermediary when compared to the perfect market.

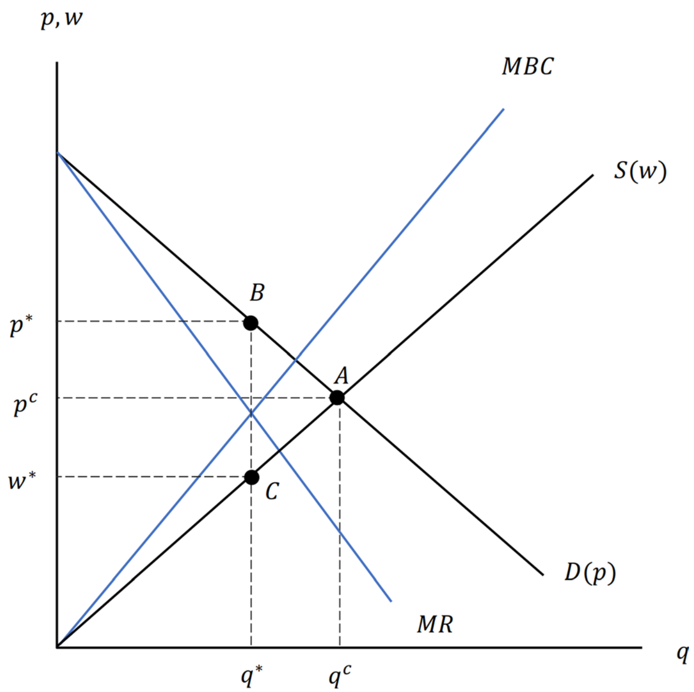

Fig. 1 Offset market with an intermediary with market power: in comparison to the competitive equilibrium (**A**), the ask price is higher, the bid price is lower and the traded land area is reduced (**B**, **C**)

Figure 1 illustrates the choice of the intermediary by Eq. (2), determined by the intersection of MBC and MR curves yielding the total land area of offset credits of habitats i, q_i^*. Profit-maximizing bid and ask prices with the intermediary, determined by demand ($D(p)$) and supply ($S(w)$) curves, are p^* and w^*. The decentralised competitive equilibrium under certainty and zero transaction costs is marked as point A. The competitive market price is p^c and the area traded q^c. Thus, relative to competitive equilibrium, market power causes a welfare loss represented by the triangle ABC. Therefore, the question is whether this welfare loss is greater or smaller than the loss caused by high transaction costs (and suboptimal production of credits) and uncertainty and time discounting (overproduction of credits) – both defined against the competitive equilibrium.

This far, we have assumed that development and compensation sites are identical. Next, we take into account the differing biodiversity values lost at the development site and gained at the compensation site in the analysis. We assume that a biodiversity index[2] is used to measure the ecological state at both sites. Multiplying the biodiversity value lost or gained with the area of the site gives the amount of habitat hectares,[3] which is used as

[2] Measuring biodiversity is one of the most challenging issues in biodiversity offsetting. Many indicators have been developed for this purpose. In this analysis, we use a metric called ELITE index which is suitable for measuring biodiversity value in Finnish habitats to which we apply our model in the next section (Kangas et al. 2021). The index value varies between 0 and 1.

[3] It is common to use biodiversity value weighted area as a measure for assessing losses and gains in offsetting. A well-known example of compound methods that supplement area-based measurement with eco-

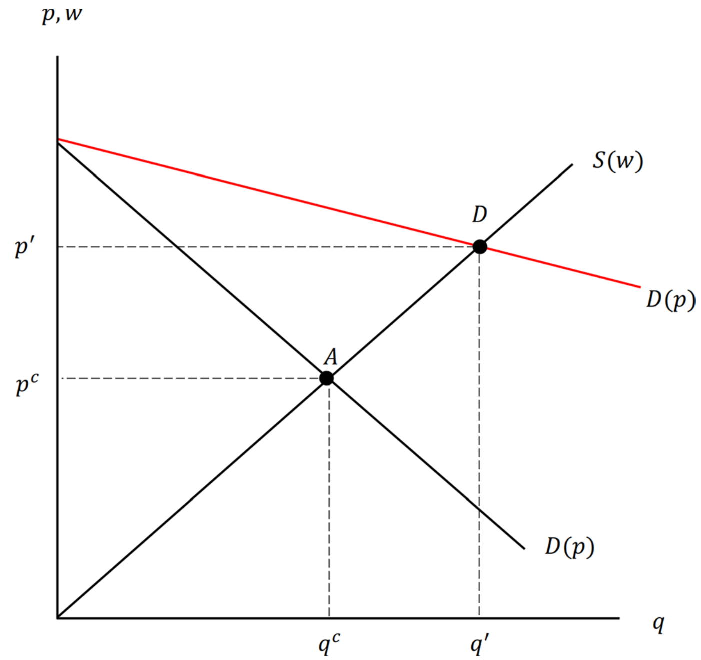

Fig. 2 Offset market with decentralised trade: increasing the trade ratio moves the demand curve ($D(p)$) outwards, which increases the traded land area and the price

a measure of the demanded and supplied amount of offset credits. Following ecological literature, we assume that'like-for-like or better' trading rule is enforced on the market: credits can only be bought from the same habitat (like-for-like) or one that is more ecologically valuable or threatened (like-for-better, trading up). Thus gains bought as offsets are for similar biodiversity components and ecological functions as those degraded (Bull et al. 2015; zu Ermgassen 2020). Our numerical analysis employs a trading rule that is based on a hierarchy of habitats proposed by Raunio et al. (2019) who define how habitat types in Finland should be traded based on their endangerment, rarity, structure and functional features.

The short-run need for offset credits is determined by the trade ratio which determines the offset requirement, i.e., how large the offset area must be relative to the degraded area to achieve the no net loss target. Assuming a like-for-like trade, the trade ratio (σ) matches the ecological values of loss (L) and expected gain (G) (Moilanen et al. 2009):

$$\sigma = \frac{L}{G\varepsilon(1+r)^{-t}} \tag{3}$$

The discount factor (r denoting the interest rate and t time in years) calculates the net present value of the gain if there is a time delay in the benefits of restoration. The

Footnote 3 (continued)
logical information is the Australian Habitat Hectares developed for measuring offsets in Victoria, Australia (Parkes et al. 2003).

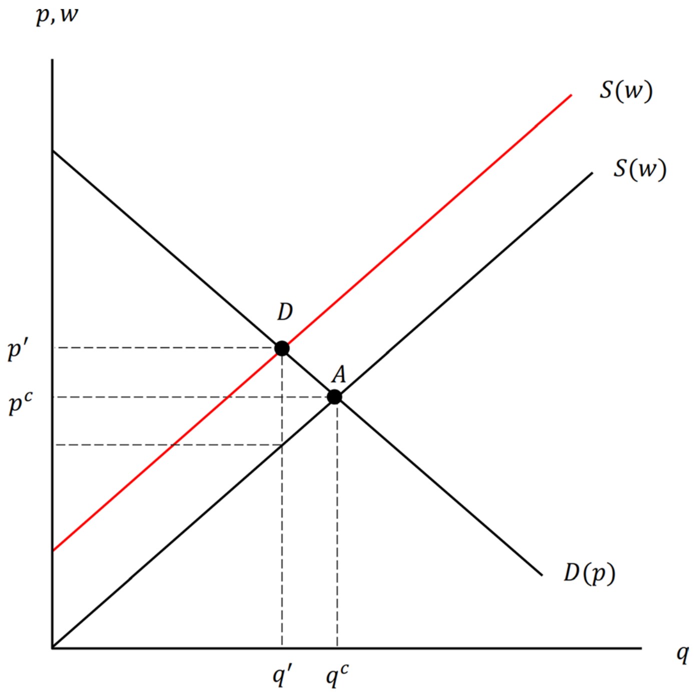

Fig. 3 Offset market with decentralised trade: transaction costs move the supply curve ($S(p)$) inwards, which reduces the traded land area and increases the price

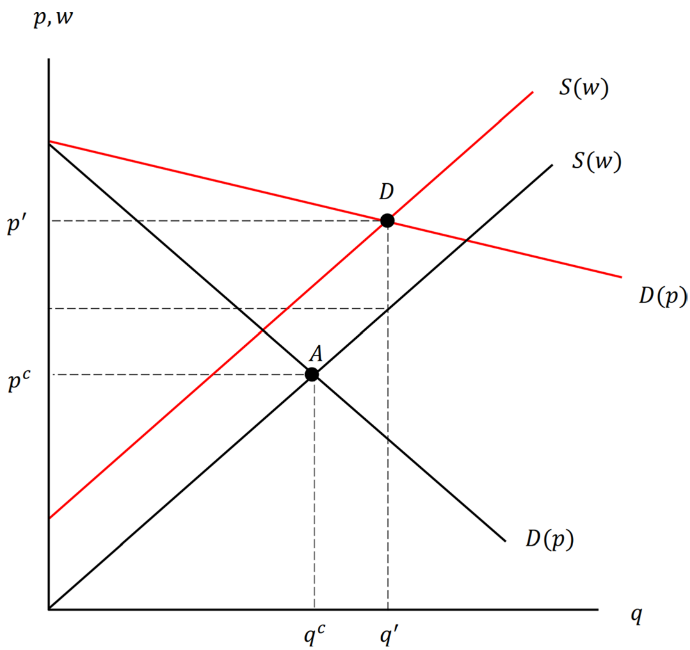

Fig. 4 Offset market with decentralised trade: the joint impact of transaction costs and trade ratios increases the price further

multiplier, ε, $(0 < \varepsilon < 1)$ decreases the amount of gain and adjusts the trade ratio to account for different sources of uncertainty. Longer time delay (higher t) or higher uncertainties (lower ε) increase the trade ratio, which increases the demand for credits (Kangas and Ollikainen 2019).

We illustrate the features of decentralised trade in offset markets in Figs. 2, 3, 4 by distinguishing between perfect competition (point A) and the presence of higher trade ratios and transaction costs (point D). In the absence of the intermediary, higher trade ratios are needed due to higher uncertainty and time delay, which requires developers to buy more land as compensation, increasing demand. Figure 2 illustrates that with higher demand, prices and traded areas increase. Zero transaction costs are highly unlikely without the intermediary as offsetting requires much information and high competence.[4] Figure 3 shows that transaction costs shrink the market as they shift the supply curve inwards, reducing the traded land area and increasing price in the equilibrium. Figure 4 shows the interplay of both mechanisms. Transaction costs move the supply curve inwards, but as the increasing trade ratio shifts the demand curve outwards, the credit price increases further. Figure 1 showed that omitting trade ratios and transaction costs, the traded quantity is higher, and the market price is lower than the ask price and higher than the bid price in decentralised trade: $q^* < q^c$ and $w^* < p^c < p^*$. However, comparing Figs. 1, 4 shows that under trade ratios and transaction costs, trading via the intermediary may become a less expensive option for developers.

To add the measured biodiversity index values to the analysis, we denote the lost biodiversity value at the development site with parameter α and use parameter β for the additional biodiversity gain produced at the compensation site. Thus, the demanded and supplied amount of offset credits in habitat hectares are αq_i and βq_i, respectively. Following Eq. (3), the trade ratio determines the required area of the compensation site when the extent of the loss (αq_i) and additional gain produced per hectare (β) is known. To fulfil the no net loss requirement, the developer must acquire at least an area of size $\sigma \times G\varepsilon(1+r)^{-t} \equiv M$. The offset requirement M matches loss accounting for multipliers and time discounting and, measured as habitat hectares, the developers needs credits at least an amount of: $M(r, t, \varepsilon) \leq \beta q_i$.

The intermediary with market power both upstream and downstream maximises its profits from delivering the required land area for compensation.

$$\pi = p\left(\alpha q_i\right)\alpha q_i - w\left(\beta q_i\right)\beta q_i \tag{4a}$$

$$s.t. \beta q_i \geq M \tag{4b}$$

The optimality condition requires that

[4] The presence of imperfect competition raises the question whether the society should take an action to promote competitive allocation. Potential instruments are promoting entry of intermediaries to the market or using subsidies to bribe the intermediary to expand intermediation (Baumol and Oates 1988). Whether the policy maker should promote the market entry of multiple intermediaries depends on the lump sum cost of information gathering. For a low cost, this policy is feasible but if this fixed cost is very high, regulating the monopoly power of the intermediary is not worthwhile because it entails duplicating the lump sum cost, as every agent on the market has to bear the cost (Motta 2004). If the intermediary has market power either upstream or downstream, a subsidy would suffice to restore competitive equilibrium. When market power covers both up- and downstream, one instrument is not enough and, for instance, a combination of entry promotion and subsidy could be considered.

$$\left(p'\left(\alpha q_i\right)\alpha q_i\alpha + p\alpha\right) - \left(w'\left(\beta q_i\right)\beta q_i\beta + w\beta\right) + \lambda\beta = 0 \tag{5a}$$

$\beta q_i - M = 0$. (5b).

Optimality condition (5a) can be expressed as $\left(p'\left(\alpha q_i\right)\alpha q_i + p\right)\alpha + \lambda\beta = \left(w'\left(\beta q_i\right)\beta q_i + w\right)\beta$. Biodiversity value parameters α and β scale the marginal revenue and marginal buyer costs to respective values. The presence of the Lagrangian multiplier indicates that the requirement is binding, meaning that the intermediary buys more sites than it would do in the free optimum, as it has now to deliver the required number of habitat hectares. Referring to previous graphics, the chosen land area would be far to the right of the crossing point of MR and MBC curves. While the choice approaches the competitive solution under certainty and without transaction costs, the demand function would actually be to the right of the optimal one. This inefficiency is not reduced or eliminated. From society's point of view, the intermediary would do better by buying sites beforehand and holding them for short-term purposes. Naturally, this requires that expected return on sites exceed the buyer costs and capital costs of having the site in storage. We next examine the basic features of this choice.

2.2 Maintaining Credit Portfolio: Liquidity, Immediacy and Future Profits

The intermediary provides liquidity and immediacy to the market. This requires keeping a portfolio of offset credits, i.e., storage of different types of habitats with different restoration measures. If this storage is big enough, the intermediary works as a seller of credits from the storage. The size of the compensation required and, consequently, the cost of offsetting depend on how certain the estimated amount of credits is. When compensation is made with credits from recent restoration, the trade ratio accounts for time delay and multipliers for uncertainty. This increases the amount of required credits, as shown above. Selling from storage with mature credits allows the intermediary to supply certain mature credits, decreasing the trade ratio and avoiding the use of multipliers and thereby saving the developer's money. The intermediary assesses the future value of sites bought. In general, it depends on the expected selling price and the increase in the biodiversity value of the restored sites. The value of these sites increases mainly via decreased uncertainty related to the success of restoration.

A simple way to examine the role of the intermediary as a buyer and securer of restored sites is to assess its decision in a two-period framework. The model consists of periods "now" and the "future" with the length of a period long enough to ensure the success of restoration (future representing the steady state, as is typical in two-period models). The amount of gain matured in storage is $\widehat{\beta}$, for which it holds that $\widehat{\beta} > \beta$. Finally, we express the expected demand using the expectation operator E, and r denotes the real interest rate.

$$\pi = (1 + r)^{-t} Ep\left(\widehat{\beta} q_i\right)\widehat{\beta} q_i - w\left(\beta q_i\right)\beta q_i \tag{6a}$$

The optimal choice is given by.

$$(1 + r)^{-t}\widehat{\beta}\left[Ep'\left(\widehat{\beta} q_i\right)\widehat{\beta} q_i + Ep\right] - \beta\left[w'\left(\beta q_i\right)\beta q_i + w\right] = 0 \tag{6b}$$

Thus, the intermediary equalises the present value of the expected marginal revenue to the current marginal buyer cost. Obviously, the greater the expected ecological value and demand, the more the intermediary buys sites for future use. Finally, a higher interest

Table 1 Parameters for market demand and supply functions

	a	b	c	d
Pine mires	13,000	0.16	7500	0.02
Herb-rich forests	20,000	4.00	11,000	0.50
Rural biotopes	47,000	5.45	28,600	0.30

rate decreases the profitability of buying credits in advance. For competitive expected offset credit price, the condition reduces to $(1+r)^{-t}\widehat{\beta}Ep - \beta\left[w'\left(\beta q_i\right)\beta q_i + w\right] = 0$, indicating that the intermediary sets the present values of the expected, value-adjusted price equal to the current marginal buyer cost.

3 Numerical Analysis of an Intermediary in the Biodiversity Offset Market: an Application to Finnish Habitats

3.1 Calibration of Demand and Supply Functions

We apply our analytical model to a hypothetical biodiversity offset market. We consider trading offset credits in three boreal habitats in Finland: pine mires, herb-rich forests and traditional rural biotopes. The habitats represent different types of restoration and nature management cases; they cover large land areas, thus providing a good potential for restoration and supply of offset credits. Pine mires are nutrient-poor peatlands with a thick peat layer. Almost half the pine mires in Finland are drained for forestry, also including large areas that have proven unsuitable for forest growth. They are restored by filling ditches and removing trees, which requires a one-time upfront investment. Herb-rich forests are fertile, the most species-rich type of forest in Finland. Forest management activities degrade the state of herb-rich forests. They are restored with nature management measures, e.g., by removing spruces regularly (every 10–20 years) to establish forests dominated by broadleaved trees with a diverse tree stand structure, decaying wood and large trees. Thus, managing herb-rich forests requires repeated measures. Traditional rural biotopes include various open wooded pastures, meadows and grasslands that support a high number of threatened species. Their area and ecological value have degraded considerably due to changes in agriculture. Rural biotopes are managed annually by grazing and mowing to prevent overgrowth and to maintain open areas.

We employ biodiversity offset credit demand and supply functions developed in Kangas and Ollikainen (2019). They defined the potential supply of offset credits from each selected habitat type based on the area suitable for restoration and management in Finland along with the costs of restoration, management and conservation. The demand for offsets was estimated drawing on the predictions of land use change through 2040. The predictions estimated how many hectares of land in each habitat type will turn into built-up areas, infrastructure, or peat extraction sites. We use these market demand and supply functions as a basis to estimate individual demand and supply functions. We postulate linear inverse demand function of form $p\left(q_i\right) = a - bq_i$ and inverse supply function of form $w\left(q_i\right) = c + dq_i$. Table 1 represents the parameters used for the market demand and supply functions.

Table 2 Results with decentralised trade and perfect competition

	Perfect market		Transaction costs		Trade ratios		Transaction costs & trade ratios	
	Price	Area	Price	Area	Price	Area	Price	Area
Pine mires	7910	91	9200	62	8500	150	9600	102
Herb-rich forests	11,310	38	13,050	30	12,660	61	14,090	47
Rural biotopes	28,850	32	33,280	23	30,970	46	34,825	34

Demand functions in Table 1 are aggregate functions, so we postulate a representative demander and supplier and one intermediary that either uses market power or behaves competitively.

3.2 Baseline: A Decentralised Offset Market

Consider first a competitive market with and without uncertainty and transaction costs. In this market the developer trades directly with suppliers. We take a perfect competitive market as the first-best benchmark and then introduce transaction costs, time delay and discounting, and uncertainty as deviation from the first-best solution.

Table 2 represents the results for decentralised trade to benchmark the three cases. The first column gives the optimal prices and land areas in perfect markets under certainty on gains and losses. We assume that the loss and gain are identical (index value 1 per hectare) under certainty, and thus the trade ratio with certain credits is 1. The second column assumes that the supplier carries a 20% transaction cost, while the ecological status of credits remains certain. In the third column, the amount of gain sold as offset is uncertain and there is a time delay between losses and gains, which are accounted for in the trade ratio [Eq. (3)]. We assume a time delay of 10 years in pine mires and herb-rich forests and 5 years in rural biotopes because ecological gains are realised faster in rural biotopes (Kangas and Ollikainen 2019). We use a 3% discount rate. For the uncertainty of the state of the habitat, we assume a 70% likelihood that the restoration fully succeeds; thus the additional biodiversity gain supplied per hectare is $\beta = 1 \times 0.7 = 0.7$. Both discounting and uncertainty decrease the amount of gain per hectare supplied, which means that compensation area must increase to meet the demand. The trade ratio determines this land area. Our assumptions for time delay and uncertainties lead to a trade ratio of 1.9 in pine mires and herb-rich forests and 1.7 in rural biotopes. Finally, the fourth column takes into account both transaction costs and trade ratios. Traded land areas are expressed as hectares and prices as €/hectare.

Table 2 confirms the previous theoretical analysis. Relative to the perfect markets, transaction costs reduce supply and thus increase the price and reduce the area of restored habitats at the equilibrium. Time delay and uncertainty shift the demand function for restored sites outwards due to a higher trade ratio. Now, the developer needs more restored land, and consequently, traded land areas increase and prices decrease. When there are both transaction costs and trade ratios, the prices increase further from the previous cases, and the traded land area is higher than in the perfect markets, but, due to transaction costs, lower than in the case of trade ratios alone. The differences concerning habitats are shown in offset credit prices which are the lowest in pine mires, where restoration is a one-time

Table 3 Results with a monopolist and monopsonist intermediary

	Certain credits[a]			Trade ratio[b]		
	Ask price	Bid price	Area	Ask price	Bid price	Area
Pine mires	9960	7460	45	10,250	7750	75
Herb-rich forests	15,150	10,150	19	15,830	10,830	30
Rural biotopes	36,920	26,420	16	37,990	27,490	23

[a]Trade ratio 1

[b]Trade ratio > 1 due to time delay and uncertainty

investment and not very expensive. Prices are highest in rural biotopes, which require costly annual management. These findings are in line with Kangas and Ollikainen (2019).

3.3 The Intermediary: the Role of Liquidity and the Impact of Market Power

Consider now the role of an intermediary with market power as a seller and a buyer. The intermediary removes transaction costs from trade. We follow the same procedure as above and consider first a case assuming that there is no uncertainty associated with credits needed for compensation ('Certain credits'). We then introduce uncertainty and time delay, which requires the use of trade ratios ('Trade ratios'). Table 3 presents the results.

Table 3 shows that, as illustrated in Fig. 1, the intermediary charges higher ask prices and pays lower bid prices than the price in perfect competition. Reflecting economic theory, the intermediary uses markup pricing when selling and markdown pricing when buying offset credits. As a consequence, the traded areas of restored habitats are lower than in perfect competition. Like in Table 2, with trade ratios, demand for restored habitats increases, and consequently, larger land areas are traded, and bid and ask prices increase. This increases the developers' costs of compensation. The difference in the two columns of Table 3 shows the importance of having liquidity in the market and certain credits immediately available for sale.[5]

The provision of certain credits is not, however, realistic unless the intermediary keeps a portfolio of credits stored to facilitate selling mature credits. Storing the credits means buying restored land parcels in advance and ascertaining that restoration successfully increases the state of the site. Thus, time delay and uncertainties of sold credits may even be entirely removed, and trade ratios decrease, which means that the developer needs smaller land areas to meet their offset requirement.[6] The nature of the market may change considerably, if keeping a storage of restored sites is economically profitable due to expectations on future demand. In this case the contribution of the intermediary to the ecological integrity of offsetting may be huge.

[5] If the developer needs a given quantity of habitat hectares (M in Eq. (4)) to meet its offset requirement and the intermediary delivers the required habitat hectares and corresponding land area, bid prices increase and ask prices decrease, decreasing the bid-ask spread and profit collected by the intermediary. Because the intermediary deviates from its optimum, the ask and bid prices and land areas traded move closer to competitive ones.

[6] Table 19 in AppendixBexamines the parameters that determine whether it is profitable for the developer to buy expensive mature credits rather than less expensive recent credits with higher trade ratios.

Table 4 Results when buying to and selling from storage

	Full certainty			Uncertain future state			Uncertain future demand		
	Ask price	Bid price	Area	Ask price	Bid price	Area	Ask price	Bid price	Area
Pine mires	12,530	7780	112	14,020	7720	103	11,840	7690	99
Herb-rich forests	18,970	10,850	44	21,180	10,760	42	18,010	10,680	40
Rural biotopes	38,010	27,410	32	48,320	28,260	41	41,420	28,040	38

We examine the role of storing by shifting from the static one-period analyses of Tables 2 and 3 to the two-period framework presented in Sect. 2.2. Under successful storage keeping the intermediary can supply certain credits from the storage, so that the additional biodiversity value sold as credits is $\widehat{\beta} = 1$ per hectare. The intermediary maximises the present value of profits from future demand using 3% real discount rate. The expectation is that demand will grow because legislation is expected to be stricter in the future, which increases future demand. Uncertainty is, however, present in the intermediary's choice. Therefore, we need to complement the analysis by introducing uncertainty to the two-period model.

We consider cases where biodiversity values obtained from restoration after storing and future demand for credits are uncertain. The intermediary is assumed to be risk-neutral, making its choices drawing on expected values of the uncertain variable. We illustrate these choices using a simple approach with two realizations of uncertainty (high or low biodiversity value and demand) with two probabilities (high and low). Let the probability be ρ for the emergence of high state of the restored habitat and thus, high biodiversity gain $\widehat{\beta}^{+}$ and $(1-\rho)$ for low gain$\widehat{\beta}^{-}$, so that the expected additional biodiversity gain of the restored habitat is simply$\widehat{\beta} = \rho\widehat{\beta}^{+} + (1-\rho)\widehat{\beta}^{-}$. As for the future demand, we assume that the shift parameter of the linear demand curve is uncertain, while the slope is known. Like above we assign a probability to a higher and lower demand allowing the intermediary to use the expected future demand curve. Thus, the future demand function is given by$Ep = (\rho a^{+} + (1-\rho)a^{-}) - \widehat{\beta}q_i$.[7]

Table 4 presents the results. Columns under 'Full certainty' represent an idealized case where the intermediary has full certainty about the restored habitats and the future demand. Columns under 'Uncertain credit' and 'Uncertain future demand' represent the intermediary's choice under the expectations on credit values and future demand.

Storage increases the amount of restored land area. Future uncertainty matters to the choice and the intermediary buys less restored land to storage than under full certainty. Under uncertain credit value, the intermediary supplies fewer mature credits and thus, receives a higher ask price. When future demand is uncertain, ask and bid prices are lower than with full certainty. Clearly, uncertainty increases the bid-ask spread, which causes welfare loss. Importantly, however, the intermediary safeguards the offset buyers against the risk of failed credits and improves ecological integrity of offset markets by shifting the uncertainty effects on market prices. Note finally that uncertainty of future demand for

[7] Parameters for expected biodiversity gains: $\rho = 0.6$, $\beta = 0.7$, $\widehat{\beta}^{+} = 1.0$, $\widehat{\beta}^{-} = 0.3$. Parameters for expected future demand: $\rho = 0.6$, a^{+}= 17 000 (pine mires), 26 000 (herb-rich forests), 60 000 (rural biotopes) and a^{-}= 14 000, 22 000, 52 000 respectively.

Table 5 Results with an intermediary when certain credits are sold from storage

	Ask price	Bid price	Area
Pine mires	9730	7460	51
Herb-rich forests	14,580	10,150	22
Rural biotopes	35,710	26,420	19

Table 6 Results with a monopsonist intermediary

	Certain credits			Trade ratios		
	Price	Bid price	Area	Price	Bid price	Area
Pine mires	8070	7530	53	8670	7830	83
Herb-rich forests	11,530	10,270	21	12,910	10,950	33
Rural biotopes	29,420	26,710	18	31,590	27,800	25

credits contains two components, conventional business uncertainty and regulatory uncertainty, as expectations on demand is also impacted by policy makers.

Table 5 presents the results for a case in which the intermediary sells certain credits from the previously bought storage in the first period. Compared to the first column in Table 3, the ask prices are lower and the traded land areas higher.

Consider finally a case in which the intermediary has market power relative to the local suppliers and thus the bid price w but is a price taker when selling credits. Table 6 represents the results with the monopsonist intermediary when the credits are certain and in the presence of trade ratios. We assume that the credit prices are as in perfect competition (Table 2). The monopsonist intermediary adds a fee of 2% (a similar brokerage fee in Hessen, Germany is 6% (OECD 2016)).

Comparing Table 6 to Table 3 shows that because the intermediary now has only monopsony power, land areas are larger, prices are below the ask prices and above the bid prices of the monopolist intermediary. The credit prices with the monopsonist are lower than in the decentralised trade in Table 2 (second and fourth columns). Still, land areas are smaller and prices higher compared to the perfect market in Table 2. Again, the use of trade ratios increases land areas, competitive prices and bid prices.

3.4 Welfare Analysis

Previous analysis has made it clear that an intermediary can help overcome the challenges related to transaction costs, time delay and uncertainty. But the costs of this help depend on the size of the welfare loss due to market power. In the strongest case, the intermediary has market power both upstream and downstream, and the most likely case is given by competitive offset credit price and monopsony power. Note that even in the presence of this welfare loss, the intermediary may represent a welfare improvement. Decentralised trading requires gathering information and knowledge on offsetting, in addition to transaction and other costs. As long as this lump sum cost is higher than the welfare loss from the intermediary, welfare is improved. Therefore, it is useful to examine the welfare effects of the

Table 7 The welfare losses in decentralised trade with transaction costs and trade ratios

	Transaction costs	Trade ratio	Transaction costs & trade ratio
Pine mires	121,060	94,490	162,310
Herb-rich forests	77,150	65,520	215,160
Rural biotopes	160,790	65,180	225,910

intermediary in the offset markets. Referring toFigs. 1, 2, 3, 4,[8] we determine first welfare losses from transaction costs, and uncertainty and time delay under perfect competition, and then relax them by the intermediary with differing degrees of market power.[9] Table 7 represents the results for decentralised trade. (Figs. 5, 6, 7, 8, 9)

The presence of transaction costs causes inefficiency to the market because it shrinks the market, which reduces both consumer and producer surpluses by the same percentage, approximately 40–50% depending on the habitat, compared to the perfect market. With trade ratios, the traded land areas increase, which increases the producer's surplus. The consumer's surplus decreases but less than with transaction costs. Compared to the impact of transaction costs, the welfare loss is lower. When both transaction costs and trade ratios are accounted for, the welfare losses are higher than they were when examined individually. Transaction costs reduce supply, which increases the price, and trade ratios increase the demand, increasing the price further. Thus, the consumer's surplus decreases more than when trade ratios or transaction costs were accounted for individually, and the producer's surplus increases but less than when only the transaction costs were accounted for.

Table 8 represents the welfare losses related to the intermediary. The first three columns give results for the monopolist and monopsonist intermediary.

When biodiversity values are certain, the welfare losses from the market power are smaller than the efficiency losses from transaction costs in the decentralised trade. Thus, under the supply and demand function parameters, the benefit of the intermediary's removing transaction costs exceeds the welfare loss from the market power, and the intermediary provides a welfare improvement. When trade ratios increase the traded land areas, the welfare losses are smaller,[10] and the welfare improvement provided by the intermediary increases.

With the monopsonist intermediary, the welfare losses are the lowest: it removes transaction costs, which causes less welfare loss than in the decentralised trade, and as it uses market power only downstream, the welfare losses are lower than with the monopsonist and monopolist intermediary. Compared to the decentralised trade, the producer's surplus

[8] Appendix A illustrates graphically the welfare losses in each case.

[9] Note that we continue to focus only on biodiversity offset markets and omit welfare effects from other economic implications to developers. These may include making investments in land areas with low ecological value instead of high-value lands and making greater efforts within the mitigation hierarchy.

[10] The impact of trade ratios to market power can also be illustrated using the Lerner index (Lerner 1934). The index value, i.e., market power, is lower with increased trade ratios than in the basic case (certain credits). The index values also vary moderately between habitats. In pine mires, the Lerner index is 0.21 with certain credits and 0.17 with a trade ratio of 1.9. In herb-rich forests, the index values are 0.25 to 0.20 and in rural biotopes, 0.22 and 0.18, respectively.

decreases, and the intermediary realises much lower profit as a monopsonist than when it also exploits monopoly power.[11]

3.5 Trading up

Next, we examine trading up (like-for-better), i.e., trading losses in a habitat of low conservation significance for gains in a more valuable (rarer or more threatened) habitat. In our analysis, it means offsetting impacts in pine mires for gains from restoration in herb-rich forests or rural biotopes (Raunio et al. 2019). As shown above, the difference in prices is significant between these habitats, with pine mires being the least expensive credits. Therefore, one could think that the developer has no incentive to buy credits from herb-rich forests or rural biotopes to offset losses in pine mires. However, if trade ratios are different depending on from which habitat credits are bought, the developer may be better off if this developer trades up (Habib et al. 2013).

We supplement Eq. (3) with a multiplier for like-for-better trades:

$$\sigma = \frac{L}{G\varepsilon\delta(1+r)^{-t}} \tag{7}$$

The multiplier, $\delta(\delta > 0)$ is used to increase the amount of gain if the habitat is more ecologically valuable than the one lost, decreasing the trade ratio. Literature suggests that when trading up, multipliers that decrease the trade ratio can be used, but choosing the exact multipliers is, however, a subjective decision (Gardner et al. 2013; Moilanen & Kotiaho 2018). To illustrate the role of trading up, we select a multiplier of 1 to trading up to herb-rich forests and 1.3 to trading up to rural biotopes.

To examine these effects, we assume that in pine mires, only recently restored credits are available: there is a 6-year time delay ($t = 6$) and a 60% probability that restoration is fully successful ($\varepsilon = 0.6$). In herb-rich forests, the probability is 80% and the time delay is four years ($t = 4, \varepsilon = 0.8$). In rural biotopes, we assume that the gain is certain and time delay is two years ($t = 2, \varepsilon = 1$).[12] First, we assume that $\delta = 1$. The trade ratios and the cost of offsetting are presented in rows 1–3 in Table 9. The total costs depend on the credit prices (€/ha) and trade ratios and are calculated assuming that the amount of loss is 1 habitat hectare, the trade ratio determines the area the compensation site required, and prices are as presented in Table 2 (incl. transaction costs), 3 and 4 (certain credits). The total cost of offsetting the loss of one habitat hectare in a pine mire thus equals trade ratio × price$€/ha$.

In rows 4–6, we add an assumption for the amount of additional gain: it is lowest in pine mires at 0.3; in herb-rich forests, it is 0.5, and in rural biotopes it is 0.9 (Kangas and Ollikainen 2019). The same uncertainties and time delays remain. Also, we employ a

[11] The Lerner index values with the monopsonist (Blair & Harrison 1992) are lower than with the monopolist. The trade ratios increase the market power. In pine mires, the index values are 0.07 with certain credits and 0.11 with higher trade ratios, in herb-rich forests 0.12 and 0.18 and in rural biotopes 0.10 and 0.15, respectively.

[12] Time delay after restoration varies considerably between sites of the same habitat, and time scales used here are examples of possible time delays: the recovery of the hydrology, structure and functions of a drained mire ecosystem may take years. Some structural characteristics of herb-rich forests can recover quite fast with spruce removal and dead wood creation, but the proportion of broad-leaved trees and diversity of the tree stand structure improve much slower. The state of a poorly managed, overgrown rural biotope can increase quickly by mowing, thinning, and removing coppice.

higher multiplier for trading up ($\varepsilon = 1.2$) in rural biotopes because they are the most ecologically valuable habitat of the three.

Filling the offset requirement by trading up is not economically wise for the developer in rows 1–3, as offsetting with pine mire credits has lowest total costs. In rows 4–6 with higher trade ratios, trading up to herb-rich forests or rural biotopes is an economically feasible option. Due to the like-for-better multiplier, trading up to rural biotopes is less expensive than herb-rich forests.

3.6 Sensitivity Analysis

The previous analysis is based on hypothetical markets, which does not undermine the comparisons made between decentralised trading and the intermediary. The results above may, however, depend on the chosen ecological and economic parameters and are worth some scrutiny. First, we examine how the levels of transaction costs, time delay and uncertainties impact the results. Second, we consider the parameters used in calculating the optimal choice with storage: the length of the period and the discount rate.

We consider low (10%) or high (35%) transaction costs in comparison to the 20% transaction costs of the analysis so far. For time delay, we employ 5 and 15 years compared to the 10-year time delay of the earlier analysis and for uncertainties, $\beta = 0.5$ for high uncertainties and $\beta = 0.9$ for low uncertainties ($\beta = 0.7$ in the main analysis). The different levels of uncertainties and time delay lead to different trade ratios: 1.3 for low uncertainties and shorter time delay and 3.1 for high uncertainties and longer time delay. Table 10 presents the results for decentralised trade and Table 11 for the intermediaries where only the level of trade ratios impacts results. The results are for pine mires, but the conclusions can be generalised to all three habitats. Results for herb-rich forests and rural biotopes can be found in Appendix B.

Tables 10, 11 show that the impacts are as expected: in comparison to Table 2, low transaction costs lead to lower prices and larger traded land areas, and higher transaction costs lead to higher prices and smaller areas. Comparing Tables 10, 11 to Tables 2, 3 and 6 shows that with lower trade ratios, prices and areas are reduced, and with higher trade ratios, prices and land areas increase. We can also infer that welfare losses increase with transaction costs and trade ratios.

In the main analysis, after perfect competition, the credit prices were the lowest in the case of the monopsonist intermediary and highest (ask prices) with the monopolist intermediary. With 35% transaction costs, decentralised trade becomes the most expensive option. Whether bid prices increase more or less with the monopolistic intermediary depends on the price sensitivity of demand and supply functions. Under our parametrisation, the bid prices increase more than the ask prices, because the slope of the demand curve is steeper than that of the supply curve. Thus, high trade ratios increase ask prices 6% and bid prices 8% from the case of certain credits.

Comparison of welfare losses in Tables 10, 11 to Tables 7, 8 shows that even with low transaction costs (10%), the decentralised trade causes a higher welfare loss than the monopolist and monopsonist intermediary (comparing to Table 8, ‘Certain credits’). For the welfare loss to be lower than one from the strong market power of the intermediary, the transaction costs can be at most 8%, and to be below the welfare loss from the monopsonist intermediary, transaction costs can be at most 1%.

Table 8 The welfare losses with the intermediary

	Monopolist & monopsonist		Monopsonist	
	Certain credits	Trade ratio	Certain credits	Trade ratio
Pine mires	56,820	7170	10,020	3190
Herb-rich forests	48,080	8330	10,990	5760
Rural biotopes	84,810	26,760	19,290	13,300

The role of the trade ratios is significant. The higher the trade ratios are, the lower is the welfare loss from the intermediary with market power both upstream and downstream. In the decentralised trade, the 3.1 trade ratio leads to very high welfare loss. Due to the overproduction of credits, the producer surplus is fivefold compared to the perfect market. When the trade ratio is high, the welfare loss from accounting for both transaction costs and the trade ratio is lower than when considering solely the trade ratio. Thus, the shrinking effect on the market from transaction costs decreases the welfare loss. With low trade ratios, the monopolist intermediary leads to the highest welfare losses.

The trade ratios' role in determining welfare losses from decentralised trade stresses the benefits of buying from the intermediary's storage, which removes the need for time discounting and uncertainty multipliers. Sensitivity analysis for the parameters used in calculating the optimal choice with storage can be found in Appendix B. A shorter length of the period (i.e., the time it takes for the site to produce biodiversity gain $\widehat{\beta}$) and a lower discount rate increase the land areas bought to storage. A longer length of the period and a higher discount rate increase the ask prices.

4 Discussion and Conclusions

We examined how an intermediary behaves in the biodiversity offset market when it may have market power upstream and downstream. Our hypothesis was that the intermediary decreases the trading parties' transaction costs, reduces uncertainty related to offsetting, and decreases the costs of offsetting. We compared the welfare gains from intermediation against the welfare losses from having market power. In our analysis, we found that with market power, ask and/or bid prices deviate from the competitive equilibrium, depending on whether the intermediary has market power upstream or downstream. The market power allows the intermediary to use markup pricing when selling and markdown pricing when buying, which shrinks the size of the market and causes welfare loss. The benefits brought by the intermediary may, nevertheless, exceed the welfare loss from its market power, even if it exploits both monopoly and monopsony power, due to the significant welfare losses from transaction costs and trade ratios in decentralised trade. The market participants can choose not to trade with the intermediary and find a trading partner by themselves, which limits the market power.

The intermediary removes transaction costs borne by the market participants in the decentralised trade. Therefore, when providing the time-consuming offset credit search, meeting high knowledge requirements and managing laborious bilateral negotiations between the buyer and seller, the intermediary is more likely beneficial. The

Table 9 Offsetting costs when trading up is allowed

	Trade ratio	Decentralised	Monopoly	Monopsony
Pine mires	2.0	18,320	19,810	16,060
Herb-rich forests	1.4	18,360	21,320	16,230
Rural biotopes	1.1	35,310	39,170	31,220
Pine mires	6.4	59,270	64,110	51,960
Herb-rich forests	2.7	35,640	41,400	31,510
Rural biotopes	1.0	32,700	36,270	28,900

intermediary turns out to be the most useful when the trade ratios are high. Recall, accounting for different sources of uncertainty and time discounting quickly increases the trade ratios from dozens to hundreds (Laitila et al. 2014; Moilanen et al. 2009). High trade ratios are the most common feature of successful offset projects (zu Ermgassen et al. 2019), but ratios employed in practice are much lower than scientific literature suggests, and the majority of realised ratios under 10 (Bull et al. 2016; Laitila et al. 2014). There is an obvious need for a well-designed market that helps to overcome the under-provision of biodiversity offsets and eliminate the extra costs of doing so.

Very high trade ratios increase crucially the developers' costs, which may be one of the reasons why the biodiversity offset market is not widespread. Now, if the intermediary anticipates future demand and buys credits to storage, the economic benefits from the intermediary may be large. In this case the developer would need a significantly smaller land area, and especially in habitats where per hectare costs are very high, the developer might be better off paying a higher per hectare price if it then needs a smaller compensation area. Even if the intermediary only removes transaction costs but does not reduce the need time discounting and multipliers, the offset credits may still be less expensive bought from the intermediary, depending on the level of transaction costs. Trading up may offer another option for the developer to fulfil its offset requirement cost-efficiently.

In addition to cost savings, the storage of the intermediary may bring benefits to biodiversity. The offset area network is different when the intermediary is on the market selling credits from storage instead of a completely decentralised market. The offset area network resulting from the intermediated market is likely smaller in size due to lower trade ratios for developers but is of higher ecological value. The decentralised market leads to a larger total area of offset sites, but as the success of restoration and conservation are uncertain, the outcomes for biodiversity vary, and some sites fail to produce the required biodiversity gains. In theory, the higher trade ratios should account for the failed sites, but uncertainty multipliers are rarely high enough in practice.

The monopsony power of the intermediary leads to lower bid prices paid for landowners, which decreases the landowners' incentives to invest in restoring and conserving habitats to produce offsets. Instead, the increasing ask prices due to monopoly power incentivises developers to minimise their biodiversity impacts further, and they may give up some development projects altogether because mandatory offsetting is more expensive with higher prices. An interesting question for further research is what sort of policy could be used to correct the market failure from intermediaries' market power. A well-functioning, mature market with high trading activity may have lower prices for offset credits, which in turn may cause more developers to offset instead of giving up a development project

Table 10 Sensitivity analysis of pine mires: decentralised market and the level of transaction costs, time delay and uncertainties

	Transaction costs		Trade ratio		Transaction costs & trade ratio	
	Low	High	Low	High	Low	High
Price	8560	10,170	8110	9050	8730	10,680
Area	77	41	111	205	94	91
Welfare loss	66,210	165,940	11,400	355,250	74,230	252,790

Table 11 Sensitivity analysis of pine mires: intermediary and the level of time delay and uncertainties

	Monopolist & monopsonist		Monopsonist	
	Low	High	Low	High
Ask price	10,060	10,520	8280	9230
Bid price	7560	8020	7640	8110
Area	56	102	64	111
Welfare loss	34,220	3560	8660	11,370

altogether if lower prices make the investment financially viable. However, a well-functioning market may also lead to higher demand, which drives prices up. In addition, a well-known set of offset prices over relevant habitats will guide developers to rethink the size and land-use need of their investments and to locate the development sites outside ecologically valuable and expensive sites. Another interesting topic for future research would be to empirically analyse these dynamics.

As data from real biodiversity offset markets is lacking, we had to make many assumptions in the numerical analysis, which naturally restricts the generalizability of the results. For instance, the demand and supply parameters, levels of transaction costs, and many ecological parameters were estimated based on literature rather than real offset trades. The sensitivity analysis shows, however, that the comparisons between decentralised trading and the intermediary hold when different economic and ecological parameters are varied. We acknowledge, though, that results regarding e.g., the credit prices, costings, and trading up could change if data on real offset trades would become available.

Based on our comparisons, we conclude that the presence of an intermediary can be beneficial for the functioning of the offset market and for the biodiversity outcomes of the scheme. Even with strong market power, the benefits from market liquidity and brokering services can exceed the welfare losses of market power, especially when transaction costs or trade ratios are high. This highlights the usefulness of intermediaries when the market is newly established, and the market uncertainties are high in the early stage. Intermediaries can mediate the inherent uncertainties related to offsetting that are among the most important challenges in achieving the no net loss objective of offsetting (Bull et al. 2013; Maron et al. 2012).

Appendix A: Welfare Losses

See Figs. 5, 6, 7, 8, 9.

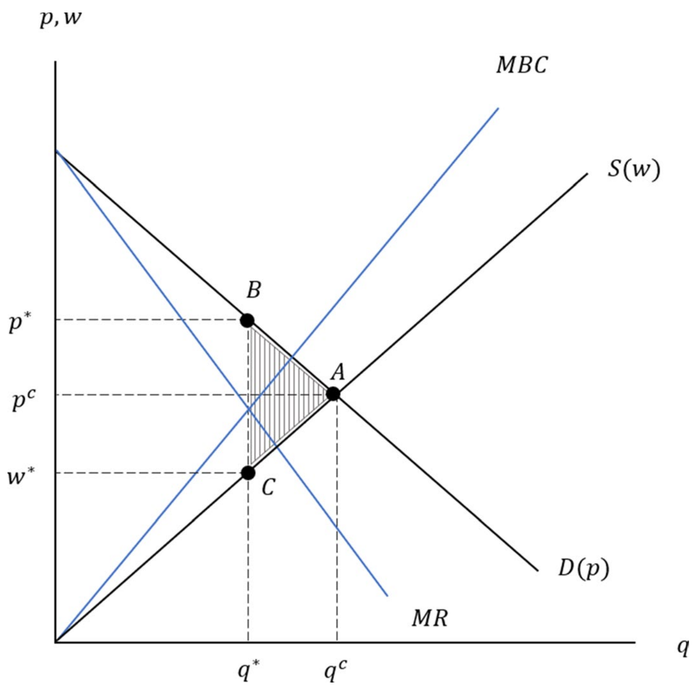

Fig. 5 A monopolist and monopsonist intermediary

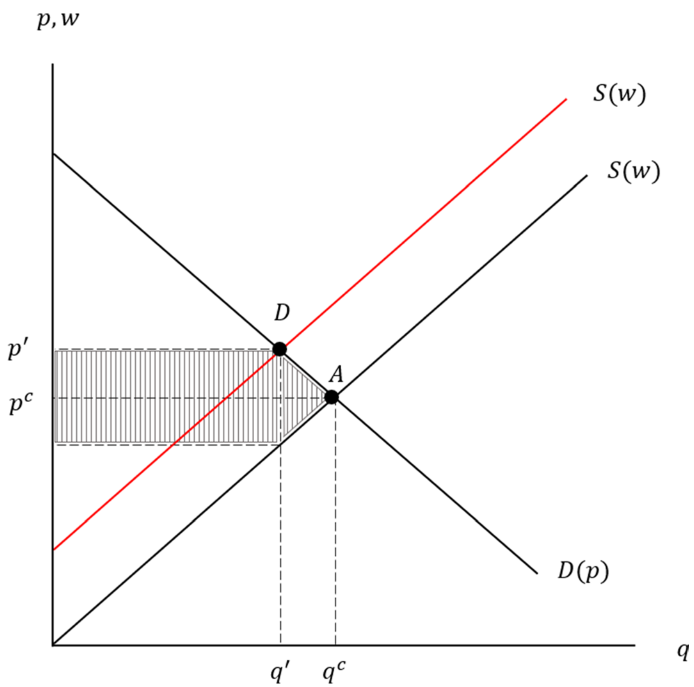

Fig. 6 Transaction costs

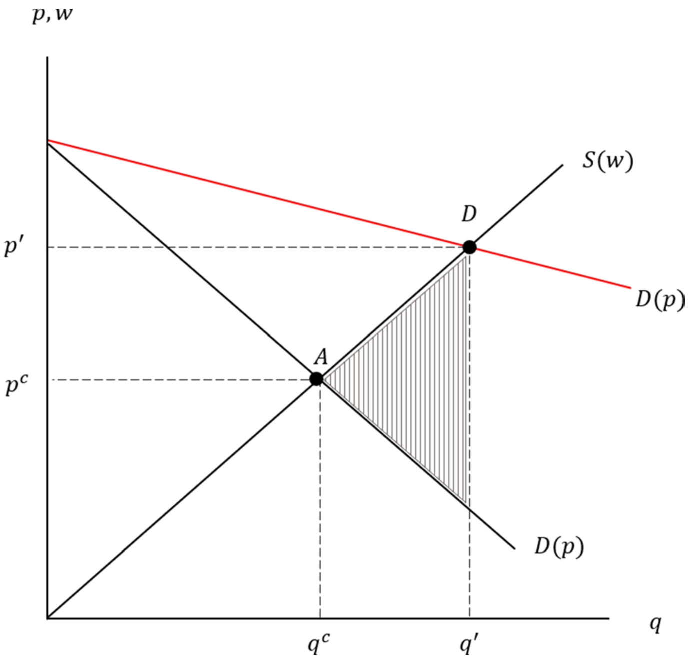

Fig. 7 Trade ratios

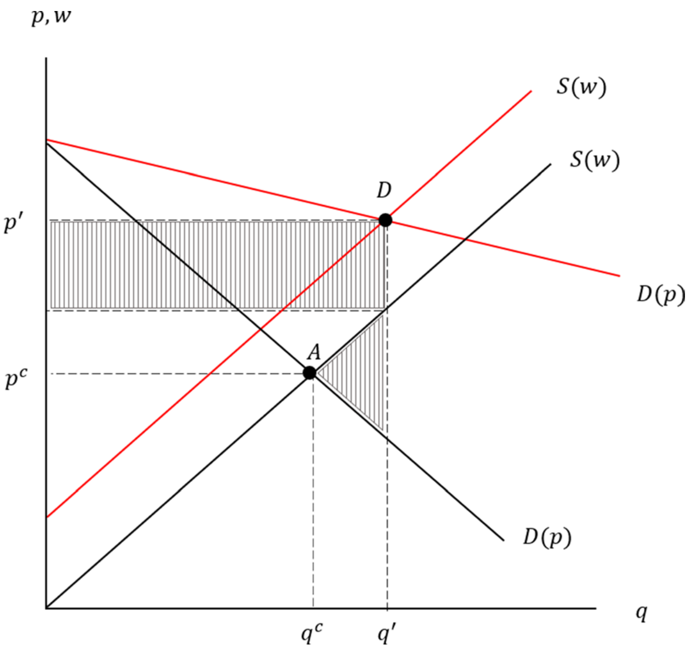

Fig. 8 Transaction costs and trade ratios

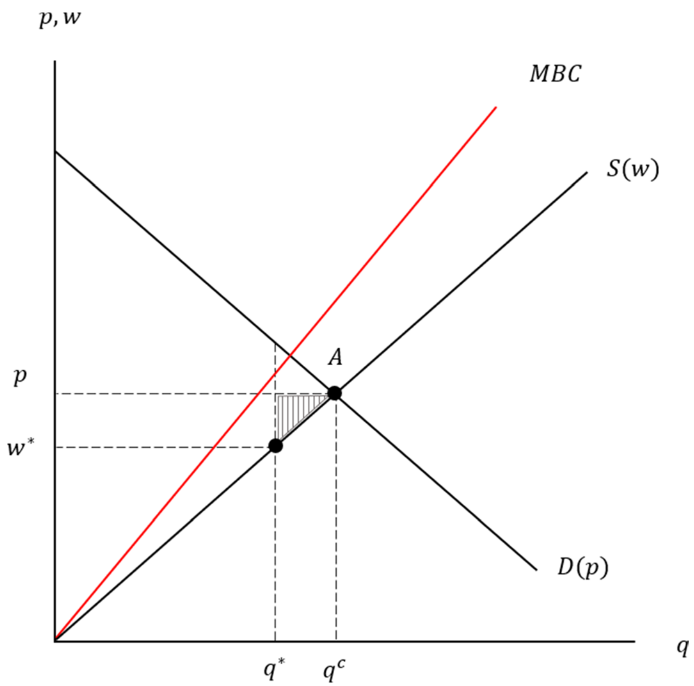

Fig. 9 The monopsonist intermediary

Appendix B: Sensitivity Analysis

Tables 12 and 14 show that results are same as reported in the main article in Sect. 3.6: low transaction costs lead to lower prices and larger traded land areas and higher transaction costs lead to higher prices and smaller areas. Tables 12, 13, 14, 15 show that with lower trade ratios, prices and areas are lower, and with higher trade ratios, prices and land areas increase. In rural biotopes, the time delays are shorter (2 and 10 years in the sensitivity analysis, 5 years in the main analysis), which reduces trade ratios and consequently, their impact to prices and areas. The transaction costs must be at least 45% in herb-rich forests and 37% in rural biotopes so that the decentralized trade becomes the most expensive option for developers.

Table 12 Sensitivity analysis in herb-rich forests for the level of transaction costs, time delay and uncertainties

	Transaction costs		Trade ratio		Transaction costs & trade ratio	
	Low	High	Low	High	Low	High
Price	12,180	14,350	11,790	13,830	12,600	15,590
Area	34	23	46	81	41	49
Welfare loss	41,030	122,100	8300	230,010	45880	195,210

Table 13 Sensitivity analysis in herb-rich forests for the level of time delay and uncertainties

	Monopolist & monopsonist		Monopsonist	
	Low	High	Low	High
Ask price	15,390	16,420	12,020	14,110
Bid price	10,390	11,420	10,510	11,550
Area	23	40	25	43
Welfare loss	30,170	420	10,030	5240

Table 14 Sensitivity analysis in rural biotopes for the level of transaction costs, time delay and uncertainties

	Transaction costs		Trade ratio		Transaction costs & trade ratio	
	Low	High	Low	High	Low	High
Price	31,070	36610	29490	33,370	31,620	38,960
Area	28	17	37	62	32.4	31.6
Welfare loss	86,790	274,770	5920	296,180	90,520	327,710

Table 15 Sensitivity analysis in rural biotopes for the level of time delay and uncertainties

	Monopolist & monopsonist		Monopsonist	
	Low	High	Low	High
Ask price	37,240	39,190	30,080	34,040
Bid price	26,740	28,690	27,040	29,020
Area	18	31	20	33
Welfare loss	63,890	370	18,310	2930

Table 16 Sensitivity analysis in pine mires for the parameters in optimizing the amount bought in storage

	Time delay		Discount rate	
	Low	High	Low	High
Ask price	12,040	13,070	12,200	13,240
Bid price	7870	7690	7840	7660
Area	124	98	120	94

Table 17 Sensitivity analysis in herb-rich forests for the parameters in optimizing the amount bought in storage

	Time delay		Discount rate	
	Low	High	Low	High
Ask price	18,290	19,710	18,520	19,940
Bid price	11,020	10,650	10,970	10,590
Area	48	39	47	38

Table 18 Sensitivity analysis in rural biotopes for the parameters in optimizing the amount bought in storage

	Time delay		Discount rate	
	Low	High	Low	High
Ask price	42,350	44,990	42,770	44,380
Bid price	28,630	27,940	28,520	28,100
Area	44	38	43	39

Table 19 Sensitivity analysis on parameters impacting the cost of offsetting for the developers

	Recent credit	Recent credit	Recent credit	Mature credit	Mature credit
Loss,α	1	1	1	1	1
Gain per ha,β	0.8	0.8	0.8	0.8	0.8
Uncertainty multiplier	1	0.8	0.6	1	1
Time delay, years	10	10	10	0	0
Discount rate	0.03	0.03	0.03	–	–
Trade ratio	1.7	2.1	2.8	1.3	1.3
Interest rate	–	–	–	0.03	0.06
Price, €/ha*	9955	9955	9955	13379	17828
Total cost of offsetting, €	16723	20903	27871	16723	22285

*The price of recent credits is from Table 3 of the article. The price of the mature credit was calculated so that the seller has the same net present value of the credit regardless of selling it now or waiting them to mature

Welfare losses increase with transaction costs and trade ratios. Comparing welfare losses shows that the decentralized trade leads to clearly higher welfare loss than the monopolist and monopsonist intermediary even with low transaction costs. The higher the trade ratios are, the lower is the welfare loss from the intermediary with market power both upstream and downstream. In the decentralized trade, the 3.1 trade ratio leads to very high welfare loss but with the monopolist intermediary, the welfare losses are minuscule. When the trade ratio is high, the welfare loss from accounting for both transaction costs and the trade ratio is lower than when considering solely the trade ratio in herb-rich forests but not in rural biotopes where the high trade ratio is lower (1.7) due to different time delays than in other habitats.

We perform sensitivity analysis also for the parameters used in calculating the optimal choice with storage by varying the length of the period (5 and 15 years in pine mires and herb-rich forests, 2 and 10 in rural biotopes) and discount rate (2% and 5%). Tables 16, 17, 18 present the results and Sect. 3.6 in the main article discusses them.

Finally, we perform sensitivity analysis concerning the impact of uncertain delayed gains on the total costs of offsetting for the developers. A comparison is made between the effect of discounting the uncertain gains of recent credits with time delay, which increases the trade ratio (columns ‘Recent credits’) and buying more expensive mature credits without uncertainty or time delay, leading to a lower trade ratio (columns ‘Mature credits’). We used different uncertainty multipliers for the recent credits and different interest rates for the mature credits. Table 19 shows that even though the price of mature credits can be up to 80% higher than with recent credits, the total cost of offsetting may still be lower, depending on the trade ratios.

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Declarations

Conflict of interest The authors have no competing interests to declare.

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