Oxford Review of Economic Policy, Volume 35, Number 1, 2019, pp. 138–161

Natural capital market design

Alexander Teytelboym*

Abstract: Renewable natural capital—terrestrial and marine ecosystems, fisheries, biodiversity, and fresh water—is in decline around the world, affecting the livelihoods of millions of people. Natural capital market design uses economic theory and analysis to develop practical solutions for maintaining, restoring, and improving natural capital. Many successful natural capital marketplaces (e.g. for emissions reduction, fish harvesting, and wetland restoration) focus on efficient trading of property rights. But many other natural capital markets (e.g. for carbon sequestration offsets, water quality, and water rights) are characterized by heterogeneity and high transaction costs that make trading difficult. We argue that, in order to fix many natural capital market failures, policy-makers should instead pay more attention to the allocation of property rights during marketplace design: this is particularly crucial in many markets for ecosystem services (e.g. biodiversity conservation and watershed protection) which exhibit strong ecological complementarities. We propose several promising designs for natural capital marketplaces which could fairly and efficiently allocate and redistribute property rights over different ecosystems.

Keywords: market design, combinatorial auctions, environmental economics, natural capital

JEL classification: D44, D47, H23, Q5, Q15

I. Introduction

Natural capital comprises stocks of natural resources—including minerals, soil, air, water, as well as all living organisms and ecosystems—which produce flows of ecosystem services (Barbier, 2019). In other words, natural capital is 'what nature provides to humanity for free' (Helm, 2015, 2019). Natural capital stocks comprise both natural assets (e.g. fresh water and clean air) and natural liabilities (e.g. pests and asteroids)

*Department of Economics, St Catherine's College, the Institute for New Economic Thinking at the Oxford Martin School, and the Smith School for Enterprise and the Environment, University of Oxford; e-mail: alexander.teytelboym@economics.ox.ac.uk

Many of the ideas in this paper were inspired by conversations with Dieter Helm, Cameron Hepburn, Paul Klemperer, Scott Duke Kominers, Sanna Laksá, Daniel Marszalec, and members of the Oxford Long-Term Ecology Laboratory. I would like to thank Martin Bichler, Jonathan Colmer, Eli Fenichel, Dustin Garrick, Dieter Helm, Cameron Hepburn, Scott Duke Kominers, Ken Mayhew, Daniela Miteva, Glen Weyl, and an anonymous referee for their detailed comments on the first draft. This work was supported by the Economic and Social Research Council grant number ES/R007470/1.

doi:10.1093/oxrep/gry030

(Fenichel *et al.*, 2015, 2018). In this paper, for simplicity, we divide natural capital into non-renewable (e.g. minerals) and renewable (e.g. marine ecosystems) natural resources.[1]

When humans use natural capital, they respond to economic incentives thereby creating *natural capital markets*. There are markets both for renewable and non-renewable natural capital. Consider markets for non-renewables commodities, such as zinc, copper, or oil. Despite many predictions of 'peak' minerals (e.g. Vaccari, 2009), there is no evidence from worldwide reserves and production data that any economically valuable minerals are running out anytime soon (Slade and Thille, 2009; Hepburn *et al.*, 2018). Most economists are not at all surprised that these natural capital markets work well because supply and demand are guided by transparent and fairly efficient prices.[2]

Yet many renewable natural capital markets are failing miserably (Seppelt *et al.*, 2014). Rainforests are disappearing (Hansen *et al.*, 2013), fisheries are being depleted (Worm *et al.*, 2009), biodiversity loss is approaching the level of another great extinction (Cardinale *et al.*, 2012; Dirzo *et al.*, 2014), clean groundwater is scarce (Vörösmarty *et al.*, 2010), and the atmosphere is quickly filling up with greenhouse gases (Allen *et al.*, 2009; Meinshausen *et al.*, 2009). We are thus entering an 'age of ecological scarcity' (Barbier, 2010). It seems painfully ironic that we are running out of renewable natural capital while enjoying a relative abundance of exhaustible natural capital.

As Helm (2015) points out, renewable natural capital markets fail for a number of reasons:

- inadequate scientific understanding of complex interactions between different forms of natural capital and its critical thresholds (Moore, 2018);
- inability to properly value and account for natural capital within current national and corporate accounting frameworks (Fenichel and Abbott, 2014; Fenichel and Hashida, 2019);
- incomplete assignment of property rights and presence of externalities due to common ownership of many renewable natural resources (Gordon, 1954; Coase, 1960; Hardin, 1968; Libecap, 1993).

In this paper, we focus on addressing Helm's third reason for renewable natural capital market failure—incomplete assignment of property rights and presence of externalities—through the lens of *market design* (Roth, 2002, 2018; Klemperer, 2004; Eisenmann *et al.*, 2006; Kominers *et al.*, 2017). The field of market design turns economic theory and analysis into practical solutions to real-world market failures (Kominers *et al.*, 2017; Eisenmann and Kominers, 2018). Market designers create *marketplaces* comprising *rules* that guide market transactions and the *infrastructure* that enables those transactions to take place (Eisenmann *et al.*, 2006; Kominers *et al.*, 2017; Roth, 2018). Well-designed marketplaces encourage participation, reduce gaming, and aggregate information in order to improve liquidity, efficiency, and equity in markets (Kominers *et al.*, 2017).

To illustrate the power of market design, we first discuss three fairly successful, large-scale natural capital marketplaces: emissions trading, individual transferrable quotas (ITQs), and wetland offsets. Despite being rather different natural capital markets,

[1] One might reasonably object to this simple division. For example, on the one hand, over long time scales a stable climate is a renewable resource, but, on the other, the capacity of the atmosphere to maintain temperatures close to pre-Industrial levels appears close to be exhausted in the near future.

[2] The same is true for many markets, such as the market for agricultural commodities, which use natural capital as a main production input.

these marketplaces share a lot in common. First, robust government regulation provided impetus for market participation and common trading standards. Second, transaction costs in these markets were kept low, as monitoring and compliance were fairly cheap relative to the value of the transactions. Third, market participants were involved in trading goods that were considered or made homogeneous, i.e. emissions permits, quotas for fish species, or offsets for wetlands. These three features allow flexible and efficient trading to take place in the marketplaces. The success of these marketplaces serves as a celebration of the so-called 'Coase Theorem' which postulated that without transaction costs, any complete assignment of property rights would give market participants an incentive to trade to an efficient outcome (Coase, 1960).

So why don't regulators or local communities simply apply the same designs to fix failures in other renewable natural capital markets? On the face of it, water quality markets look similar to ITQs and to emissions trading, yet, thus far, they have had limited success. I argue that three features of many natural capital markets require us to think carefully about how natural capital marketplaces should be designed.

- Heterogeneity:
  - natural capital typically comprises many distinct assets which affect each other in complex ways;
  - holders of property rights over natural assets usually have different costs of participating in natural capital investment.
- High monitoring and transaction costs:
  - the costs of monitoring and ensuring compliance might eliminate gains from trade;
  - profitable bilateral or multilateral transactions can be hard to find.
- Ecological complementarities:
  - natural capital is typically more valuable when large, contiguous areas are protected;
  - heterogeneous natural assets (e.g. fish species) often rely on each other for survival.

In this paper, we first argue that, as a result of heterogeneity and high transaction costs alone, frictionless trade of property rights in many natural capital markets can be difficult to organize. Heterogeneity of tradable goods means it can be hard to match willing buyers and sellers. On the other hand, costs of ensuring compliance of every traded contract can often wipe out any gains of trade. Indeed, as Coase himself pointed out (1960, pp. 15–16):

> In order to carry out a market transaction it is necessary to discover who it is that one wishes to deal with, to inform people that one wishes to deal and on what terms, to conduct negotiations leading up to a bargain, to draw up the contract, to undertake the inspection needed to make sure that the terms of the contract are being observed, and so on. These operations are often extremely costly, sufficiently costly at any rate to prevent many transactions that would be carried out in a world in which the pricing system worked without cost. . . . [Thus] the initial delimitation of legal rights does have an effect on the efficiency with which the economic system operates. One arrangement of rights may bring about a greater value of production than any other.

We give three examples of natural capital marketplaces with substantial heterogeneity and transaction costs where trading of property rights has had limited success: forest-based carbon sequestration, water quality, and water access rights. We argue that instead of simply hoping that market participants would trade, policy-makers and communities should carefully consider how property rights are (re)assigned within new natural capital marketplaces. A property right is the authority to undertake particular actions related to a specific domain (Commons, 1968). In the context of land ownership, property rights often comprise a bundle of different rights, e.g. a right to access a property, a right to withdraw resources from a property, a right to improve the property, a right to exclude others from the property, and finally a right to sell or lease the property (Schlager and Ostrom, 1992; Ostrom, 2009). As it is often too costly to write down all the specific rights in a contract, property rights give the owner residual rights of control, i.e. to enjoy whatever rights the owner has not explicitly agreed to contract out (Grossman and Hart, 1986). Different rights give rise to different incentives to manage natural resources (Schlager and Ostrom, 1992) and marketplace rules can take advantage of this.

While strong private property rights provide powerful incentives for investment and improvement, they can result in allocative inefficiency because the owner may 'hold out', i.e. be unwilling to trade even if trading is socially efficient (Jevons, 1871; George, 1879; Vickrey, 1961; Walras, 1896; Posner and Weyl, 2017). As Myerson and Satterthwaite (1983) showed, under asymmetric information and private property rights, guaranteeing efficient trade is impossible even between two parties unless participants are forced into the marketplace. However, in addition to heterogeneities, asymmetric information, and high transaction costs, ecosystem conservation also exhibits ecological complementarities.[3] When ecological complementarities are present, the hold-out problem is exacerbated: if a contiguous parcel of land needs to be conserved, every landowner becomes a monopolist. In this case, private property rights can truly be a curse: even if it is common knowledge among landowners that the conservation action is efficient, the probability of agreeing to conservation goes to zero as the number of landowners gets large (Mailath and Postlewaite, 1990). However, when ownership of natural capital assets is shared reasonably equally, then it becomes possible to allocate investment efficiently (Cramton *et al.*, 1987; Segal and Whinston, 2011). This opens an intriguing opportunity to create environmental marketplaces in which rules and property rights are jointly designed.[4]

We offer several possible designs of marketplaces for ecosystems where property rights allocation is a key feature. We suggest that these marketplaces have the potential to reverse the degradation of many ecosystems, including fisheries, forests, and watersheds. It is worth noting that none of our designs necessarily requires a central planner

[3] Conserving highly complementary ecosytems resembles 'weakest-link' public goods while protection of less complementary ecosystems looks like a 'summation' or a 'best-shot' public good (Hirshleifer, 1983).

[4] One example of joint design of property rights and marketplace rules is the Incentive Auction in the US. In order to avoid the hold-out problem, the Federal Communications Commission permitted reassignment of TV channels that remained on air to different parts of the spectrum (Kominers and Weyl, 2012; Rosston, 2012; Milgrom and Segal, 2014; Leyton-Brown *et al.*, 2017; Kominers *et al.*, 2017).

or a government regulator; indeed, in many cases small-scale local organization of commons regulation would be both preferable and more likely (Ostrom, 1990).[5]

This paper is organized as follows. In section II, we discuss three examples of successful natural capital marketplaces. In section III, we describe three examples of natural capital marketplaces that have only had limited success because of heterogeneity and high transaction costs. In section IV we turn to the potential designs of marketplaces for natural capital in the presence of ecological complementarities. We conclude on an optimistic note of urgency in section V.

II. Successes of natural capital market design

Let us now briefly review three examples of fairly successful natural capital marketplaces.[6] These marketplaces have focused on establishing property rights over the natural resources in common ownership and creating conditions for efficient trading of these property rights.

(i) Emissions trading

Ambient air pollution and anthropogenic carbon emissions are respectively the leading local and global environmental problems around the world. Classic economics dictates that the most efficient way to reduce emissions is to set a price on them in such a way that the marginal social benefit of emissions equals the marginal social cost. Different mechanisms to implement the optimal outcome—an emissions tax (Pigou, 1920; Baumol, 1972), a cap-and-trade scheme (Montgomery, 1972), or a simple auction (Montero, 2008)—have different pros and cons (e.g. Weitzman, 1974). Nevertheless, several cap-and-trade schemes that regulate emissions have become textbook examples of the power of market design (Schmalensee and Stavins, 2017). Let us consider two such schemes.

The SO_2 trading scheme was implemented in the US in 1995 in order to prevent acid rain and to reduce damage to natural ecosystems. Its first phase covered 263 SO_2-generating units in 110 electricity-generating plants owned by 61 utilities. The permits were given out for free in order to ensure buy-in from the industry. The target of halving emissions from the 1980 level by 2000 was achieved well in advance. Indeed, by 2004, emissions fell by 36 per cent compared to 1990, while electricity generation from coal-fired power plants increased 25 per cent (Schmalensee and Stavins, 2017). The cost savings compared to counterfactual mechanisms have been estimated at between 15 and 90 per cent (Stavins, 1998; Schmalensee and Stavins, 2017). Indeed, if the designers

[5] We give an example of a marketplace driven by local organization in section III(iii). Ostrom (1990) convincingly argued that the success of locally organized common regulation relies on her *Design Principles Illustrated by Long-enduring Common Pool Resource Institutions*.

[6] The definition of 'success' here is, of course, quite relative: the atmosphere is still filling up with carbon, fisheries in many developing countries are still being depleted, and American wetlands are still disappearing. Yet we argue that within their remits these marketplaces have done a good job achieving the designers' goals. Nevertheless, the marketplaces might still raise some serious ethical issues (Roth, 2008; Li, 2017).

exploited the fact that SO_2 emissions have spatially differentiated impacts, they could have increased net benefits even more (Muller and Mendelsohn, 2009).

The EU Emissions Trading Scheme (EU ETS) was launched across the EU in 2005 after unsuccessful attempts during the 1990s to introduce an EU-wide carbon tax (see also, Cramton *et al.* (2017)). The EU ETS is the largest carbon trading scheme in the world covering carbon dioxide, nitrous oxide, and perfluorocarbon emissions from 11,000 stationary industrial sources (as well as some airline emissions) in 31 countries (three of which are outside the EU), which are responsible for 45 per cent of the EU's total greenhouse gas emissions (Hepburn and Teytelboym, 2017). By 2020, emissions covered by the EU ETS will be 21 per cent lower compared to 2005. Originally, almost all allowances were given away for free (resulting, predictably, in windfall profits; see Laing *et al.* (2013)). However, today around half of all allowances are auctioned off and some of the proceeds are used to fund low-carbon innovation. A number of sectors, deemed to be at risk of 'carbon leakage' are still given free allowances. The EU ETS is a good example of the adaptive nature of market design. It proceeded in Phases with small tweaks and major rule changes between each one. For example, after the collapse of allowance prices at the end of the Phase I (2005–7), banking of allowances was permitted between Phase II (2008–12) and Phase III (2013–20) (Hepburn and Teytelboym, 2017).

There is evidence that the EU ETS has been reducing emissions in a broadly cost-effective way (Laing *et al.*, 2013) and encouraging covered sectors to invest in innovation (Calel and Dechezleprêtre, 2016). More recently, the EU ETS has been plagued by low permit prices due to reduced output by energy-intensive sectors. The Commission has attempted to fix low prices by a patchwork of measures including the 'market stability reserve' (which automatically withdraws allowances when there are too many), shifting the timing of allowance release to later years, and tightening the emissions reduction target (Hepburn and Teytelboym, 2017).

(ii) Individual transferrable quotas

The overexploitation of fisheries, especially in developing countries, creates a strong case for urgent reform of fisheries management (Willman *et al.*, 2009). Regulators and local fishing communities use many policies to limit the total catch, including area closures as well as restrictions on mesh, engine size, gear dimensions, and season length (Homans and Wilen, 1997). However, many of these policies have been ineffective at limiting total catch or have maintained the cap very inefficiently. One particularly successful policy has been the introduction of individual transferrable quotas (ITQs), i.e. rights to a share in the total allowable catch (TAC) (Grafton *et al.*, 2006; Branch, 2009). ITQs function in much the same way as emissions permits: a quota entitles a fisher to land a certain amount of a particular fish species (Tietenberg, 2003). In fisheries, where several or all species are covered by quota, fishers typically require quotas covering many different species.[7] ITQs are often used alongside other fisheries management policies (Bjørndal and Munro, 2012). ITQs have led both to well-enforced caps and,

[7] In fisheries where only some of the species are covered, one might worry about 'leakage' as fishers substitute and overexploit unregulated species.

as the theory would predict, to an increase in the efficiency of the fishing industries in many countries around the world. As one fisheries economist succinctly puts it: 'It seems that ITQs are the only fisheries management system currently employed around the world that can claim [a] degree of general success' (Arnason, 2005, p. 245). Consider two examples of fisheries in New Zealand and Iceland which have successfully adopted ITQ schemes.

New Zealand set up the world's first and largest ITQ system in 1986. The marketplace has since been expanded from just a few dozen species to over 70. Originally, quotas were granted for free in perpetuity. Quotas can be either leased or sold and most transactions are leases. Market transactions—around 9,000 leases and 1,500 sales annually—are handled by brokers and the vast majority of quota owners participate in transactions (Newell *et al.*, 2005). While some markets for rarer species are quite thin, most markets seem to have a lot of trading activity. In a careful analysis of market performance, Newell *et al.* (2005) show that the ITQ prices rose whenever stocks fell due to shocks, indicating that the marketplace provides correct signals to the participants.

The Icelandic ITQ system has been in force since 1991 after years of experimentation in fisheries policies. It covers 19 species accounting for 97 per cent of the harvest. Quotas are almost completely transferrable, grandfathered, and allocated (effectively) indefinitely. In the first 10 years of operation of the ITQ system, the size of the fleet halved and the economic value of the quotas doubled, while profits and productivity in the industry increased dramatically (Arnason, 2005). Many species (though not all), such as haddock and saithe, recovered well.

(iii) Wetland banking

Between 1950s and 1970s, the US was losing 458,000 acres of wetlands annually to urbanization and agriculture (United States Department of Agriculture, 2018). Section 404 of the 1972 Clean Water Act forces anyone who wants to fill or dredge a wetland to apply for a permit from the US Army Corps of Engineers.[8] Beyond requiring that damage to existing wetlands be minimized, about a tenth of these permits insist on 'compensatory mitigation', i.e. offsetting of the damaged wetland in the same watershed. Following George H. Bush's 1989 'no net loss of wetlands' policy, the first application for a for-profit 'mitigation bank' was granted in 1991. Since then hundreds of mitigation banks, which mediate the financing between land developers and conservationists, have sprung up and today most mitigation banks are for-profit. Such intermediation makes a lot of sense: banks can direct pool mitigation funding from many landowners to perform mitigation at a large scale. Because mitigation must take place locally, the average bank is only about 440 acres on average (Forest Trends, 2015). The costs of mitigation, unsurprisingly, vary considerably across different areas (Zentner *et al.*, 2003). As a result of these policies, between 1998 and 2004 the United States was *gaining* 32,000 acres of wetlands per year (United States Department of Agriculture, 2018). In 2004, George W. Bush felt confident enough to announce a 'net gain' target

[8] In 1977, President Carter also signed an executive order ordering government agencies to take steps to 'minimize the destruction, loss or degradation of wetlands'.

of 3,000,000 acres by 2009. However, between 2004 and 2009 there was a net loss of 13,800 acres annually.

Wetland mitigation in the US is by far the largest ecosystem services marketplace in the world, worth around \$1.5–\$2.5 billion annually (Forest Trends, 2015). But despite its apparent success in dramatically reducing the rate of wetland loss area, wetland restoration has been controversial (Palmer and Filoso, 2009). It appears that many restored wetlands provide lower-quality ecosystem services than healthy ones (Moreno-Mateos *et al.*, 2012). Such *de facto* net loss might well be a consequence of an acre-for-acre mitigation policy rather than a fault of the marketplace itself. Stricter monitoring of restored sites and a higher 'exchange rate' between restored and destroyed wetlands can alleviate the resulting net losses. Moreover, tighter regulations could be applied to 'irreplaceable' wetlands.

(iv) Discussion

Let us recap what these three successful natural capital marketplaces have in common. First, we looked at three marketplaces for homogeneous goods with many market participants. Homogeneity is completely crucial for market thickness and therefore the ability to quickly find profitable trades. When the market is thick, the timing of all transactions does not need to be coordinated, allowing for trade to take place across time. A moment's reflection makes it apparent that homogeneity is not intrinsic in all three markets: it was a deliberate choice of market designers. In the case of carbon trading, homogeneity is difficult to argue with: a ton of CO_2 emitted in England has exactly the same effect on global temperatures as a ton of CO_2 emitted in Poland. In the case of wetlands, however, developers are able to offset an acre of wetland for another acre of wetland in the same watershed as far as 15 miles away: it is unlikely this can possibly be a perfect like-for-like substitution (Robertson and Hayden, 2008). It is unclear whether or not the liquidity and efficiency benefits of trading outweigh the costs of 'recreating' ecosystems. Many environmentalists reasonably worry about excessive homogenization of ecosystems in order to encourage offset trading (Bull *et al.*, 2013; Maron, 2015). Second, participation in all three marketplaces is legally compulsory, which also helps thicken the market. This not only drives efficiency of trading, but also creates a perception of fairness in the marketplace. Third, all three markets have clear goals and benchmarks, e.g. a cap on emissions/quotas or 'no net loss' of wetlands, which were measurable and verifiable at fairly low costs. Finally, neither the designer nor the participants appear overburdened with excessively high compliance and monitoring costs.[9]

III. Natural capital marketplaces with limited success

In this section, we briefly review three examples of natural capital marketplaces that have had limited or no success despite concerted efforts to design and launch them. In these examples, market designers sought to create marketplaces that permitted trading

[9] For example, in the EU ETS small aviation emitters can use a simplified monitoring tool.

of rights. However, since these natural capital markets exhibit a lot heterogeneity and high transaction costs, trade proved difficult to organize and the marketplaces have been rather ineffective.

(i) Land-based carbon sequestration

When trees grow, they soak up carbon from the atmosphere via photosynthesis. Therefore, planting more trees (e.g. by creating new forests or restoring existing ones) and reducing deforestation (Pan *et al.*, 2011) helps mitigate the increase in atmospheric carbon and slows down climate change. Several marketplaces to promote forest-based carbon sequestration have sprung up. First, there is a substantial international voluntary market for forestry-based carbon offsets. For example, an individual or a company can voluntarily buy credits in order to offset its carbon emissions. An offset can be generated by avoiding deforestation relative to a baseline, by improving forest management, or by planting new trees. In recent years, the bulk of forestry-based carbon offsets was generated with the support of the United Nations *Reductions in Emissions from Deforestation and Forest Degradation, Plus Related Proforest Activities* (REDD+) programme and funding from donor countries, such as Norway (Salzman *et al.*, 2018). However, the marketplace appears to be dysfunctional: there is a substantial variation in prices depending on project type and location as well as a large surplus of unsold offsets (Forest Trends, 2017). Although forestry projects can generate a different amount of social value depending on their co-benefits, it does not appear that the price mechanism is guiding an efficient allocation of sequestration investment.

Second, several existing carbon cap-and-trade schemes have experimented with including forestry-based carbon offsets. Afforestation and reforestation projects in developing countries were permitted under the Clean Development Mechanism (CDM) of the Kyoto Protocol, through which industrialized countries could meet their emissions obligations (Zomer *et al.*, 2008). However, only four out of 1,600 CDM projects involved afforestation or reforestation (Thomas *et al.*, 2010). The California Air Resources Board also allows companies covered by its carbon cap-and-trade programme to generate offset credits by investing in forest-based sequestration projects in the US. However, take-up has been fairly limited: while forestry is the most popular type of offset credit, forestry offsets still represent only a small fraction of total credits issued. Forest-based carbon sequestration is still relatively expensive in the US due to high fixed costs, long-term monitoring obligations, and legislative uncertainty (Kerchner and Keeton, 2015).

(ii) Water quality markets

Rivers, lakes, and streams get polluted by waste from industrial and agricultural activities. From an economics perspective, this might look a lot like a problem of atmospheric emissions: there is too much pollution in the water because the price of polluting is too low. The solution might therefore be tempting: measure and cap emissions at each pollution source and allow polluters to trade emissions permits (Dales, 1968).

But the water quality market has a lot more heterogeneity than the market for carbon emissions. First, water pollution comes from point polluters (i.e. a single place, such as pipe spewing industrial sewage) and non-point polluters (i.e. from many places, such as nutrient run-off from a farm). Point pollution is obviously easier to measure than non-point pollution, but it might often be insufficient to only cover point polluters in order to maintain water quality. Second, different types of pollution (e.g. nitrogen or phosphorus) coming from different parts of the watershed can have different effects on the quality of water for consumers. In principle, this could be handled by setting 'trading ratios' that would assign exchange rates to trading permits for different types of pollution (Montgomery, 1972; Muller and Mendelsohn, 2009). However, in practice these trading ratios can be hard to set with a sufficient level of precision (Shortle and Horan, 2008, 2013).

There are many designs of water quality trading that have been introduced in the US, Canada, and Australia, including bilateral trading, clearinghouses, as well as full-blown permit exchanges (Woodward and Kaiser, 2002; Breetz *et al.*, 2004; Fisher-Vanden and Olmstead, 2013). Yet, almost all such water quality permit markets, especially point-to-non-point markets, have been thin (Fisher-Vanden and Olmstead, 2013; Shortle, 2013). The most successful active permit exchange programme is probably Australia's Hunter River Salinity Trading programme, which started operating in 2004 (Cañedo-Argüelles *et al.*, 2016). As the name suggests, this programme sets out to control saline discharges from coal mines and electricity generators. Interestingly, it includes only individual point sources and involves no trading ratios: these features make compliance costs lower and trading more straightforward.

(iii) Markets for water access and abstraction rights

Surface water and groundwater are a precious common-pool resource, especially in many rural areas that are dependent on agriculture (Pereau *et al.*, 2017). Surface water and groundwater are intimately linked: pollution and abstraction of one type of water affects the other (Winter *et al.*, 1998). Groundwater abstraction has been increasing dramatically around the world because, typically, groundwater is treated as an open-access resource. It is not surprising therefore that 'tradable water permits are commonly considered as one of the most efficient market-based instruments for groundwater allocation' (Latinopoulos and Sartzetakis, 2015, p. 350). Groundwater marketplaces exist in several countries including the US, Chile, Australia, China, and Spain (Montginoul *et al.*, 2016), but they are only present alongside a host of additional regulations on water use. In American groundwater marketplaces, there have been difficulties with metering and monitoring wells as well as restrictions on trading (e.g. water permits cannot be traded upstream or outside specified zones and many trades require pre-approval), creating large transaction costs (Krutilla *et al.*, 2011; Garrick *et al.*, 2013). As a result, typically little trade takes place in these marketplaces, even though trade appears to be highly beneficial (Wheeler *et al.*, 2016). Yet groundwater trading has had some success in southern Australia (Garrick, 2015). For example, the surface water and groundwater permit marketplace in the Murray–Darling Basin is rather active, with over four-fifths of landowners participating in at least one permit trade annually (Wheeler *et al.*, 2014, Grafton and Wheeler, 2018), and prices appear to track seasonality and droughts

(Wheeler *et al.*, 2008). Despite their promise, however, surface water and groundwater permit marketplaces have not taken off at scale in the developing world.

One of the most fascinating tradable groundwater abstraction permit schemes is the *falaj* irrigation system and water allocation markets in Northern Oman (Al-Marshudi, 2007). The *falaj* management committee auctions off time intervals during which a villager can have access to a common water resource. It then possible to exchange *falaj* rights to common-access water by trading one time interval for another. The auction revenue is used as the primary source of maintenance and operation of the irrigation system. The market appears to work well, with prices reflecting preferences to access water during the daytime and greater need for water during droughts (Al-Marshudi, 2007). The *falaj* irrigation system is therefore a great example of community-led natural capital market design.

(iv) Discussion

The three types of markets described in this section suffer from high transaction costs and heterogeneity and, as a result, they are often thin (i.e. very little trade takes place). For example, few companies are incentivized to participate in voluntary carbon markets. Moreover, it is extremely difficult to evaluate a forest-based carbon sequestration project: first, it is difficult to estimate the additional value of the project, and second, because trees take some time to grow, it is often hard to ensure long-term compliance, especially in countries with weak institutions (Phan *et al.*, 2017). In water quality markets, it can be hard to control and measure non-point pollution and difficult to establish fair trading ratios. In markets for groundwater and surface water access rights, incomplete coverage and high monitoring costs mean that trades barely happen. As Coase astutely noticed, if a marketplace designer does not attempt to ensure a sufficiently efficient initial allocation of property rights in a thin market, there is little hope that market transactions will guide the market to efficiency. Instead, the marketplace will produce inefficient and unfair outcomes. Efficient trade is only likely to occur in marketplaces that are liquid and transparent. But trade among market participants is not the only route toward marketplace success. For example, practitioners have noticed that direct payments to land- and resource-owners have been much more effective in carbon sequestration and various watershed markets than permit trading (Kinzig *et al.*, 2011). The reason is that direct payment systems focus on allocating rather than trading property rights. As we shall now see, many other natural capital market failures can be remedied by a greater focus on the initial allocation of property rights.

IV. The potential of new natural capital marketplaces

In this section, we look at the potential new natural capital marketplaces. First, we revisit fisheries governed by ITQs. Drawing on the success of the EU ETS, we describe how combinatorial auctions and exchanges could be used to improve the initial allocation of ITQs, even in the presence of heterogeneity and complementarities. We then suggest how market design could be used to conserve and restore entire ecosystems.

These natural capital markets not only involve heterogeneity and ecological complementarities, but also high transaction costs: the three features together make trade even more difficult and the initial allocation of relevant property rights even more important. We discuss two types of 'payment for ecosystem services' (PES) schemes. PES are voluntary transactions in which a seller secures the provision of an environmental service in return for a payment from a buyer (Engel *et al.*, 2008). To work well, a PES scheme must target relevant ecosystem service providers, give them appropriate incentives to improve ecosystems, and measure outcomes of providers' actions. Of course, there is a substantial variation in the types of ecosystem services and in economically relevant features of institutional contexts (Wunder *et al.*, 2008; Engel *et al.*, 2008; Kinzig *et al.*, 2011; Wunder *et al.*, 2018; Salzman *et al.*, 2018). Hundreds of marketplaces which channel payments for ecosystem services have been designed and evaluated around the world. But many PES schemes appear to be extremely inefficient. Wunder *et al.* (2018) show that hardly any PES schemes simultaneously use spatial targeting, payment differentiation, and payment conditionality, which are necessary (though hardly sufficient) conditions for a cost-effective PES scheme. Yet well-designed PES schemes have the potential to dramatically improve both ecological and development outcomes at a low cost (e.g. Jayachandran *et al.*, 2017).

To fix ideas visually, Figure 1 serves as an illustration of complementarity and heterogeneity in each proposed marketplace. In each example, depending on the context, differently shaded boxes will either represent substitutable objects (such as quota for a single fish species or marginal land plots) or complementary objects (such as quota for the different fish species or land plots connected by an ecosystem).

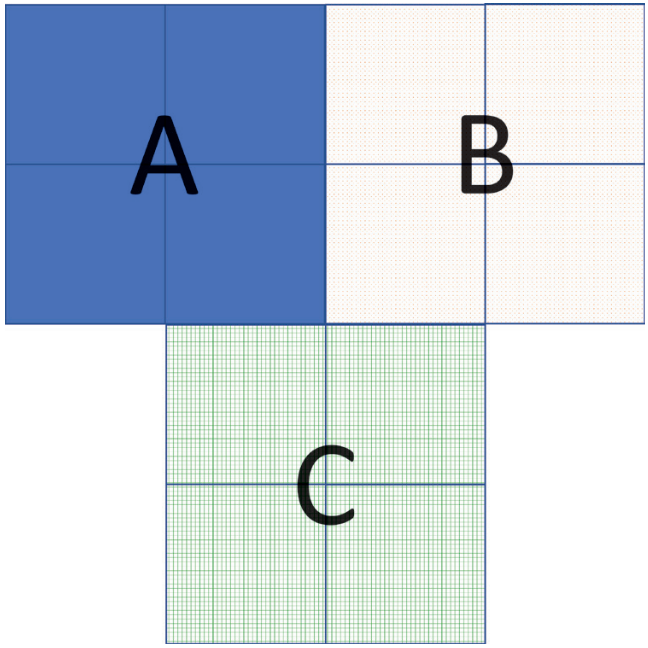
(i) Allocation of ITQs

As we argued in section II(ii), ITQs are (in principle) an extremely effective way to manage fisheries. However, before quota trading can take place, the market designer needs to solve an important problem: the initial allocation of quotas. One might argue that since the market is thick and trading has low costs, efficiency of the marketplace outcome should be independent of the initial allocation of quotas (Coase, 1960). But markets for some species covered by ITQs can be fairly thin (Newell *et al.*, 2005), hence the initial allocation of quotas is likely to matter for achieving an efficient outcome. Yet almost everywhere around the world, even in the most mature ITQs schemes, quotas are still allocated by grandfathering. Grandfathered allocation favours incumbents, distorts investment decisions, prevents entry, yields no public revenue, and can create huge windfalls for some market participants.

As we suggested above, grandfathering is typically justified at the initial stages of permit trading systems in order to get political buy-in from market participants. But a reallocation of grandfathered quotas from a very distorted initial outcome can be extremely difficult. For example, as a consequence of policy change, the government of New South Wales in Australia recently paid out AUD11.2m through an ingenious marketplace in order to reallocate dozens of types of fishing quotas across hundreds of fishers (Bichler *et al.*, 2018).

A far more efficient approach is to regularly auction off (at least some of) the ITQs. In other cap-and-trade settings, such as EU ETS, auctioning of permits is becoming the

Figure 1: Heterogeneity and complementarity



norm (Hepburn and Teytelboym, 2017). Surprisingly, auctioning of ITQs still remains controversial because of the fear that it creates uncertainty for fishers and reduces their incentives to invest (Anderson *et al.*, 2011). But economic theory and practice suggest auctioning permits should increase dynamic[10] and investment efficiency (Green and Laffont, 1977; Holmström, 1979; Rogerson, 1992) while the auction revenue could be used to lower distortionary taxes elsewhere (Cramton and Kerr, 2002).

Several countries, including New Zealand and the Faroe Islands, have experimented with auctions, but their success has been limited (e.g. Lakså *et al.*, 2018). Auctioning ITQs is, however, a lot more complex than auctioning emission permits. First, ITQs cover multiple species and most fishers catch more than one species. Let Figure 1 therefore represent three species, A, B, and C (divided into fractions of quota). Some fishers might target species A and B, while others might try to catch all three species. Second, because of complexities of marine biology and discard prohibitions in many countries (Borges, 2015), ITQs for different species can be highly complementary: if one catches a cod (A) whenever one catches a mackerel (B), then whenever one surrenders a cod quota (A), one must buy a mackerel quota (B). Therefore, in addition to ecological complementarities, preference complementarities arise in fishing due to different fishing technologies, different fishing sites, and due to by-catch (incidental capture of non-target species) whenever by-catch species are covered by quotas. Indeed, many recent improvements in technology allow for accurate tracking of discarded catch, making enforcement of discard bans much more likely.

[10] To encourage investment, auctioned ITQs could also have different lifetimes, e.g. 1 year, 3 years, or 10 years.

In a quota auction, if bidders have preference complementarities but can only place bids on individual quota, then they run the risk of finding themselves 'exposed', i.e. buying a portfolio of quotas that is not valuable. Exposure is a particular concern if post-auction trade in the species is thin and fishers can exercise market power. Therefore, bidders need the ability to place bids on packages of items (e.g. AB or ABC) in order for the auctions to allocate quota efficiently (Porter *et al.*, 2003; Kwasnica *et al.*, 2005; Cramton *et al.*, 2006; Brunner *et al.*, 2010).[11] For example, Marszalec (2018*a*) discusses how different types of sealed-bid combinatorial auctions for indivisible goods could be applied to sell ITQs.[12] But since quota is, in principle, divisible, an alternative approach is to allow bidders to bid for combinatorial *shares* (Wilson, 1979; Klemperer, 2010). To capture the complementarities, bidders could be allowed to submit entire demand curves not only for any individual species, but also for any subset of species.[13]

Indeed, ideas from combinatorial auctions for initial allocation of ITQs can also be used design more efficient quota trading systems. For example, the government could hold regular (e.g. monthly) post-auction combinatorial exchanges in which bidders can submit offers to buy *and sell* packages of fishing quota (Milgrom, 2007). In fact, the New South Wales quota marketplace was a pioneering and outstanding example of such a combinatorial exchange for quota (Bichler *et al.*, 2018). There is therefore great potential for such regular exchanges to allow fishers to make more efficient investment and harvesting decisions.

(ii) Watershed protection

The typical newspaper picture of river pollution is that of rusty industrial pipe spewing out sticky effluent. But, in fact, today the main reason for the poor state of rivers, lakes, and coastal waters in the US is non-point pollution: nitrogen and phosphorus run-off, mainly from agriculture (EPA, 2017). Moreover, watersheds do not just provide us with clean water—they also regulate floods and are homes to birds and many other species (Salzman *et al.*, 2018). Watershed improvement typically focuses on certain ecosystem services—clean water or flood prevention—rather than on the protection of a contiguous tract of land (Wunder *et al.*, 2018). Watershed improvement allows landowners to make a variety of possible investments: landowners could plant trees or certain crops to prevent soil erosion and nutrient run-off[14] or they can enhance biodiversity to lock nutrients in the soil and improve water quality (Cardinale, 2011). Consider for example, the world's largest PES scheme in the developing world: the Natural Forest Conservation Program (NFCP) and the Sloping Land Conversion Program (SLCP) in

[11] Iftekhar and Tisdell (2012), Iftekhar *et al.* (2012), Iftekhar and Tisdell (2015), and Tisdell and Iftekhar (2013) confirm this finding in the lab and with computational experiments.

[12] His experimental findings indicate that first-price sealed-bid auctions perform surprisingly compared to alternatives in terms of revenue and efficiency, contradicting Bayesian equilibrium results (Ausubel and Baranov, 2013).

[13] Anderson and Holland (2006) experimentally test auctions for shares of quota, but we are unaware of a precedent for an auction of combinatorial shares with complements.

[14] One example of a marketplace that aims to tackle this problem is Poole Harbour nitrogen offsetting project, called EnTrade, in the UK. Wessex Water, a water utility, ran a reverse auction to incentivize landowners to plant certain crops to reduce leaching of nitrogen into the rivers.

China, which invested over $50 billion and involved 120m farmers in 32m households by 2009 (Ouyang *et al.*, 2016). Through these programmes, farmers were incentivized to convert cropland on sloping land into forest cover which improves water quality and controls floods (Bennett, 2008).

A carefully designed auction might be effective in encouraging landowners to allocate investment efficiently to watershed improvements. The designer would start by considering the whole watershed. Since the watershed is connected, protecting one part of it while letting the other parts degrade is counterproductive. The designer would then suggest a set of possible investments that the landowners could take. For example, landowners could indicate where they might restore a hedgerow or plant a new crop. The designer would then run a hydrological value-for-money model which would select the best possible combination of investments and give landowners an opportunity to revise their bids. The winning bidders would be paid to make the most valuable set of investments. Monitoring investment in physical infrastructure or agricultural practices is more cost-effective (either by using satellite data, self-reporting, or on-site verification) than trying to precisely measure the individual landowners' contribution to water pollution or flood risk. Indeed, a simpler version of this auction in which Australian landowners were simply asked to indicate their reserve prices for making pre-determined land improvements resulted in substantial cost savings for the local government (Stoneham *et al.*, 2003).

If the participation in the auction we suggest is voluntary, one might be reasonably concerned about holdout. But, to improve a watershed, we do not need 100 per cent compliance from all the participants. It might well be sufficient that *enough* landowners undertake a set of activities—reforesting the hillside, reducing the use of pesticides, or giving up certain crops—that improve the overall quality of the watershed. In Figure 1 this might mean encouraging the participation of at least one landowner in regions A, B, *and* C (which perhaps indicate different land uses, such as forestry, agriculture, or urban development). In this case, the potential inefficiency from holdout would be limited.[15]

(iii) Conservation of entire ecosystems

Ecosystems are bundles of complementary natural capital assets which need to be maintained together in order to sustain their function. A watershed can be one such example, but many ecosystems can exhibit much greater ecological complementarity. For ecosystem protection, what matters is contiguity and scale because of the benefits to recreation and biodiversity that these create (Kennedy *et al.*, 2016; Yun *et al.*, 2017). While some PES models of conservation target a few marginal landowners (Ferraro and Kiss, 2002; Jayachandran *et al.*, 2017), others attempt to focus on the whole landscape (Pagiola, 2008). Often, however, ownership of many natural ecosystems is dispersed among hundreds or even thousands of landowners who might prefer to exploit the natural capital. Let Figure 1 therefore represent the geography of three connected ecosystems and 12 landowners.

[15] As Example 2 in Kominers and Weyl (2012) shows, it turns out that in this case the probability of holdout is likely to be fairly low as the market grows large.

The problem with incentivizing landowners to conserve their land is that if one landowner overexploits her natural capital then this has an adverse impact on the value of efforts by the others. Polasky *et al.* (2014) suggest running a Vickrey auction to efficiently allocate payments that incentivize landowners to conserve or improve their natural capital. They argue that this (procurement) auction would incentivize all landowners to honestly reveal their costs of maintenance and therefore allocate public funds to conservation efficiently. But suppose that only conservation on any of four plots of the same colour yields positive social benefits. In the presence of such complementarities, the Vickrey auction is prone to collusion, can be inefficient, and can result in high payments for the conservation funder (Milgrom, 2004): this has been confirmed experimentally (Marszalec, 2018*b*) and in practice (Ausubel *et al.*, 2017). Thus first-price or 'core-selecting' package auctions would be superior to Vickrey auctions for ecosystem protection for the same reason that they are often preferred in spectrum allocation and procurement (Erdil and Klemperer, 2010; Day and Cramton, 2012; Bünz *et al.*, 2018).

In fact, combinatorial auctions for ecosystem conservation could also be used as offsetting mechanisms alongside infrastructure development. Nemes *et al.* (2008) propose an elegant unified auction in which developers bid on parts of the infrastructure project which generate compulsory offsets. On the other side of the market, landowners offer mitigation and offsetting services on their land. This allows the value of ecosystem services to be fully internalized into the development process and ensures cost-effective allocation of offsetting funds.

If landowners cannot be coerced into participating in the auction, the designer should worry about holdout, especially when the ecosystem is highly ecologically complementary and land ownership is dispersed. In some ecosystems, such as woodlands or wetlands, contiguity and scale matter more than the precise identity and location of the sellers, i.e. one merely wants to protect some contiguous fraction of the forest. In Figure 1 this might mean conserving the *whole* of *one* of ecosystems A, B, *or* C. If there any many more landowners in each ecosystem than there are ecosystems, the designer's problem is almost identical to one in which she needs to get all the landowners to participate.[16] As Mailath and Postlewaite (1990) show, the probability of efficient assembly of complementary plots in any mechanism in which every seller has the right to opt out and no external subsidies are provided goes to zero as the number of complementary sellers grows large.

If participation in an ecosystem protection marketplace is to remain voluntary, successful design requires us to make at least three related choices about subsidies, location, and participants' property rights. First, if the benefit of conservation actions spills outside the market, then a subsidy is likely to be necessary to induce efficient conservation investment. Second, the designer could select conservation areas that exhibit both less ecological complementarity and fewer pivotal landowners in order to minimize the possibility of holdout. Third, the designer should look for conservation areas where the benefits are shared as equally as possible among participants: in this case, it is easier to organize an efficient auction mechanisms. Cramton *et al.* (1987) propose such an auction for a common-value object in which the winner takes the conservation action on behalf of all participants (by winning the subsidy) and compensates the losers. If the market designer provides a subsidy to the market, then she could, in fact, choose to

[16] See Example 3 in Kominers and Weyl (2012).

allocate initial property rights over the benefits and the subsidy as equally as possible among the market participants.

(iv) Discussion

Let us draw some general lessons about the marketplaces proposed in this section. First, similar to markets in section III, ecosystem markets exhibit substantial heterogeneity and high transaction costs and are therefore likely to be thin. Hence, we focused on the design of marketplaces that allocate initial property rights rather than simply facilitate trade. These ecosystem marketplaces need to be shaped around realistic technologies for monitoring and verification. In some cases, it might be cheaper to monitor actions (watershed investment), while in others one could focus on outcomes (ecosystem conservation). For example, we are now able to monitor the state of biodiversity and ecosystem services at local level using satellite data (Asner *et al.*, 2005; Maron *et al.*, 2015; Pettorelli *et al.*, 2016; Jetz *et al.*, 2016; Long *et al.*, 2018). Second, ecosystem markets additionally exhibit ecological complementarities because ecosystems need to be protected as a whole. This creates the possibility of holdout and requires careful planning and design in order to avoid inefficient allocation of property rights. Without some form of coercion to participate or an external subsidy, even the most sophisticated marketplace design might fail in these cases. This clearly justifies a role for robust policy-making.

Finally, let us mention one other marketplace design that could redefine and reallocate property rights in at least two of our examples: Harberger Taxation (Harberger, 1965). The idea is straightforward: every market participant who owns property (e.g. land or fishing quota) is asked to state how much he values the property. Then the designer applies a proportional tax on stated valuations. However, anyone has a right to buy the property at the price that the market participant stated. If the tax is appropriately set, property owners have no incentive to misreport their property valuation. Therefore, resources will always be allocated efficiently. Consider the example of fishing quota. Instead of auctioning off quota, one could achieve an efficient allocation of fishing rights by issuing 'depreciating licences' (Posner and Weyl, 2017; Weyl and Zhang, 2018). Quota would have an indefinite length, but would 'decay' at a constant monthly rate τ which could be set optimally using quota turnover rates and other observable market characteristics. Every month, a fisher who 'owns' quota would be asked to publicly announce the price p at which they would be willing to 'buy back' quota share τ from the government. Hence, the fisher would then pay a Harberger Tax of $p\tau$. Any market participant could then buy any of the fisher's quota at the stated price p. Thus by putting all the quota into common ownership, this system removes any incumbency advantage and allocates the quota to the fishers who value it the most. This novel property rights regime still requires careful design before Harberger Taxation can be applied to environmental markets. First, how can Harberger Taxation work well in context with complementary preferences, e.g. when valuation of one type of quota depends on ownership of all other types of quota? Second, how can Harberger Taxation deal with contexts with externalities—such as ecosystem conservation—where benefits of market participants' actions are enjoyed outside of the marketplace?

V. Conclusion

In 1913, Woodrow Wilson remarked that 'we have squandered a great part of what we might have used, and have not stopped to conserve the exceeding bounty of nature, without which our genius for enterprise would have been worthless and impotent' (Barbier, 2010). Insights from the modern theory and practice of market design—in particular from combinatorial auctions and exchanges—coupled with new technology, brave regulation, novel property rights regimes, and powerful social organization might be able to help to help stop this 'squander' and recover the 'exceeding bounty of nature'. Natural capital market design must tackle complexities present in natural capital markets including pervasive heterogeneity, high transactions costs, as well as ecological and preference complementarities. In this paper, we argue that economic designers should focus attention on natural capital marketplaces that appropriately allocate property rights and support liquidity in order to facilitate efficient trade. There is little doubt that natural capital markets will serve as an inspiration and challenge for market design theorists and practitioners in the coming decades. Today, Bob Lucas's comment about economic development surely applies to natural capital: 'The consequences for human welfare involved in questions like these are simply staggering: once one starts to think about them, it is hard to think about anything else' (Lucas, Jr, 1988). One would hope that the paralysing urgency of this thought would not prevent natural capital market designers from action.

References

Allen, M. R., Frame, D. J., Huntingford, C., Jones, C. D., Lowe, J. A., Meinshausen, M., and Meinshausen, N. (2009), 'Warming Caused by Cumulative Carbon Emissions towards the Trillionth Tonne', *Nature*, **458**(7242), 1163–6.

Al-Marshudi, A. S. (2007), 'The *Falaj* Irrigation System and Water Allocation Markets in Northern Oman', *Agricultural Water Management*, **91**(1–3), 71–7.

Anderson, C. M., and Holland, D. S. (2006), 'Auctions for Initial Sale of Annual Catch Entitlement', *Land Economics*, **82**(3), 333–52.

Anderson, T., Arnason, R., and Libecap, G. D. (2011), 'Efficiency Advantages of Grandfathering in Rights-based Fisheries Management', *Annual Review of Resoure Economics*, **3**(1), 159–79.

Arnason, R. (2005), 'Property Rights in Fisheries: Iceland's Experience with ITQs', *Reviews in Fish Biology and Fisheries*, **15**(3), 243–64.

Asner, G. P., Knapp, D. E., Broadbent, E. N., Oliveira, P. J., Keller, M., and Silva, J. N. (2005), 'Selective Logging in the Brazilian Amazon', *Science*, **310**(5747), 480–2.

Ausubel, L. M., and Baranov, O. V. (2013), 'Core-selecting Auctions with Incomplete Information', Technical Report, August.

— Aperjis, C., and Baranov, O. (2017), 'Market Design and the FCC Incentive Auction', Technical Report, October.

Barbier, E. B. (2010), *Scarcity and Frontiers: How Economies Have Developed Through Natural Resource Exploitation,* Cambridge, Cambridge University Press.

— (2019), 'The Concept of Natural Capital', *Oxford Review of Economic Policy*, **35**(1), 14–36.

Baumol, W. J. (1972), 'On Taxation and the Control of Externalities', *American Economic Review*, **62**(3), 307–22.

Bennett, M. T. (2008), 'China's Sloping Land Conversion Program: Institutional Innovation or Business as Usual?', *Ecological Economics*, **65**(4), 699–711.

Bichler, M., Fux, V., and Goeree, J. K. (2018), 'Designing Combinatorial Exchanges for the Reallocation of Resource Rights', Technical Report, February.

Bjørndal, T., and Munro, G. (2012), *The Economics and Management of World Fisheries,* Oxford, Oxford University Press.

Borges, L. (2015), 'The Evolution of a Discard Policy in Europe', *Fish and Fisheries*, **16**(3), 534–40.

Branch, T. A. (2009), 'How Do Individual Transferable Quotas Affect Marine Ecosystems?', *Fish and Fisheries*, **10**(1), 39–57.

Breetz, H. L., Fisher-Vanden, K., Garzon, L., Jacobs, H., Kroetz, K., and Terry, R. (2004), 'Water Quality Trading and Offset Initiatives in the US: A Comprehensive Survey', Technical Report, Dartmouth College and the Rockefeller Center for the US Environmental Protection Agency.

Brunner, C., Goeree, J. K., Holt, C. A., and Ledyard, J. O. (2010), 'An Experimental Test of Flexible Combinatorial Spectrum Auction Formats'. *American Economic Journal: Microeconomics*, **2**(1), 39–57.

Bull, J. W., Suttle, K. B., Gordon, A., Singh, N. J., and Milner-Gulland, E. (2013), 'Biodiversity Offsets in Theory and Practice', *Oryx*, **47**(3), 369–80.

Bünz, B., Lubin, B., and Seuken, S. (2018), 'Designing Core-selecting Payment Rules: A Computational Search Approach', in *Proceedings of the 2018 ACM Conference on Economics and Computation*, Association for Computing Machinery.

Calel, R., and Dechezleprêtre, A. (2016), 'Environmental Policy and Directed Technological Change: Evidence from the European Carbon Market', *Review of Economics and Statistics*, **98**(1), 173–91.

Cañedo-Argüelles, M., Hawkins, C., Kefford, B., Schäfer, R., Dyack, B., Brucet, S., Buchwalter, D., Dunlop, J., Frör, O., Lazorchak, J., *et al*. (2016), 'Saving Freshwater from Salts', *Science*, **351**(6276), 914–16.

Cardinale, B. J. (2011), 'Biodiversity Improves Water Quality through Niche Partitioning', *Nature*, **472**(7341), 86–9.

— Duffy, J. E., Gonzalez, A., Hooper, D. U., Perrings, C., Venail, P., Narwani, A., Mace, G. M., Tilman, D., Wardle, D. A., *et al*. (2012), 'Biodiversity Loss and its Impact on Humanity', *Nature*, **486**(7401), 59–67.

Coase, R. H. (1960), 'The Problem of Social Cost', *Journal of Law and Economics*, **3**(October), 1–44.

Commons, J. R. (1968), *Legal Foundations of Capitalism,* Madison, WI, University of Wisconsin Press.

Cramton, P., and Kerr, S. (2002), 'Tradeable Carbon Permit Auctions: How and Why to Auction not Grandfather', *Energy Policy*, **30**(4), 333–45.

— Gibbons, R., and Klemperer, P. (1987), 'Dissolving a Partnership Efficiently', *Econometrica*, **55**(3), 615–32.

— Shoham, Y., and Steinberg, R. (2006), *Combinatorial Auctions,* Cambridge, MA, MIT Press.

— MacKay, D. J., Ockenfels, A., and Stoft, S. (2017), *Global Carbon Pricing: The Path to Climate Cooperation,* Cambridge, MA, MIT Press.

Dales, J. H. (1968), *Pollution, Property and Prices*, Cheltenham, Edward Elgar Publishing.

Day, R. W., and Cramton, P. (2012), 'Quadratic Core-selecting Payment Rules for Combinatorial Auctions', *Operations Research*, **60**(3), 588–603.

Dirzo, R., Young, H. S., Galetti, M., Ceballos, G., Isaac, N. J., and Collen, B. (2014), 'Defaunation in the Anthropocene', *Science*, **345**(6195), 401–6.

Eisenmann, T., and Kominers, S. D. (2018), 'Making Markets', Technical Note, HBS Case Collection, February.

— Parker, G., and Van Alstyne, M. W. (2006), 'Strategies for Two-sided Markets', *Harvard Business Review*, **84**, 92–101.

Engel, S., Pagiola, S., and Wunder, S. (2008), 'Designing Payments for Environmental Services in Theory and Practice: An Overview of the Issues', *Ecological Economics*, **65**(4), 663–74.

EPA (2017), *National Water Quality Inventory: Report to Congress,* Technical Report, August, United States Environmental Protection Agency.

Erdil, A., and Klemperer, P. (2010), 'A New Payment Rule for Core-selecting Package Auctions', *Journal of the European Economic Association*, **8**(2–3), 537–47.

Fenichel, E. P., and Abbott, J. K. (2014), 'Natural Capital: From Metaphor to Measurement', *Journal of the Association of Environmental and Resource Economists*, **1**(1–2), 1–27.
— Hashida, Y. (2019), 'Choices and the Value of Natural Capital', *Oxford Review of Economic Policy*, **35**(1), 120–37.
— Abbott, J. K., and Do Yun, S. (2018), 'The Nature of Natural Capital and Ecosystem Income', in P. Dasgupta, S. Pattanayak, and K. Smith (eds), *Handbook of Environmental Economics,* Vol. **4**.
— Gopalakrishnan, S., and Bayasgalan, O. (2015), 'Bioeconomics: Nature as Capital', ch. 7 in R. Halvorsen and D. F. Layton (eds), *Handbook on the Economics of Natural Resources,* Cheltenham, Edward Elgar, 165–205.
Ferraro, P. J., and Kiss, A. (2002), 'Direct Payments to Conserve Biodiversity', *Science*, **298**, 1718–19.
Fisher-Vanden, K., and Olmstead, S. (2013), 'Moving Pollution Trading from Air to Water: Potential, Problems, and Prognosis', *Journal of Economic Perspectives*, **27**(1), 147–72.
Forest Trends (2015), *Ecosystem Markets and Finance: A Global Primer,* Technical Report, Forest Trends Ecosystem Marketplace, January.
— (2017), *Unlocking Potential State of the Voluntary Carbon Markets 2017,* Technical Report, Forest Trends Ecosystem Marketplace, May.
Garrick, D. E. (2015), *Water Allocation in Rivers under Pressure: Water Trading, Transaction Costs and Transboundary Governance in the Western US and Australia,* Cheltenham, Edward Elgar.
— Whitten, S. M., and Coggan, A. (2013), 'Understanding the Evolution and Performance of Water Markets and Allocation Policy: A Transaction Costs Analysis Framework', *Ecological Economics*, **88**, 195–205.
George, H. (1879), *Progress and Poverty,* Boston, E.P. Dutton & Co.
Gordon, H. S. (1954), 'The Economic Theory of a Common-Property Resource: The Fishery', *Journal of Political Economy*, **62**(2), 124–42.
Grafton, R. Q., and Wheeler, S. A. (2018), 'Economics of Water Recovery in the Murray-Darling Basin, Australia', *Annual Review of Resource Economics*, **10**.
— Arnason, R., Bjørndal, T., Campbell, D., Campbell, H. F., Clark, C. W., Connor, R., Dupont, D. P., Hannesson, R., Hilborn, R., *et al*. (2006), 'Incentive-based Approaches to Sustainable Fisheries', *Canadian Journal of Fisheries and Aquatic Sciences*, **63**(3), 699–710.
Green, J., and Laffont, J.-J. (1977), 'Characterization of Satisfactory Mechanisms for the Revelation of Preferences for Public Goods', *Econometrica*, **45**(2), 427–38.
Grossman, S. J., and Hart, O. D. (1986), 'The Costs and Benefits of Ownership: A Theory of Vertical and Lateral Integration', *Journal of Political Economy*, **94**(4), 691–719.
Hansen, M. C., Potapov, P. V., Moore, R., Hancher, M., Turubanova, S., Tyukavina, A., Thau, D., Stehman, S., Goetz, S., Loveland, T., *et al*. (2013), 'High-resolution Global Maps of 21st-century Forest Cover Change', *Science*, **342**(6160), 850–3.
Harberger, A. C. (1965), 'Issues of Tax Reform for Latin America', in *Fiscal Policy for Economic Growth in Latin America*, Joint Tax Program, Organization of American States, Inter-American Development Bank, Economic Commission for Latin America, Johns Hopkins University Press, 110–21.
Hardin, G. (1968), 'The Tragedy of the Commons', *Science*, **162**(3859), 1243–8.
Helm, D. (2015), *Natural Capital: Valuing the Planet,* New Haven, CT, Yale University Press.
— (2019), 'Natural Capital: Assets, Systems, and Policies', *Oxford Review of Economic Policy*, **35**(1), 1–13.
Hepburn, C., and Teytelboym, A. (2017), 'Reforming the EU ETS—Where Are We Now?', in I. Parry, K. Pittel, and H. Vollebergh (eds), *Energy Tax and Regulatory Policy in Europe: Reform Priorities,* Cambridge, MA, MIT Press.
— Pfeiffer, A., Pretis, F., and Teytelboym, A. (2018), 'On the Inexhaustibility of Exhaustible Resources', Institute for New Economic Thinking Working Paper.
Hirshleifer, J. (1983), 'From Weakest Link to Best Shot: The Voluntary Provision of Public Goods', *Public Choice*, **41**(3), 371–86.
Holmström, B. (1979), 'Groves' Scheme on Restricted Domains', *Econometrica*, **47**(5), 1137–44.
Homans, F. R., and Wilen, J. E. (1997), 'A Model of Regulated Open Access Resource Use', *Journal of Environmental Economics and Management*, **32**(1), 1–21.

Iftekhar, M. S., and Tisdell, J. G. (2012), 'Comparison of Simultaneous and Combinatorial Auction Designs in Fisheries Quota Market', *Marine Policy*, **36**(2), 446–53.
— — (2015), 'Bidding and Performance in Multiple Unit Combinatorial Fishery Quota Auctions: Role of Information Feedbacks', *Marine Policy*, **62**, 233–43.
— Hailu, A., and Lindner, R. (2012), 'The Effect of Bidder Heterogeneity on ComBinatorial Conservation Auction Designs', *Environmental and Resource Economics*, **53**(1), 137–57.
Jayachandran, S., de Laat, J., Lambin, E. F., Stanton, C. Y., Audy, R., and Thomas, N. E. (2017), 'Cash for Carbon: A Randomized Trial of Payments for Ecosystem Services to Reduce Deforestation', *Science*, **357**(6348), 267–73.
Jetz, W., Cavender-Bares, J., Pavlick, R., Schimel, D., Davis, F. W., Asner, G. P., Guralnick, R., Kattge, J., Latimer, A. M., Moorcroft, P., Schaepman, M. E., Schildhauer, M. P., Schneider, F. D., Schrodt, F., Stahl, U., and Ustin, S. L. (2016), 'Monitoring Plant Functional Diversity from Space', *Nature Plants*, **2**(3), 1–5.
Jevons, W. S. (1871), *The Theory of Political Economy,* London, Macmillan and Co.
Kennedy, C. M., Miteva, D. A., Baumgarten, L., Hawthorne, P. L., Sochi, K., Polasky, S., Oakleaf, J. R., Uhlhorn, E. M., and Kiesecker, J. (2016), 'Bigger is Better: Improved Nature Conservation and Economic Returns from Landscape-level Mitigation', *Science Advances*, **2**(7), e1501021.
Kerchner, C. D., and Keeton, W. S. (2015), 'California's Regulatory Forest Carbon Market: Viability for Northeast Landowners', *Forest Policy and Economics*, **50**, 70–81.
Kinzig, A. P., Perrings, C., Chapin, F. S., Polasky, S., Smith, V. K., Tilman, D., and Turner, B. (2011), 'Paying for Ecosystem Services—Promise and Peril', *Science*, **334**(6056), 603–4.
Klemperer, P. (2004), *Auctions: Theory and Practice,* Princeton, NJ, Princeton University Press.
— (2010), 'The Product-mix Auction: A New Auction Design for Differentiated Goods', *Journal of the European Economic Association*, **8**(2–3), 526–36.
Kominers, S. D., and Weyl, E. G. (2012), 'Holdout in the Assembly of Complements: A Problem for Market Design', *American Economic Review*, **102**(3), 360–5.
— Teytelboym, A., and Crawford, V. P. (2017), 'An Invitation to Market Design', *Oxford Review of Economic Policy*, **33**(4), 541–71.
Krutilla, K., Krause, R., *et al*. (2011), 'Transaction Costs and Environmental Policy: An Assessment Framework and Literature Review', *International Review of Environmental and Resource Economics*, **4**(3–4), 261–354.
Kwasnica, A., Ledyard, J., Porter, D., and DeMartini, C. (2005), 'A New and Improved Design for Multiobject Iterative Auctions', *Management Science*, **51**(3), 419–34.
Laing, T., Sato, M., Grubb, M., and Comberti, C. (2013), 'Assessing the Effectiveness of the EU Emissions Trading System', Technical Report, Grantham Research Institute on Climate Change and the Environment.
Laksá, S., Marszalec, D., and Teytelboym, A. (2018), 'Epic Fail: How Below-bid Pricing Backfires in Multiunit Auctions', CIRJE Discussion Paper No. 1096, October.
Latinopoulos, D., and Sartzetakis, E. S. (2015), 'Using Tradable Water Permits in Irrigated Agriculture', *Environmental and Resource Economics*, **60**(3), 349–70.
Leyton-Brown, K., Milgrom, P., and Segal, I. (2017), 'Economics and Computer Science of a Radio Spectrum Reallocation', *Proceedings of the National Academy of Sciences*, **114**(28), 7202–9.
Li, S. (2017), 'Ethics and Market Design', *Oxford Review of Economic Policy*, **33**(4), 705–20.
Libecap, G. D. (1993), *Contracting for Property Rights,* Cambridge, Cambridge University Press.
Long, P. R., Benz, D., Martin, A. C., Holland, P. W., Macias-Fauria, M., Seddon, A. W., Hagemann, R., Frost, T. K., Simpson, A., Power, D. J., *et al*. (2018), 'Left—A Web-based Tool for the Remote Measurement and Estimation of Ecological Value Across Global Landscapes', *Methods in Ecology and Evolution*, **9**(3), 571–9.
Lucas, Jr, R. E. (1988), 'On the Mechanics of Economic Development', *Journal of Monetary Economics*, **22**(1), 3–42.
Mailath, G. J., and Postlewaite, A. (1990), 'Asymmetric Information Bargaining Problems with Many Agents', *Review of Economic Studies*, **57**(3), 351–67.
Maron, M. (2015), 'Stop Misuse of Biodiversity Offsets', *Nature*, **523**(7561), 401–3.

Maron, M., Gordon, A., and Mackey, B. G. (2015), 'Agree on Biodiversity Metrics to Track from Space', *Nature*, **523**, 403–5.
Marszalec, D. (2018*a*), 'Auctions for Quota: A Primer and Perspectives for the Future', *Fisheries Research*, **203**, 84–92.
— (2018*b*), 'Fear Not the Simplicity—An Experimental Analysis of Auctions for Complements', *Journal of Economic Behavior and Organization*, **152**, 81–97.
Meinshausen, M., Meinshausen, N., Hare, W., Raper, S. C., Frieler, K., Knutti, R., Frame, D. J., and Allen, M. R. (2009), 'Greenhouse-gas Emission Targets for Limiting Global Warming to 2°C', *Nature*, **458**(7242), 1158–62.
Milgrom, P. R. (2004), *Putting Auction Theory to Work,* Cambridge, Cambridge University Press.
— (2007), 'Package Auctions and Exchanges', *Econometrica*, **75**(4), 935–65.
— Segal, I. (2014), 'Deferred-acceptance Auctions and Radio Spectrum Reallocation', in *Proceedings of the Fifteenth ACM Conference on Economics and Computation*, ACM, 185–6.
Montero, J.-P. (2008), 'A Simple Auction Mechanism for the Optimal Allocation of the Commons', *American Economic Review*, **98**(1), 496–518.
Montginoul, M., Rinaudo, J.-D., Brozović, N., and Donoso, G. (2016), 'Controlling Groundwater Exploitation through Economic Instruments: Current Practices, Challenges and Innovative Approaches', in A. J. Jakeman, O. Barreteau, R. J. Hunt, J.-D. Rinaudo, and A. Ross (eds), *Integrated Groundwater Management: Concepts, Approaches and Challenges*, Springer, 551–81.
Montgomery, W. D. (1972), 'Markets in Licenses and Efficient Pollution Control Programs', *Journal of Economic Theory*, **5**(3), 395–418.
Moore, J. C. (2018), 'Predicting Tipping Points in Complex Environmental Systems', *Proceedings of the National Academy of Sciences*, **115**(4), 635–6.
Moreno-Mateos, D., Power, M. E., Comín, F. A., and Yockteng, R. (2012), 'Structural and Functional Loss in Restored Wetland Ecosystems', *PLoS Biology*, **10**(1), e1001247.
Muller, N. Z., and Mendelsohn, R. (2009), 'Efficient Pollution Regulation: Getting the Prices Right', *American Economic Review*, **99**(5), 1714–39.
Myerson, R. B., and Satterthwaite, M. A. (1983), 'Efficient Mechanisms for Bilateral Trading', *Journal of Economic Theory*, **29**(2), 265–81.
Nemes, V., Plott, C. R., and Stoneham, G. (2008), 'Electronic BushBroker Exchange: Designing a Combinatorial Double Auction for Native Vegetation Offsets', Technical Report.
Newell, R. G., Sanchirico, J. N., and Kerr, S. (2005), 'Fishing Quota Markets', *Journal of Environmental Economics and Management*, **49**(3), 437–62.
Ostrom, E. (1990), *Governing the Commons: The Evolution of Institutions for Collective Action,* Cambridge, Cambridge University Press.
— (2009), 'Design Principles of Robust Property-rights Institutions: What Have We Learned?', ch. 2 in G. K. Ingram and Y. Hung Hong (eds), *Property Rights and Land Policies*, Lincoln Institute of Land Policy.
Ouyang, Z., Zheng, H., Xiao, Y., Polasky, S., Liu, J., Xu, W., Wang, Q., Zhang, L., Xiao, Y., Rao, E., *et al*. (2016), 'Improvements in Ecosystem Services from Investments in Natural Capital', *Science*, **352**(6292), 1455–9.
Pagiola, S. (2008), 'Payments for Environmental Services in Costa Rica', *Ecological Economics*, **65**(4), 712–24.
Palmer, M. A., and Filoso, S. (2009), 'Restoration of Ecosystem Services for Environmental Markets', *Science*, **325**(5940), 575–6.
Pan, Y., Birdsey, R. A., Fang, J., Houghton, R., Kauppi, P. E., Kurz, W. A., Phillips, O. L., Shvidenko, A., Lewis, S. L., Canadell, J. G., *et al*. (2011), 'A Large and Persistent Carbon Sink in the World's Forests', *Science*, 1201609.
Pereau, J.-C., Mouysset, L., and Doyen, L. (2017), 'Groundwater Management in a Food Security Context', *Environmental and Resource Economics*, 1–18.
Pettorelli, N., Wegmann, M., Skidmore, A., Mücher, S., Dawson, T. P., Fernandez, M., Lucas, R., Schaepman, M. E., Wang, T., O'Connor, B., *et al*. (2016), 'Framing the Concept of Satellite Remote Sensing Essential Biodiversity Variables: Challenges and Future Directions', *Remote Sensing in Ecology and Conservation*, **2**(3), 122–31.

Phan, T.-H. D., Brouwer, R., and Davidson, M. D. (2017), 'A Global Survey and Review of the Determinants of Transaction Costs of Forestry Carbon Projects', *Ecological Economics*, **133**, 1–10.
Pigou, A. C. (1920), *The Economics of Welfare,* 1st edn, London.
Polasky, S., Lewis, D. J., Plantinga, A. J., and Nelson, E. (2014), 'Implementing the Optimal Provision of Ecosystem Services', *Proceedings of the National Academy of Sciences*, **111**(17), 6248–53.
Porter, D., Rassenti, S., Roopnarine, A., and Smith, V. (2003), 'Combinatorial Auction Design', *Proceedings of the National Academy of Sciences*, **100**(19), 11153–7.
Posner, E. A., and Weyl, E. G. (2017), 'Property is Only another Name for Monopoly', *Journal of Legal Analysis*, **9**(1), 51–123.
Robertson, M., and Hayden, N. (2008), 'Evaluation of a Market in Wetland Credits: Entrepreneurial Wetland Banking in Chicago', *Conservation Biology*, **22**(3), 636–46.
Rogerson, W. P. (1992), 'Contractual Solutions to the Hold-up Problem', *Review of Economic Studies*, **59**(4), 777–93.
Rosston, G. (2012), 'Incentive Auctions', *Communications of the ACM*, **55**(2), 24–6.
Roth, A. E. (2002), 'The Economist as Engineer: Game Theory, Experimental Economics and Computation as Tools of Design Economics', *Econometrica*, **70**(4), 1341–78.
— (2008), 'What Have We Learned from Market Design?', *The Economic Journal*, **118**(527), 285–310.
— (2018), 'Marketplaces, Markets, and Market Design', *American Economic Review*, **108**(7), 1609–58.
Salzman, J., Bennett, G., Carroll, N., Goldstein, A., and Jenkins, M. (2018), 'The Global Status and Trends of Payments for Ecosystem Services', *Nature Sustainability*, **1**(3), 136.
Schlager, E., and Ostrom, E. (1992), 'Property-rights Regimes and Natural Resources: A Conceptual Analysis', *Land Economics*, 249–62.
Schmalensee, R., and Stavins, R. N. (2017), 'The Design oOf Environmental Markets: What Have We Learned from Experience with Cap and Trade?', *Oxford Review of Economic Policy*, **33**(4), 572–88.
Segal, I., and Whinston, M. D. (2011), 'A Simple Status Quo that Ensures Participation (With Application to Efficient Bargaining)', *Theoretical Economics*, **6**(1), 109–25.
Seppelt, R., Manceur, A. M., Liu, J., Fenichel, E. P., and Klotz, S. (2014), 'Synchronized Peak-rate Years of Global Resources Use', *Ecology and Society*, **19**(4).
Shortle, J. S. (2013), 'Economics and Environmental Markets: Lessons from Water-quality Trading', *Agricultural and Resource Economics Review*, **42**(1), 57–74.
— Horan, R. D. (2008), 'The Economics of Water Quality Trading', *International Review of Environmental and Resource Economics*, **2**(2), 101–33.
— — (2013), 'Policy Instruments for Water Quality Protection', *Annual Review of Resource Economics*, **5**(1), 111–38.
Slade, M. E., and Thille, H. (2009), 'Whither Hotelling: Tests of the Theory of Exhaustible Resources', *Annual Review of Resource Economics*, **1**(1), 239–60.
Stavins, R. N. (1998), 'What Can We Learn from the Grand Policy Experiment? Lessons from SO2 Allowance Trading', *Journal of Economic Perspectives*, **12**(3), 69–88.
Stoneham, G., Chaudhri, V., Ha, A., and Strappazzon, L. (2003), 'Auctions for Conservation Contracts: An Empirical Examination of Victoria's BushTender Trial', *Australian Journal of Agricultural and Resource Economics*, **47**(4), 477–500.
Thomas, S., Dargusch, P., Harrison, S., and Herbohn, J. (2010), 'Why Are There So Few Afforestation and Reforestation Clean Development Mechanism Projects?', *Land Use Policy*, **27**(3), 880–7.
Tietenberg, T. (2003), 'The Tradable-Permits Approach to Protecting the Commons: Lessons for Climate Change', *Oxford Review of Economic Policy*, **19**(3), 400–19.
Tisdell, J. G., and Iftekhar, M. S. (2013), 'Fisheries Quota Allocation: Laboratory Experiments on Simultaneous and Combinatorial Auctions', *Marine Policy*, **38**, 228–34.
United States Department of Agriculture (2018), 'Natural Resource Conservation Service: Wetlands', https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/water/wetlands/
Vaccari, D. A. (2009), 'Phosphorus: A Looming Crisis', *Scientific American*, **300**(6), 54–9.
Vickrey, W. (1961), 'Counterspeculation, Auctions, and Competitive Sealed Tenders', *Journal of Finance*, **16**(1), 8–37.
Vörösmarty, C. J., McIntyre, P. B., Gessner, M. O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S. E., Sullivan, C. A., Liermann, C. R., *et al.* (2010), 'Global Threats to Human Water Security and River Biodiversity', *Nature*, **467**(7315), 555.

Walras, L. (1896), *Études d'Economie Sociale: Théorie de la Répartition de la Richesse Sociale, translated as Studies in Social Economics*, Paris, F. Rouge.

Weitzman, M. L. (1974), 'Prices vs Quantities', *Review of Economic Studies*, **41**(4), 477–91.

Weyl, E. G., and Zhang, A. L. (2018), 'Depreciating Licenses', Technical Report.

Wheeler, S. A., Schoengold, K., and Bjornlund, H. (2016), 'Lessons to Be Learned from Groundwater Trading in Australia and the United States', in A. J. Jakeman, O. Barreteau, R. J. Hunt, J.-D. Rinaudo, and A. Ross (eds), *Integrated Groundwater Management: Concepts, Approaches and Challenges*, Springer, 493–517.

— Bjornlund, H., Shanahan, M., and Zuo, A. (2008), 'Price Elasticity of Water Allocations Demand in the Goulburn–Murray Irrigation District', *Australian Journal of Agricultural and Resource Economics*, **52**(1), 37–55.

— Loch, A., Zuo, A., and Bjornlund, H. (2014), 'Reviewing the Adoption and Impact of Water Markets in the Murray–Darling Basin, Australia', *Journal of Hydrology*, **518**, 28–41.

Willman, R., Kelleher, K., Arnason, R., and Franz, N. (2009), *The Sunken Billions: the Economic Justification for Fisheries Reform,* IBRD/FAO.

Wilson, R. (1979), 'Auctions of Shares', *Quarterly Journal of Economics*, **93**(4), 675–89.

Winter, T. C., Harvey, J. W., Franke, O. L., and Alley, W. M. (1998), *Ground Water and surface Water: A Single Resource,* Volume US Geological Survey Circular 1139, USGS.

Woodward, R. T., and Kaiser, R. A. (2002), 'Market Structures for US Water Quality Trading', *Review of Agricultural Economics*, **24**(2), 366–83.

Worm, B., Hilborn, R., Baum, J. K., Branch, T. A., Collie, J. S., Costello, C., Fogarty, M. J., Fulton, E. A., Hutchings, J. A., Jennings, S., *et al*. (2009), 'Rebuilding Global Fisheries', *Science*, **325**(5940), 578–85.

Wunder, S., Engel, S., and Pagiola, S. (2008), 'Taking Stock: A Comparative Analysis of Payments for Environmental Services Programs in Developed and Developing Countries', *Ecological Economics*, **6**(4), 834–52.

— Brouwer, R., Engel, S., Ezzine-de Blas, D., Muradian, R., Pascual, U., and Pinto, R. (2018), 'From Principles to Practice in Paying for Nature's Services', *Nature Sustainability*, **1**(3), 145.

Yun, S. D., Hutniczak, B., Abbott, J. K., and Fenichel, E. P. (2017), 'Ecosystem-based Management and the Wealth of Ecosystems', *Proceedings of the National Academy of Sciences*.

Zentner, J., Glaspy, J., and Schenk, D. (2003), 'Wetland and Riparian Woodland Restoration Costs', *Ecological Restoration*, **21**(3), 166–73.

Zomer, R. J., Trabucco, A., Bossio, D. A., and Verchot, L. V. (2008), 'Climate Change Mitigation: A Spatial Analysis of Global Land Suitability for Clean Development Mechanism Afforestation and Reforestation', *Agriculture, Ecosystems, and Environment*, **126**(1–2), 67–80.