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Nature's decline and recovery — Structural change, regulatory costs, and the onset of resource use regulation[☆]

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ABSTRACT

Many renewable natural resources have been extracted beyond sustainable levels. While some resource stocks have recovered, others are still over-extracted, causing substantial economic losses. This paper develops a model motivated by empirical facts about resource use and regulation to understand these patterns. The model is a dynamic model of a dual economy with technological progress, structural change, and costly resource regulation. Based on this model, we show that technological progress explains the initial increase in resource use. Technological progress also induces structural change and a decline in resource users. While the declining number of resource users does not directly lead to resource recovery, it does reduce regulatory costs, paving the way for resource regulation and recovery. Our results show that although technological progress can contribute to resource degradation, it also helps resource recovery through reduced regulatory costs. Our results suggest further that a temporal use beyond sustainable levels can be socially optimal until regulatory costs fall below the benefits of regulation.

1. Introduction

Human well-being depends on renewable resources such as fish stocks, forests, groundwater, or rangelands. Over time, many renewable resources have gone through a period of use beyond sustainable levels and degradation with subsequent recovery. Fig. 1 illustrates this process for the fisheries in some of the world's most important fish-producing countries.[1] The figure shows that the median resource extraction rate increased over time beyond sustainable levels and eventually converged back to this level in several countries. This article seeks to understand the mechanisms behind this pattern and their implications for resource regulation in growing economies. While many resources have recovered after periods of over-exploitation, other resources have collapsed and remain at low levels (e.g. Newfoundland cod stock Hamilton et al., 2004). Here, we also ask which conditions make resource stocks more susceptible to collapse without recovery.

Environmental degradation and subsequent environmental improvements are often associated with economic development. An extensive literature explores this relationship, which is often described by an inverted U-shape termed the Environmental Kuznets

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[1] For details on the data and the normalization, see Appendix A.7.

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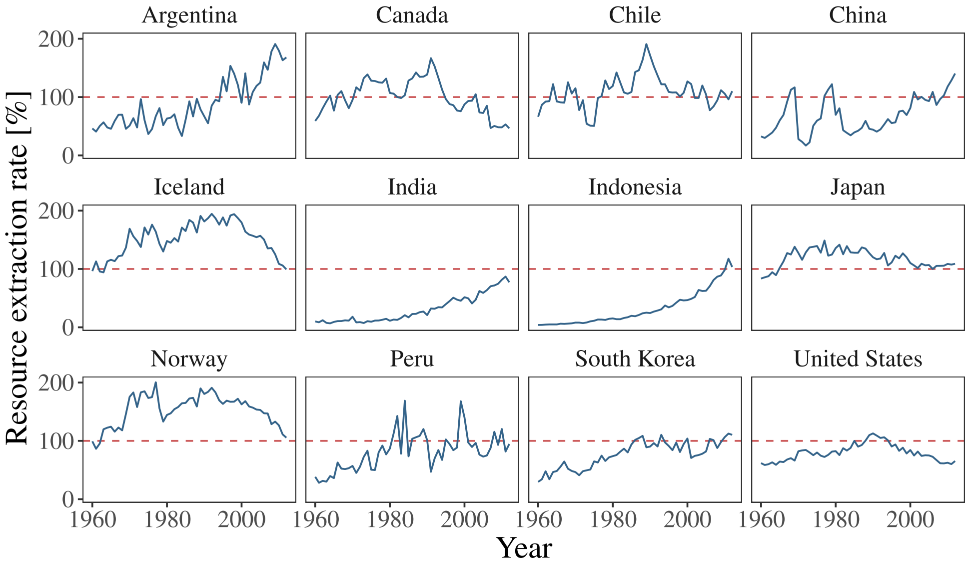

Fig. 1. Resource extraction over time.
Notes: Median resource extraction rates (fishing mortality) relative to extraction rates that maximize long-run harvest (maximum sustainable yield, MSY). The dashed line corresponds to the MSY extraction level.
Source: The data are from Costello et al. (2016).

Curve (Grossman et al., 1995; Copeland and Taylor, 2004; Brock and Taylor, 2005; Smulders et al., 2011). However, the traditional explanations for the initial increase in environmental degradation and the subsequent recovery relate to pollution and cannot explain why resources are used beyond economically optimal levels. Why do countries allow the overuse of resources with substantial economic losses to the same industry that causes overharvesting? For example, a recent study by the World Bank estimated that the annual losses from overfishing are 83 billion US dollars per year (Arnason et al., 2017). Costello et al. (2016) arrive at similar estimates.

This paper develops an analytical framework to understand the pattern of resource use beyond sustainable levels with the subsequent recovery of resource stocks. It also takes a new look at the economic losses from resource overuse. While we use fisheries as an example, we argue that our results apply to many common pool resources, including forests, groundwater, and rangelands.

We build our analytical framework on several stylized facts. Here, we introduce these facts and provide more evidence in the next section. Fig. 1 suggests that initially, resource extraction increases with economic development. This observation is often related to increasing harvesting capacity (capital accumulation) and technological progress (Hannesson, 2007; Hannesson et al., 2010; Squires and Vestergaard, 2013a; Gordon and Hannesson, 2015). In line with these findings, our first stylized fact shows that resource extraction initially increases with economic development.

While technology levels in resource use increase over time, our second stylized fact shows that the number of resource users declines over time. This observation is related to the general decline of the agricultural workforce during the structural transformation of growing economies (e.g. Acemoglu, 2008). Similar declining numbers of resource users have been reported for the fisheries (Hannesson, 2007; Hannesson et al., 2010).

Still, these two facts cannot explain why resource users extract resources beyond sustainable levels with substantial economic losses to the resource users themselves. A common explanation for the over-extraction of natural resources relates to their common pool characteristic. Because of this characteristic, resource users extract more resources than are socially optimal, ignoring their impact on the resource stock. Regulation (or some other form of coordination) is necessary for the resource users to internalize their impact on the resource stock and to reduce their extraction to the socially optimal level. The resource economics literature generally finds that regulation reduces extraction rates and supports the recovery of depleted resources (Costello et al., 2008; Isaksen and Richter, 2019; Hilborn et al., 2020; Frank and Oremus, 2022).

However, regulation (or coordination) costs can be substantial. For example, in the fishery, regulatory costs may reach up to 25% of the gross value of fish landings (Arnason et al., 2000).[2] While some regulatory costs may be fixed, such as resource stock assessments, other components, such as monitoring and enforcement, depend directly on the actual and the potential number of resource users, i.e., those that would like to gain access to the resource.

Based on these empirical observations, we develop a multi-period partial equilibrium model of a dual economy with a resource-harvesting and a manufacturing sector. We include resource dynamics and exogenous technological progress as well as three types

[2] Regulation in a fishery is often monitored by a mix of on-board and shore-based observers as well as electronic monitoring systems such as vessel monitoring systems that track individual vessels and electronic on-board monitoring cameras recording all catches.

of regulatory costs: ‘fixed costs’ such as the expenditures for research or general administration; ‘monitoring costs’ such as the costs of on-board observers in the fishery to ensure that resource users follow the regulations, and ‘enforcement costs’ such as coastguard patrols to combat illegal fishing. We distinguish between monitoring and enforcement costs to separate costs related to the actual number of resource users (monitoring costs) and the costs associated with the potential resource users i.e. individuals who would like to gain access to the resource (enforcement costs). This distinction has profound implications for resource management. While the regulator can influence the monitoring cost by setting a cap on the number of resource users, enforcement costs and the number of potential resource users are determined by the status of the resource and the opportunity costs of harvesting, i.e., the outside options.[3] However, while the regulator can set a cap on the number of resource users, the state of the technology determines how many resource users are necessary to harvest the target amount of resources. This combination of regulation costs and general economic development in the economy creates resource use dynamics that mimic the observed pattern of resource use beyond the sustainable levels and the subsequent resource recovery.

Our first result replicates the finding from the previous literature that resource extraction initially increases with technological progress. However, under open access, this increasing trend of overexploitation comes to a halt once resource incomes have dropped to the incomes in the manufacturing sector. Further technological progress does not lead to further resource depletion but to labor reallocation to the manufacturing sector. Therefore, the long-run resource stock under open access depends on the income in the manufacturing sector relative to the income in resource harvesting. If incomes in the manufacturing sector are relatively high, resource users start to leave the resource sector at high resource stock levels. The initiated structural change prevents further resource depletion. With relatively low incomes in the manufacturing sector, the resource is used beyond sustainable levels and does not recover despite declining resource users. In this scenario, technological progress compensates for the labor loss in resource harvesting.

With regulation at zero costs, harvest increases initially until the resource stock reaches the socially optimal level (Maximum Economic Yield – MEY). The regulation then keeps the resource stock at this level. In these settings (open access and zero regulatory costs), the pattern of temporary resource use beyond sustainable levels and a subsequent recovery does not occur. However, with regulatory costs, the observed pattern of temporary resource use beyond sustainable levels and the subsequent recovery emerge. The mechanisms behind this pattern are the initial increase in resource extraction due to technological progress and the delayed onset of regulation due to high regulatory costs. Regulation is only socially optimal if the benefits from regulation outweigh its costs. While the benefits of regulation are nearly constant once resource users start to leave the resource sector, monitoring and enforcement costs decline with the reduced number of resource users and the higher opportunity costs of resource harvesting. With monitoring costs, regulation at the time of introduction is stricter than regulation without monitoring costs, as fewer resource users are less costly to monitor. The regulator, therefore, initially admits fewer resource users when regulation is costly than when regulation has zero costs. However, the number of admitted resource users converges in both scenarios because the number of resource users that are necessary to harvest a given level of the resource declines with technological progress. Finally, fixed costs can be so high that regulation is never introduced.

We also examine which conditions make a resource more prone to overuse. In general, higher regulatory costs, a lower intrinsic growth rate, and lower identical rates of technological progress – the latter translating into lower income levels – delay the introduction of regulation, everything else equal. This may be especially problematic for slow-growing resources, as they require stricter regulation for long-term survival. Thus, a renewable resource is more prone to collapse if it has a low growth rate, if no resource manager is assigned, if fixed regulatory costs are high, and if there are no attractive income alternatives for resource harvesters. If we also consider additional scenarios with unequal productivity and price developments in both sectors, depletion of a stock under open access will result if the productivity or the price growth is faster in the resource sector than in the manufacturing sector.

These predictions of our model are consistent with the pattern of Fig. 1. They also align with anecdotal evidence from the fishery. For example, commercial fisheries in developed countries with relatively few resource users are often highly regulated, and the regulations are strictly enforced, including individual catch limits, onboard observers, and electronic systems that track fishing activities and catches in real time (cameras, tracing systems, sensors). In contrast, recreational fishing or small-scale fisheries with many highly dispersed resource users are much less regulated, and the regulations are often incompletely enforced. Further anecdotal evidence from Costello et al. (2012) suggests that small fisheries are often more overexploited than large fisheries, consistent with fixed costs of regulation (e.g. stock assessments).

The main contribution of our work is to show that technological progress and costly endogenous resource regulation can explain the pattern of resource decline and recovery. The key insight from the model is that technological progress drives resource (over-)use under open access (see e.g. Squires and Vestergaard, 2013a) and that resource degradation, together with productivity growth in the manufacturing sector, leads to structural transformation reducing the number of resource users. A decline in resource users does not reduce fishing mortality because the increased productivity compensates for the labor losses. Still, fewer resource users reduce regulatory costs, paving the way for resource regulation and recovery.

A related insight from our paper is that resource use beyond sustainable levels, and the subsequent recovery of the resource stock can be efficient if regulation is costly. Regulation is only efficient if the benefits of regulation, i.e., the avoided losses from overuse, outweigh the costs. Regulation may not be efficient if the regulatory costs are too high or the benefits from regulation

[3] Note that monitoring costs also include enforcing rules among actual resource users.

are low. In other words, it may be worthwhile to wait with the introduction of regulation until the number of resource users has declined sufficiently to reduce the cost of regulation below its benefits.

Our paper fits into the broad literature on economic growth and the environment. The seminal paper by Grossman et al. (1995) started a discussion on the impact of economic growth on the environment that is still ongoing. For example, Suphaphiphat et al. (2015) and Riekhof et al. (2018) have re-examined the result of optimal exhaustion of a renewable resource (Clark, 1973) in a setting with endogenous growth. Jayachandran (2021) summarizes the recent microeconomic evidence on the impact of economic development on the environment.

While the paper by Grossman et al. (1995) focused on the empirical pattern, subsequent literature suggested different mechanisms to explain these patterns, including changes in the composition and efficiency of economic production, preferences for environmental quality or technological progress in pollution abatement (Copeland and Taylor, 2004; Brock and Taylor, 2005, 2010; Carson, 2010; Smulders et al., 2011; Acemoglu et al., 2012).[4] However, none of these mechanisms can explain the observed pattern in the exploitation of common pool resources visualized in Fig. 1.

In contrast to the broad literature on the environmental Kuznets curve, a smaller literature has focused on the impact of economic development and technological progress on the sustainability of common pool resources (Hannesson et al., 2010; Squires and Vestergaard, 2013a). While technological progress and economic growth can explain the decline of resource stocks, they cannot explain their recovery. Here, we suggest that the recovery is driven by resource regulation (as e.g. in Noack et al., 2018) but also that resource regulation responds to technological progress, economic development, and structural change. Our study, therefore, relates to the literature that studies the impact of property rights (Costello and Grainger, 2018; Tajibaeva, 2012; Costello and Grainger, 2022; Noack and Costello, forthcoming) or international trade (e.g. Copeland and Taylor, 2009) on resource regulation. We differ from these studies by focusing on how the onset of resource regulation depends on the decline of the regulatory costs caused by economic development and technological progress. Our study is complementary to Smulders et al. (2011), who include exogenous regulation in their analysis of the Kuznets Curve. In contrast to their study, regulation in our study is endogenous and responds to economic development and the overuse of resources. A related excellent recent paper by Libois (2022) studies the ability of communities to manage their natural resources depending on the resource characteristics and the community's ability to impose sanctions. We expand the literature on endogenous resource regulation to a growing economy with technological progress and structural change.

In Section 2, we derive two stylized facts from literature and data on global fisheries and give further background information. The following Section 3 introduces the analytical model. We then present outcomes under open access and with zero regulatory costs before we come to our main results related to a setting with positive regulatory costs, all in Section 4. In the following Section 5, we discuss our results. In Section 6, we conclude.

2. Background

In this section, we present empirical facts on resource use, economic growth, and resource regulation to motivate our model set-up. We use data from fisheries, as the economic value of fish stocks is dominated by their consumptive value, thus excluding alternative explanations that rely on environmental preferences. However, other common pool resources may follow similar patterns because the proposed mechanisms behind these patterns are fairly general.

2.1. Economic growth, resource use and the number of resource users

Resource extraction rates and economic growth are correlated. Fig. 2 shows the relationship between GDP per capita and resource extraction rates. It resembles an environmental Kuznets Curve (Grossman et al., 1995; Copeland and Taylor, 2004) i.e., an inverted U-shaped pattern.[5] This inverted U-shaped pattern is confirmed by a polynomial regression that we report in Appendix A.8. The following fact summarizes this pattern.

Stylized Fact 1: Resource extraction first increases and then decreases with economic development.

The previous literature suggests increasing harvesting capacity (capital accumulation) and technological progress as the main drivers of the increase in extraction rates during economic development (Hannesson, 2007; Hannesson et al., 2010; Squires and Vestergaard, 2013a,b; Gordon and Hannesson, 2015). However, the causes of the subsequent decline in extraction rates are rarely discussed in relation to economic development.

While technology levels generally increase in agriculture and resource extraction, the share of employment in agriculture generally declines with economic development (e.g. Acemoglu, 2008). A similar relationship also holds for economic development and employment in the fishery, as shown in Fig. 3. The following fact summarizes the relationship between economic growth and the number of resource users.

Stylized Fact 2: The number of resource users declines with economic development.

[4] A similar literature studies the Environmental Kuznets Curve related to deforestation. Kaczan (2020) is a recent example and Meyfroidt and Lambin (2011) provides a summary of the literature.

[5] Here, we follow the convention to express resource extraction rates (i.e. the share of the resource stock that is extracted) relative to levels that would maximize the sustainable harvest. Levels above 100% are unsustainable and can lead to the collapse of the resource stock. Note that the width of the confidence interval in the figure increases towards both extremes of GDP because of the small number of observations for these values.

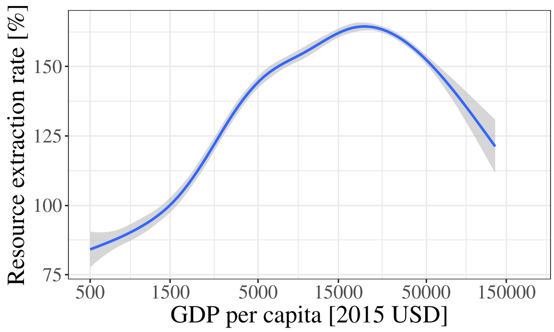

Fig. 2. Resource extraction and GDP.
Notes: Resource extraction rates are measured relative to extraction rates that maximize long-run harvest (maximum sustainable yield, MSY) and are expressed in percent. GDP per capita is measured in constant 2015 USD. The line shows the conditional mean and 95% confidence intervals using cubic splines across all 6360 fish stocks in the data set. The resource extraction data are from Costello et al. (2016) (see Appendix A.7). The GDP data are from the World Bank World Development Indicators. We show regression results of a polynomial regression in Appendix A.8.

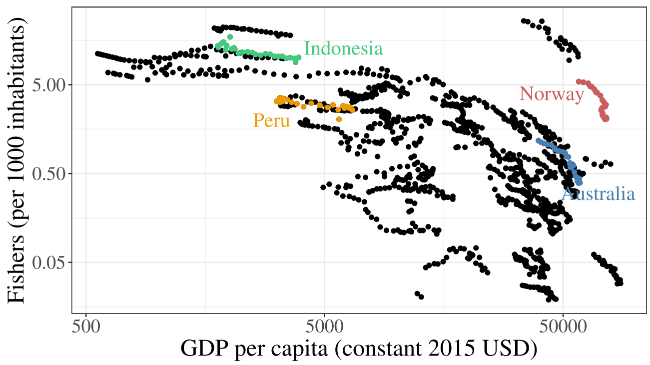

Fig. 3. Number of fishers and GDP.
Notes: The figure shows the number of fishers per 1000 inhabitants. The data includes all countries with complete information in the OECD database between 1995 and 2021. GDP per capita is measured in constant 2015 USD. The employment data are from the OECD Fisheries and Aquaculture Statistics database. The GDP and population data are from the World Bank World Development Indicators.

The number of fishing vessels similarly declined over time. Fig. 4 shows the trends in the number of fishing vessels in five developed countries. While the number of fishing vessels declined overall, the share of large fishing vessels increased over time. This suggests a trend towards larger fishing vessels during economic development which may (partly) compensate for the capacity losses from the declining numbers of fishing vessels. It further suggests that the productivity per fisher increases over time. Thus, it is unclear whether a reduction in fishers can explain the resource recovery. The decline of fishers and fishing vessels may also coincide with the introduction of resource regulation.

2.2. Fisheries regulation and resource recovery

Regulation reduces extraction rates and supports the recovery of depleted resources (Costello et al., 2008; Isaksen and Richter, 2019; Hilborn et al., 2020; Frank and Oremus, 2022), but enforcing regulation is costly. Fig. 5 shows a positive relationship between the reduction in overfished fish stocks and management expenditures by country. The figure suggests that countries with low fisheries management expenditures were unable to reduce the number of overfished fish stocks.

The expenditures on fisheries management are often substantial, ranging between 10 to 25% of the harvest values (OECD, 2003; Arnason et al., 2000) or between several hundred to several thousand USD per fisher (Fig. 5).[6] Enforcement and monitoring, research, and the general administration of fisheries management are the main components of these management costs. Fig. 6 suggests that management costs are, on average, equally divided between those components, while Arnason et al. (2000) find that enforcement composes the largest share of fisheries management costs. Enforcement and monitoring include onboard observers who continuously record compliance or catch composition of individual fishing vessels as well as the inspection of catch, by-catch, and vessel licenses

[6] For example, a study by the OECD reports management costs that range between 0.1% (Mexico) to 38.5% (Turkey) of the landing value, with countries like Canada or the United States in the middle of this range (14 and 17%, respectively) (OECD, 2003).

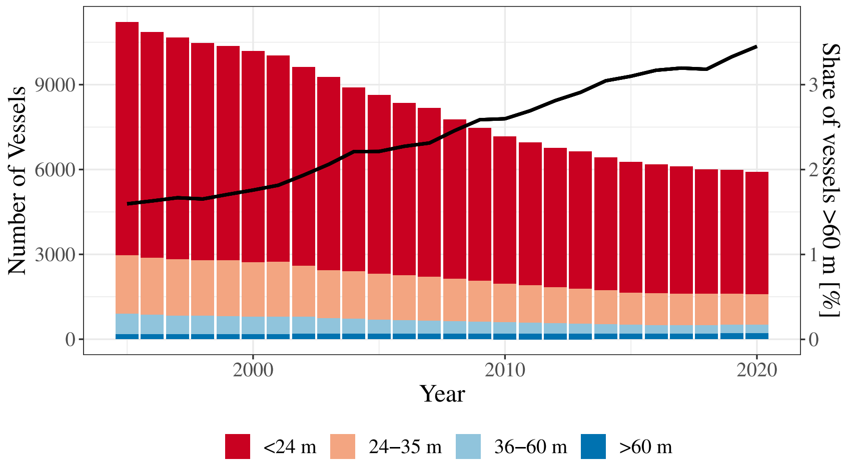

Fig. 4. Number of fishing vessels and the share of large vessels.
Notes: The number of fishing vessels in France, Norway, Portugal, Spain, and the United Kingdom combined. The black line shows the share of vessels above 60 m in the total fishing fleet. The data are from the OECD Fisheries and Aquaculture Statistics database. Countries with incomplete data are removed.

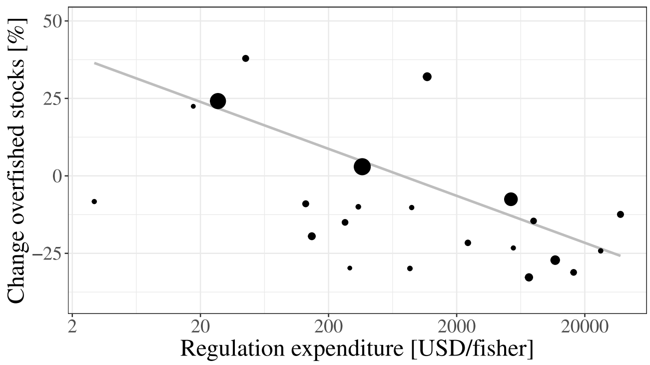

Fig. 5. Changes in overfished fish stocks and regulatory expenditures by country.
Notes: Each dot represents one country from the OECD database. Changes in overfished stocks are measured as the number of overfished fish stocks in 2012 compared to the number of overfished fish stocks in 2003. We define a stock as overfished if the extraction rate exceeds sustainable (MSY) levels. The expenditure data are mean annual expenditures on fisheries regulation per fisher from 2003 to 2012. We convert regulatory expenditures to constant 2015 USD using the World Bank World Development Indicator conversion rate. The line shows a linear regression line. The dot size and regression weights are the mean aggregate fishery revenues by country and year. The extraction and revenue data are from Costello et al. (2016). The data on fisheries management expenditures and the number of fishers are from the OECD Fisheries Support Estimates data.

by enforcement personnel.[7] This component of management costs depends on the number of fishing vessels or fishers. In contrast, research such as fish stock assessments and the administration of the management system may not depend on the number of fishing vessels.

In the following, we develop a theoretical framework based on this information to understand the drivers of and interrelations between economic development and resource use. To verify our model, its outcome should reproduce the two derived stylized facts.

3. A dual economy model with costly regulation

In this section, we describe our partial equilibrium multi-period model of economic development and resource regulation. The model includes two sectors, namely, a natural resource harvesting and a manufacturing sector. The economy is populated by a resource manager and working individuals. The setup is that of a small open economy with exogenous prices. It is motivated by local economies that are small relative to the world market. We assume exogenous but sector-specific technological progress. This describes a situation, for example, in which producers can adopt technologies developed elsewhere at minimal costs. Our partial

[7] Generally, OECD (2003) defines enforcement and monitoring costs as "boarding of fishing vessels and checking of catch, by-catch, vessel licenses, fishing licenses, fishing gear and the size of fish" as well as "checking of landings at the port and auctions".

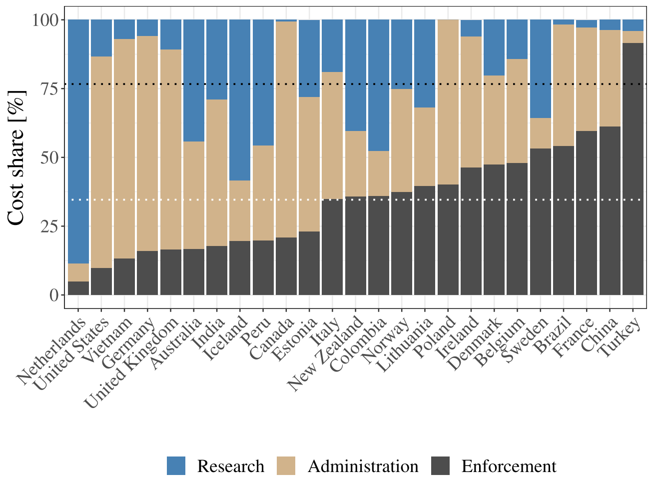

Fig. 6. Management cost components.
Notes: The expenditure data are mean annual expenditures on fisheries regulation from 2000 to 2020 from the OECD Fisheries Support Estimates data. The white dotted line is the mean enforcement share. The black dotted line is the mean enforcement plus administration share.

equilibrium model focuses only on the production sectors of the economy and abstracts from decisions related to consumption and saving, building on the idea that decisions on generating income and on spending can be separated to a large extent.

Related to resource regulation, the local resource manager can decide whether to restrict access to the resource and, if, to what level. Limiting access and thus harvest activities is costly, however. Regulation is often local, and even if it is decided upon nationally, enforcement is usually local, rendering effective regulation a local decision.

The economy is inhabited by $\bar{n} > 1$ individuals. Each individual is endowed with one indivisible unit of labor that can be allocated to either of the sectors in order to generate income. Individuals, therefore, specialize in one activity. Individual effort in harvesting is a combination of labor and the current technological level in the sector. In the following, $n^r(t)$ denotes the number of resource-harvesting individuals in period t. At the beginning of each period t, each individual maximizes income by choosing in which sector to work.

If access to the resource sector is restricted due to regulation, the decision of who is allowed to harvest the resource is made by a lottery. In the regulation case, a resource rent is generated that is divided between all resource users, implying that the income in the resource sector lies above the income in the manufacturing sector.[8]

Individuals live for several periods and new individuals are born that replace the old ones, such that the constant number of individuals $\bar{n}$ results. The individual income per period in the natural resource sector is denoted by $Y_R(t)$. It combines the (constant) resource price P_R and the harvested amount $H(t)$. Individual harvest is defined according to a Gordon-Schaefer-type technology (Scott, 1954; Schaefer, 1957) that combines individual effort – here labor (one unit per resource harvester), enhanced by the level of technology $A_R(t)$ – and the resource stock $S(t)$ according to

$$H(t) = A_R(t)S(t). \tag{1}$$

Labor costs in this setting are the opportunity costs of not working in the manufacturing sector. Individual income in the resource sector is

$$Y_R(t) = P_R A_R(t)S(t). \tag{2}$$

Productivity increases exogenously over time, according to

$$A_R(t+1) = A_R(t)(1+\gamma_{AR}) \tag{3}$$

with the rate of technological progress γ_{AR}. This describes, for example, a local economy that benefits from worldwide technological progress. Natural resource dynamics in continuous time τ are

$$\begin{aligned} \frac{dS(\tau)}{d\tau} &= \rho S(\tau)\left(1 - \frac{S(\tau)}{\kappa}\right) - \sum_1^{\bar{n}} S(\tau)A_R(t) \\ &= \rho S(\tau)\left(1 - \frac{S(\tau)}{\kappa}\right) - S(\tau)n^r(t)A_R(t) \end{aligned}$$

[8] In principles, this resource rent could then be used to cover regulatory costs. We do not model the distribution of the resource rent and the financing of regulatory costs explicitly, but discuss this in Section 5.

with intrinsic growth rate ρ, carrying capacity κ, and one unit labor supplied by each individual at time t. Aggregate harvest is described by $S(\tau)n^r(t)A_R(t)$, counting only labor input from those individuals in the resource sector. Units are such that $\tau = 1$ equals one period, i.e. τ and t are measured in the same units (see Noack et al., 2018). We assume that resource dynamics are fast relative to technological progress – having fast-growing fish and game species, and pasture in mind –, such that a steady state with $dS(\tau)/d\tau = 0$ is reached within a period and transition time is negligible. This assumption simplifies the dynamics of the model. Let $\bar{S}(t)$ denote the resulting resource stock, which is

$$\bar{S}(t) = \kappa \left(1 - \frac{n^r(t)A_R(t)}{\rho}\right). \tag{4}$$

Individual income in the resource sector can therefore be written as

$$Y_R(t) = P_R A_R(t)\kappa \left(1 - \frac{n^r(t)A_R(t)}{\rho}\right), \tag{5}$$

with $0 \leq n^r(t) \leq \bar{n}$.

Income of an individual in the manufacturing sector $Y_M(t)$ depends on the world price for manufacturing goods P_M and on productivity A_M according to

$$Y_M(t) = P_M A_M(t). \tag{6}$$

The world price for manufacturing goods is exogenous for the individuals living in the small open economy.

Productivity increases over time according to

$$A_M(t+1) = A_M(t)(1 + \gamma_{AM}) \tag{7}$$

with the rate of technological progress γ_{AM}. As for the resource sector, we assume that the small open economy benefits from general technological progress in manufacturing.

At the beginning of each period, the regulator decides whether to regulate the resource or not and, in case of regulation, how many individuals are allowed to harvest the resource. As labor is indivisible, restricting harvesting effort is equivalent to limiting the number of resource users. We denote the number of resource users under regulation by $n^*(t)$.[9]

The regulator faces different types of regulatory costs. We organize them along three themes: fixed costs C_f (e.g. from stock assessment), costs depending on actual resource users (termed "monitoring costs", related to observing whether actual users comply with rules), and enforcement costs to combat illegal resource use. With the term "enforcement" we want to stress that regulations only affect resource use if it is enforced. These costs are related to the actual number of resource users at the time when the regulation is introduced, i.e. the users under open access n^{OA}. They include political costs from the opposition of resource users that lose resource access through the regulation or costs to register all resource users initially. In Appendix A.2, we discuss further aspects, e.g. related to buy-outs to reduce capacity (related to $n^{OA}-n^*$) or to keep out potential entrants once regulation is introduced (related to $n^{OA} - n^*$ or $\bar{n} - n^*$). We assume that enforcement and monitoring costs are linear in the respective number of resource users with marginal costs c_e and c_m, respectively. Regulatory costs C_R are therefore given by $C_R = c_m n^* + c_e n^{OA} + C_f$.

As a benchmark, we assume an altruistic regulator who maximizes aggregate income in resource harvesting, taking regulatory costs into account.[10] Then, the regulator enacts $n^*(t)$ in t if the net total income in the resource sector under regulation $n^*(t)(Y_R(t) - P_M A_M) - C_R$ is larger than income under open access, if i.e.

$$n^*(Y_R(n^*) - P_M A_M) - c_m n^* - c_e n^{OA} - C_f > n^{OA}(Y_R(n^{OA}) - P_M A_M). \tag{8}$$

If regulation is enacted, its level is determined by maximizing the LHS of (8).[11] The regulator takes opportunity costs of labor into account. Without regulation, the allocation of individuals across sectors is determined by

$$\max \left\{ P_R A_R(t)\kappa \left(1 - \frac{n^{OA}(t)A_R(t)}{\rho}\right), P_M A_M(t) \right\}. \tag{9}$$

Some remarks on the timing in our model, on the potential strategic behavior of resource harvesters, on potential heterogeneity of the individuals, on the altruistic resource manager, and on the type of regulation are in order. First, we focus on set-ups in which resources grow fast relative to technological progress, as resource dynamics reach a steady state *within* a period and technological progress materializes *between* periods. We think of this as technological change embodied in harvesting equipment: once in a while – here, every period –, resource harvesters need to buy new equipment. For example, the average age of fishing vessels in Europe was 28 years, 36 years in North America, and 38 years in South America, based on the vessel registration of the International Maritime Organization.[12] In contrast, the average fishing mortality of all fish stocks in the RAM legacy stock assessment database version 4.495 (Ricard et al., 2012) is 0.36, implying that about one-third of all fish from exploited fish stocks are caught annually. This

[9] Appendix A.1 lists the notation used to denote different groups of resource users.

[10] In Section 5, we discuss how alternative settings may change results.

[11] We omit t if we only look at one period.

[12] Note that the average lifespan of fishing vessels is substantially larger than their average age, especially for growing fishing fleets. However, the database mostly includes large vessels.

translates roughly into an average fish age of 3 years for exploited fish stocks, much shorter than the boats' average age. We use these differences in average ages to motivate the differential dynamics of technology and resource stocks in our model.

Assuming that investment costs in both sectors are similar, we do not include them in the model. The impact of (different) investment costs as a potential barrier to structural change is discussed in Noack et al. (2018).

Second, we assume that the number of individuals is sufficiently large such that their impact on resource use – when all harvest the resource – is sufficiently small, such that no strategic behavior occurs. Later, strategic behavior is impaired by the threat of entry from non-resource users. For further discussions, see Section 5. Third, we assume that individuals are identical in their endowments and preferences. We could relax this assumption easily to have an ordering of productivity without impacting the results qualitatively.

Fourth, a resource manager may not be altruistic. One could also think of a resource manager who captures resource rents or who is controlled by the resource users. Costello and Grainger (2018) provide evidence that in the latter case, strong property rights – which we arguably have in our setting once regulation is introduced – lead to conservative management compared to rapid exploitation, which we interpret as the maximization of resource income. Thus, also this interpretation of the regulator's behavior fits with the current configuration of our model. Still, one could also imagine that the regulator is able to capture resource rents. If the regulator is able to capture all the rents, one would still observe the same number of resource users once regulation is introduced as before, as this is the number of resource users that maximizes the rent. The difference to our setting is, that resource users are now indifferent between the two sectors, as they will not receive an additional resource rent in the resource sector.[13]

Last, in our set-up, the regulation only occurs at the extensive margin, i.e. the number of resource harvesters can be restricted by regulation, but not individual effort. This is just an approximation. On the one hand, we observe a steady decline both in the number of fishers with their main business being fisheries and in the numbers of those for whom the fishery is only a side business, e.g. in the German Baltic Sea fishery. Often, fishers switch from main to side business and then eventually leave the fishery. On the other hand, especially when the number of resource users becomes low, cultural preferences or resource harvesters' utilities may favor a relatively larger number of resource users with restricted effort. Here, we focus on the onset of regulation when the number of resource users is still relatively large.

4. Results

We are interested in whether structural change, in combination with technological progress, can explain the observed pattern of resource use beyond sustainable levels and the subsequent recovery of the resource stocks. We propose regulation as the key mechanism behind resource stock recovery. To show the role of endogenous regulation for the observed dynamics, we first present results for the settings of open access, i.e. without regulation, and for the case of zero regulatory costs. Also, we limit the parameter space to the cases relevant to the present analysis.

4.1. Additional assumptions

We make additional assumptions to limit the number of scenarios to empirically relevant cases and to simplify the analysis. First, technological progress in resource harvesting has been roughly on par with other industries in the long-term (e.g. Hannesson et al., 2010). We therefore assume $\gamma_{AR} = \gamma_{AM} > 0$. Second, structural change implies a shift of labor from the resource to the manufacturing sector. To potentially generate this pattern, we start our analysis in a setting where everyone initially works in resource harvesting, i.e. we assume $n^{OA}(0) = \bar{n}$. This situation will only be observed when incomes are higher in the resource sector, $Y_R(0) > Y_M(0)$ or, equivalently, $P_R S(0) A_R(0) > P_M A_M(0)$. Third, we start our analysis with an abundant resource above the maximum sustainable yield level, $S(0) > S^{MSY}$, i.e., $\rho > 2n^{OA}(0)A_R(0)$. The maximum sustainable yield level refers to the steady state harvest at the stock level with the highest natural resource growth. It is often used in fishery management (as suggested e.g. in the UN Convention on the Law of the Sea—UNCLOS 1982). The corresponding stock level is

$$S^{MSY} = \kappa/2. \tag{10}$$

Setting S^{MSY} equal to $\bar{S}$ gives

$$n^{MSY}(t) = \frac{\rho}{2A_R(t)}. \tag{11}$$

Assumption 1 summarizes how we restrict parameters for the subsequent analysis.

Assumption 1 (*Parameter Restrictions*)**.** We assume

(a) $\gamma_{AR} = \gamma_{AM} > 0$;
(b) $P_R A_R(0)\bar{S}(0) > P_M A_M(0)$;

[13] One could also imagine two layers of regulation: the upper level determining the number of allowed users and an employed regulator on a lower level enforcing the regulation. Then, the 'official' resource users pay a certain price to the institution to be allowed to harvest the resource and still earn a resource rent. In this setting, the employed regulator has an incentive to deviate from the regulation and, for example, admit additional users with whom he or she shares the rent. Additional users would lower the income from the official users, but if the difference is not too large, it is too expensive for the official users to take action. Then, one would see more than the optimal number of users in the resource sector, but less than under open access.

(c) $\rho > 2A_R(0)\bar{n}$.

While Assumption 1 ensures an initial resource stock above the MSY-level, Assumption 2 ensures an initial resource stock above the Maximum Economic Yield (MEY) Level. The MEY level relates to the maximum (positive) difference between fishing revenues and costs in a given period. Costs relate to opportunity costs for working in the manufacturing sector in our model setting. MEY will be calculated in Lemma 2.

Assumption 2 (*Additional Parameter Restriction*)**.** We assume

$$\kappa\left(1-\frac{2\bar{n}A_R(0)}{\rho}\right) > \frac{P_M A_M(0)}{P_R A_R(0)}.$$

4.2. Open access and zero regulatory costs

The following lemma summarizes resource use in the absence of regulation.

Lemma 1 (*Development in the Resource Sector Under Open Access*)**.** *Under open access and with Assumption 1, the number of resource users are given by*

$$n^{OA}(t) = \begin{cases} \bar{n} \text{ for } \frac{\rho}{A_R(t)}\left(1-\frac{P_M A_M(t)}{P_R A_R(t)\kappa}\right) > \bar{n} \\ \frac{\rho}{A_R(t)}\left(1-\frac{P_M A_M(t)}{P_R A_R(t)\kappa}\right) \text{ else.} \end{cases} \tag{12}$$

The stock level is given by

$$\bar{S}^{OA}(t) = \begin{cases} \kappa\left(1-\frac{\bar{n}A_R(t)}{\rho}\right) \text{ for } \frac{\rho}{A_R(t)}\left(1-\frac{P_M A_M(t)}{P_R A_R(t)\kappa}\right) > \bar{n} \\ \frac{P_M A_M(t)}{P_R A_R(t)} \text{ else.} \end{cases} \tag{13}$$

The stock declines over time and the long-run resource stock at some $t = T$ is

$$\bar{S}(T) = \frac{P_M A_M(0)}{P_R A_R(0)}.$$

Proof in Appendix A.4.

Resource extraction initially increases due to technological progress. For the long-run development, three scenarios are possible, namely

$$\frac{P_M A_M(0)}{P_R A_R(0)} \begin{cases} > & \kappa/2 \\ = & \kappa/2 \\ < & \kappa/2. \end{cases}$$

A long-run resource stock above, at, or below the MSY level can result, depending on the relative productivity of the manufacturing sector. If it is relatively productive, resource users already switch sectors at relatively high levels of the natural resource stock. In the following, we focus on $P_R A_R(0)\kappa > 2P_M A_M(0)$, i.e. on situations when a long-run stock level below the MSY-level results under open access.

The next lemma summarizes resource use with a regulator and zero regulatory costs. This setting can be seen as a benchmark case. The number of resource users, in this case, is depicted by n^Z.

Lemma 2 (*Development in the Resource Sector Under Zero Regulatory Cost*)**.** *Under a resource manager who faces zero regulatory costs and given Assumption 1 and Assumption 2, the number of resource users develops according to*

$$n^{Z}(t) = \begin{cases} \bar{n} \text{ for } \frac{\rho}{2A_R(t)}\left(1-\frac{P_M A_M(t)}{P_R A_R(t)\kappa}\right) > \bar{n} \\ \frac{\rho}{2A_R(t)}\left(1-\frac{P_M A_M(t)}{P_R A_R(t)\kappa}\right) \text{ else.} \end{cases} \tag{14}$$

The resource stock develops according to

$$\bar{S}^{Z}(t) = \begin{cases} \kappa\left(1-\frac{\bar{n}A_R(t)}{\rho}\right) \text{ for } \frac{\rho}{2A_R(t)}\left(1-\frac{P_M A_M(t)}{P_R A_R(t)\kappa}\right) > \bar{n} \\ \frac{\kappa}{2}+\frac{P_M A_M(t)}{2P_R A_R(t)} \text{ else.} \end{cases} \tag{15}$$

The long-run level at some $t = T$ is

$$\bar{S}^{Z}(T) = \underbrace{\frac{\kappa}{2}}_{S^{MSY}} + \frac{P_M A_M(0)}{2P_R A_R(0)} = S^{MEY}.$$

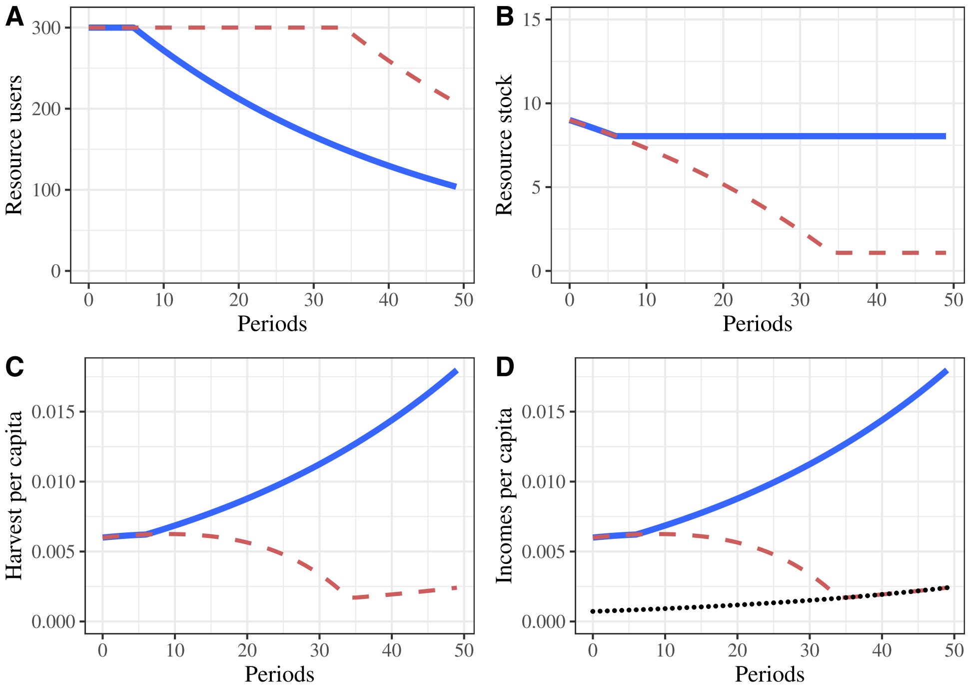

Fig. 7. Development in a dual economy with no regulatory costs.
Notes: The figure shows the dynamics of key variables under open access (dashed red lines) and zero regulatory costs (solid blue lines), and income development in the manufacturing sector (thin dotted line in lower right panel) for $\kappa = 15$; $\rho = 0.5$, $P_R(0) = 1$, $P_M(0) = 1.2$, $A_R(0) = 0.00067$, $A_M(0) = 0.0006$, $\gamma_{AR} = \gamma_{AM} = 0.025$; $\bar{n} = 300$. For the given parameters, $S^{MSY} = 7.5$ and $S^{MEY} = 8.04$.

Proof in Appendix A.4.

Under Assumptions 1 and 2, all individuals are initially in resource harvesting. Resource use increases up to the MEY level due to technological progress. The MEY stock level lies above the MSY level. It is equal to the MSY level for zero opportunity costs, i.e., for $P_M A_M = 0$. Once the MEY level is reached and when regulatory costs are zero, the resource manager keeps the effort constant at the MEY level by reducing the number of resource users to compensate for the productivity increases of the existing resource users due to technological change. The resource manager, therefore, accelerates structural change.

Fig. 7 illustrates the development over time under open access and zero regulatory costs. The development of resource incomes under open access is illustrated by the red dashed lines in Fig. 7 while the development under zero regulatory costs is depicted by the solid blue lines. Parameter values to run the model are inspired by the example of an Indian fishery in Noack et al. (2018), but the numerical exercise is purely used for illustrative purposes.

Initially, all individuals work in the resource sector under both regimes (see upper left panel). While the resource stock declines initially (see upper right panel), individual resource harvest and individual income are initially constant or increasing due to technological progress (see lower left and right panel, respectively). This does not hold on aggregate levels. The constant or initially increasing individual harvest is because the initial technology level is so low that resource users are unable to overharvest. Eventually, the decline in the resource stock dominates, and individual harvest and individual resource income decline under open access. Individual income in the resource sectors declines until it equals income in the manufacturing sector (additional line in the lower right panel) and individuals start to leave the resource sector. Under zero regulatory costs, an earlier start of structural change due to the introduction of regulation keeps the resource stock at its MEY level and prevents harvest and income from declining. Resource rents are created, which translates into high individual incomes in the resource sector. When natural resource harvesting is regulated, the difference in individual incomes between the two sectors grows over time, while its ratio is constant.[14]

So far we have treated prices as exogenous. However, prices may respond to the harvested amount if the economy is large compared to the rest of the world or the economy is closed. With an inverse demand function given by $P_R(h) = h^{-\sigma}$ the individual income of Eq. (5) becomes

$$Y_R(t) = \left(A_R(t)\kappa \left(1 - \frac{n^r(t) A_R(t)}{\rho} \right) \right)^{1-\sigma}.$$

[14] The income difference is given by $P_M A_M(0)(1+\gamma_{AM})^t - 0.5\kappa P_R A_R(0)(1+\gamma_{AR})^t$, with the optimal number of resource users inserted into the equation that describes individual income in the resource sector. For $\gamma_{AR} = \gamma_{AM}$, the equation can be written as $(P_M A_M(0) - 0.5\kappa P_R A_R(0))(1+\gamma_{AR})^t$. When the resource is regulated, the ratio between incomes is constant for $\gamma_{AR} = \gamma_{AM}$, it is $P_M A_M(0)/(0.5\kappa P_R A_R(0))$.

It can easily be seen that for $\sigma < 1$, the results are similar to the results with exogenous prices. Prices may also respond to an increasing demand due to income growth. This effect is discussed e.g. in Riekhof et al. (2018).

Further, we have assumed homogeneous technological progress across both sectors. However, technological progress may be higher in the manufacturing sector. Then, individuals will eventually leave the resource sector and there will be no resource use in the long-run, independent from regulation. The same result holds for relatively stronger price growth in the manufacturing sector. All individuals would eventually leave the resource sector and the stock would recover to its carrying capacity — given no critical threshold has been crossed. In contrast, when prices (or productivity) grow faster in the resource sector than in the manufacturing sector, the resource stock tends towards exhaustion (see Appendix A.3).

4.3. Costly regulation

We start this subsection by considering some general conditions that make regulation necessary. For identical technological progress in both sectors, structural change is driven by a declining resource stock. Harvesting effort is as high as possible, i.e. $n^r(t) = \bar{n}$, as long as $\bar{S}(t) > S^{MEY}$. This is true under open access as well as under regulation with zero costs. Thus, regulation in such a situation would not be necessary (i.e. would not make a difference). Once $\bar{S}(t) = S^{MEY}$, different harvest levels result with and without regulation. Let $\tilde{t}$ refer to this point in time, i.e. the point in time when the resource stock, which starts above its MEY-level, reaches the MEY-level. Thus, $\tilde{t}$ can be implicitly defined by

$$\begin{aligned}\bar{S}(\tilde{t}) = \kappa\left(1-\frac{\bar{n}A_R(\tilde{t})}{\rho}\right) = \frac{\kappa}{2}+\frac{P_M A_M(0)}{2P_R A_R(0)}\\ \Leftrightarrow \frac{1}{2}-\frac{P_M A_M(0)}{2\kappa P_R A_R(0)} = \frac{\bar{n}A_R(0)}{\rho}(1+\gamma_{AR})^{\tilde{t}}.\end{aligned} \tag{16}$$

We now turn to the cases with positive regulatory costs. The following proposition summarizes how these costs influence optimal resource use.

Proposition 1 (*Resource Use with Regulatory Costs*)**.** *If Assumptions 1 and 2 hold,*

$$c_m < P_R A_R(0)\kappa - P_M A_M(0),$$

and

$$\begin{aligned}&\left(P_R A_R(0)\kappa - \frac{c_m}{(1+\gamma_{AR})^{\tilde{t}}} - P_M A_M(0)\right)^2\\ &<4\left(\frac{P_R A_R(0)\kappa}{(1+\gamma_{AR})^{\tilde{t}}} - P_M A_M(0)\frac{P_M A_M(0)}{(1+\gamma_{AR})^{\tilde{t}}}\right)c_e + C_f\frac{4A_R(0)^2 P_R\kappa}{\rho}\\ &<\left(P_R A_R(0)\kappa - P_M A_M(0)\right)^2,\end{aligned} \tag{17}$$

with $\tilde{t}$ implicitly defined by (16), a harvesting path results that temporarily reduces the resource stock below the MEY level and recovers the stock to its MEY level in the long-run. The related number of optimal resource users is given by

$$n^*(t) = \begin{cases}\bar{n} \text{ for } \frac{\rho}{2A_R(t)}\left(1-\frac{c_m+P_M A_M}{P_R A_R(t)\kappa}\right) > \bar{n}\\ \underbrace{\frac{\rho}{2A_R(t)}}_{n^{MSY}(t)}\left(1-\frac{c_m+P_M A_M}{P_R A_R(t)\kappa}\right) \text{ else.}\end{cases} \tag{18}$$

Proof in Appendix A.4.

The proposition states that the existence of sufficiently high regulatory costs leads to a temporary use of the resource that leads to a resource stock below the long-run optimal level and subsequent recovery of the stock to its long-run optimal level. In other words, a temporary overuse and subsequent regulation can be efficient if regulatory costs are sufficiently high.

For $C_f = 0$, regulation will always be introduced in the long-run (see proof of Proposition 1). However, the fixed costs of regulation may be so high that it is never optimal to regulate if the second inequality in Eq. (17) does not hold.

Fig. 8 illustrates the development over time for $c_m > 0$ and $c_e > 0$, but keeping $C_f = 0$, with dotted lines. In addition, outcomes under open access and under zero regulatory costs are depicted in red dashed and blue solid lines, respectively.

The figure shows that the variables initially follow the open access path and only eventually – after a period of driving the resource stock below long-run sustainable levels – switch to a path similar to the path with zero regulatory costs. The 'overshoot' is due to the monitoring costs that make a relatively lower number of resource users under regulation optimal. In the long-run, the variables approach the MEY level. Fig. 13 in Appendix A.9 illustrates the development over time for $c_m = C_f = 0$ and $c_e > 0$, where no overshoot occurs and once regulation is introduced, the path is identical to the one with zero regulatory costs.

The jump in the variables when regulation is introduced is due to the different paces of technological change and resource dynamics. The resource dynamics are faster such that new steady states are reached within each period. Slow resource dynamics may reduce these jumps.

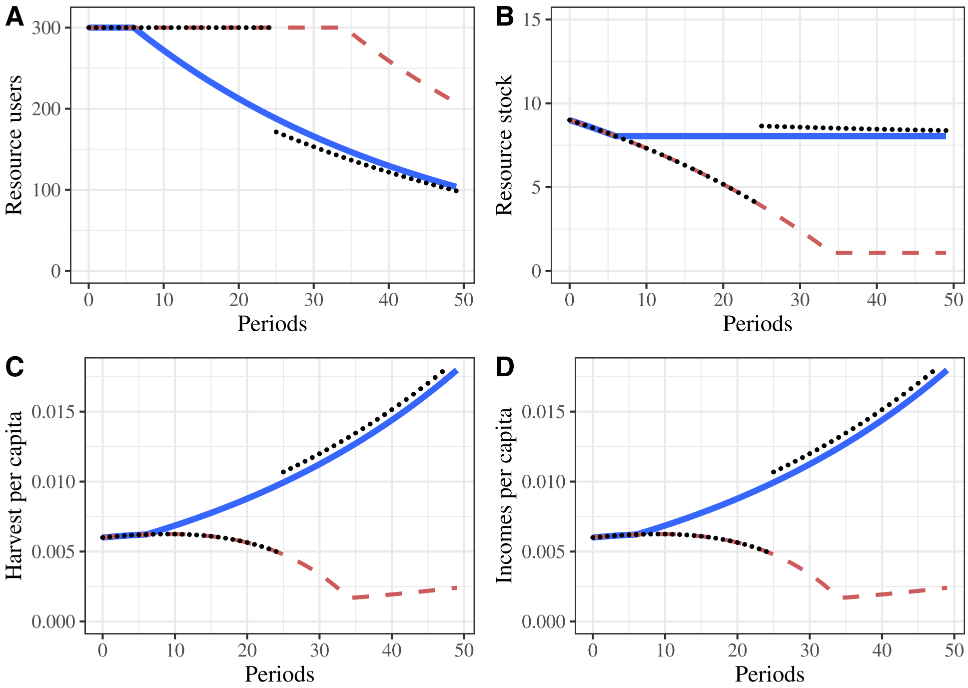

Fig. 8. Development in a dual economy when regulation is costly.
Notes: The figure shows the dynamics of key variables under costly regulation ($c_m > 0$, $c_e > 0$, $C_f = 0$) with dotted black lines. In addition, results under open access (dashed red lines) and zero regulatory costs (solid blue lines) are depicted. Parameter values are $\kappa = 15$; $\rho = 0.5$, $P_R(0) = 1$, $P_M(0) = 1.2$, $A_R(0) = 0.00067$, $A_M(0) = 0.0006$, $\gamma_{AR} = \gamma_{AM} = 0.025$; $\bar{n} = 300$; $c_e = 0.0025$, $c_m = 0.0025$, $C_f = 0$.

To understand the introduction of resource use regulation, it is helpful to consider how the different components of Eq. (8) change over time. To do so, we rewrite Eq. (8) to obtain

$$\underbrace{n^* Y_R(n^*) - n^{OA} Y_R(n^{OA})}_{\text{Regulatory benefits}} - \underbrace{P_M A_M (n^* - n^{OA})}_{\text{Change in opportunity costs}} \underbrace{- c_m n^* - c_e n^{OA} - C_f}_{\text{Regulatory costs}} > 0. \tag{19}$$

Regulatory benefits are the difference between aggregate resource incomes under optimal management and the aggregate open access resource income, while the regulatory costs relate to the sum of monitoring, enforcement, and fixed costs. In Appendix A.5 we show that the benefits of regulation, i.e. the first part of Eq. (19), are constant unless there are monitoring costs. The impact of monitoring costs declines with technological progress. A constant aggregate resource income relates to the fact that the overall productivity of the sector is bounded from above by the productivity of the resource. It is bounded from below by structural change. Shifting individuals to the manufacturing sector implies that individual incomes still grow in the resource sector, that the stock is – in most cases – kept at a positive level, and that the overall economy also grows due to technological progress in the manufacturing sector and due to a labor re-allocation to this sector.

Monitoring, enforcement, and fixed costs also directly affect the incentives of the regulator to introduce regulation as shown by the third part of Eq. (19). Changes in monitoring and enforcement costs due to changes in the number of actual and potential resource users also affect the regulator's incentives to regulate the resource. Assuming $A_R(0) = A_M(0)$ and $P_M = 1$,[15] the number of resource users from Proposition 1 and Lemma 1 can be written as

$$n^* = \frac{\rho}{2A_R} - \frac{\rho c_m + A_M}{2P_R A_R^2 \kappa} \quad \text{and} \tag{20}$$

$$n^{OA} = \frac{\rho}{A_R}\left(1 - \frac{1}{P_R \kappa}\right) \tag{21}$$

for the interior solution. It shows that there are two opposing effects of technological progress on the optimal number of resource users (n^*) when regulation is costly: First, technological progress reduces the number of resource users necessary to reach the optimum harvest level but second, technological progress also reduces the monitoring costs in relative terms and incentivizes the regulator to allow a larger number of resources users. In contrast, technological progress has a negative impact on the number of

[15] These assumptions imply identical technological levels across both sectors and express resource prices relative to prices in the manufacturing sector.

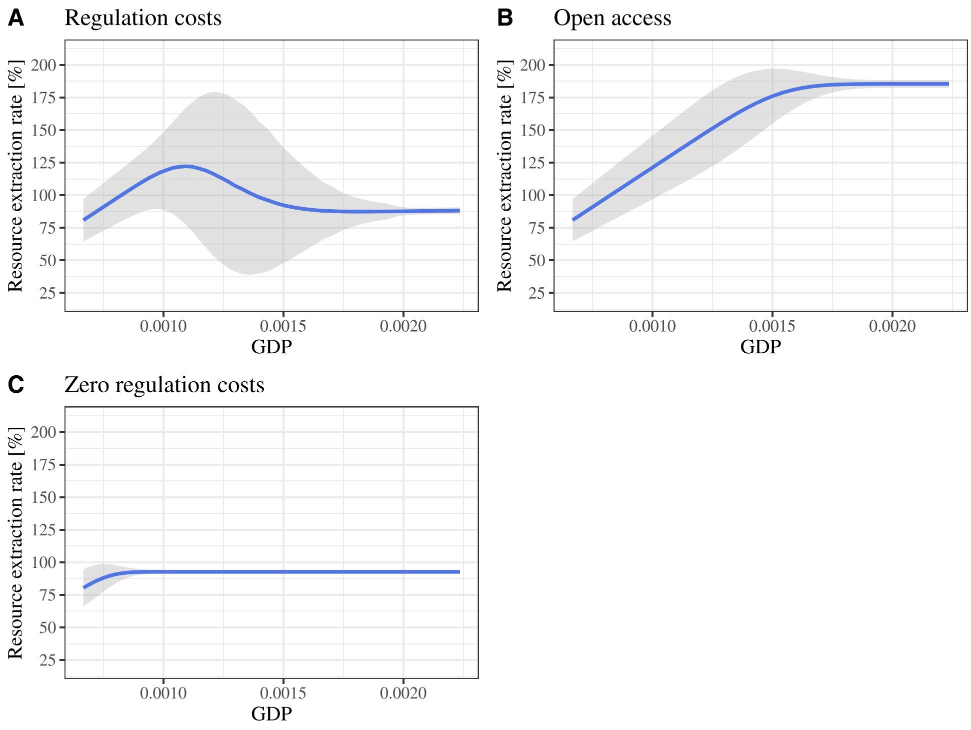

Fig. 9. Resource extraction related to GDP.
Notes: The figure shows results from 5000 model runs. Resource extractions are measured as resource extraction rates relative to extraction rates that maximize long-run harvest (maximum sustainable yield, MSY). GDP (per capita) is measured as the technological level in the model. The line shows the mean with the 95% confidence interval (shaded area).

open access resource users (n^{OA}). This effect is directly related to the structural change of economies during the development process in which labor is reallocated from resource use to the manufacturing and service sectors. It illustrates how technological progress as a driver of structural change impacts the incentives for resource regulation.

For a further understanding on regulation and resource use, we summarize the main effects from a comparative statics examination next (see Appendix A.6 for details). Regulation is stricter if the resource price is smaller, the intrinsic growth rate is lower or the carrying capacity is lower. Also, one would expect to see an unregulated resource, everything else equal, when regulatory costs are higher or the income level is lower (depicted by accumulated technological progress). Interestingly, the intrinsic growth rate has no or even a negative (in the case of positive fixed costs) impact on the introduction of the regulation.

4.4. Model outcomes, empirical facts and welfare implications

To relate our theoretical results to the empirical facts and to illustrate the welfare implications, we simulate our numerical results for different combinations of resource productivity (ρ, κ) and regulatory costs (c_m and c_e) using 5000 random draws from a normal distribution.[16]

The technology level corresponds to GDP per capita in the manufacturing sector for manufacturing prices equal to one. We use this equivalence in the following to facilitate the comparison between the simulated results and the empirical facts.

Fig. 9 shows the resource extraction rate for different technology levels (see above) for scenarios with positive regulatory costs (Panel A), open access (Panel B), and zero regulatory costs (Panel C). Only Panel A resembles the inverted-U-shaped pattern of Fig. 5 and our Stylized Fact 1.

Fig. 10 shows the number of resource users over time for the case with positive regulatory costs, under open access, and with zero regulatory costs. In all cases and in line with the prediction of structural change and our Stylized Fact 2, the numbers of resource users decline over time. As expected, structural change starts earliest under zero regulatory costs and latest under open access.

Fig. 11 compares how resource rents develop over time for different cases. Resource rents are the difference between an individual income in the resource sector and in the manufacturing sector, as the latter are the opportunity costs of resource harvesting,

[16] For each parameter, a value is randomly drawn from a normal distribution, with means based on our previous numerical examples and standard deviation corresponding to one-tenth of the mean. Baseline parameter values are $\kappa = 15$; $\rho = 0.5$, $P_R(0) = 1$, $P_M(0) = 1.2$, $A_R(0) = 0.00067$, $A_M(0) = 0.0006$, $\gamma_{AR} = \gamma_{AM} = 0.025$; $\bar{n} = 300$; $c_e = 0.0025$, $c_m = 0.0025$, $C_f = 0$.

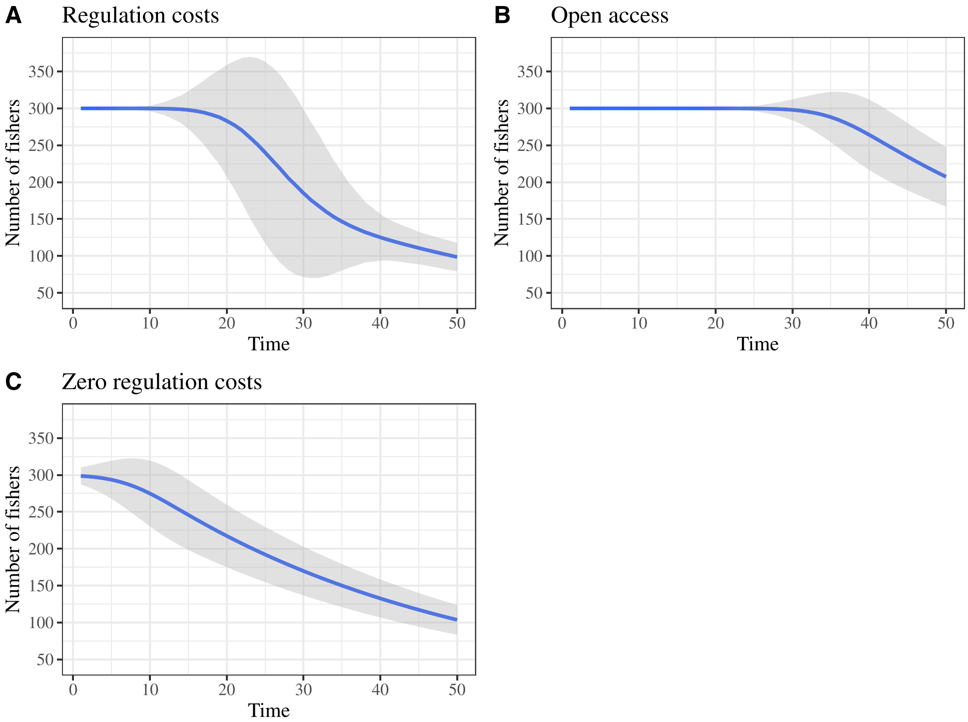

Fig. 10. Fishers over time.
Notes: The figure shows results from 5000 model runs. The line shows the mean with the 95% confidence interval (shaded area).

multiplied by the number of resource harvesters. Regulatory costs may or may not be subtracted. We compare five cases. In all cases, resource rents increase initially, because initial technology levels are too low to maximize economic yields. In the first case of zero regulatory costs, the rent is then kept at a maximum level that corresponds to the MEY stock. In most other scenarios, resource rents start declining once this level is reached. In the second case with positive regulatory costs that are not subtracted from the rents, rents eventually start increasing again. Obviously, resource rents are lower when these regulatory costs are subtracted from the rents (case three). Under open access (case four), rents eventually become zero. We create an additional hypothetical fifth case, in which a stock is managed as if there were no regulatory costs, but where the enactment of the regulation (enforcement and monitoring) in reality creates costs which are subtracted from the rents. In that case, rents are still positive in the depicted mean of our model runs, but they are initially below open access rents. Although this case is the worst in terms of initial resource rents, one could say that it is widespread in real-world resource management where policy often mandates regulation at a certain level (e.g. MSY) without considering regulatory costs. Still, there may be good reasons for doing so, e.g. related to ecosystem services.

We show further empirical support for our theoretical results in the working paper version of this paper (Riekhof and Noack, 2022).

5. Discussion

This paper presents a tractable model to examine the drivers of resource use beyond sustainable levels and subsequent recovery of the resource stock. Based on data from fisheries as an example of a renewable resource, we develop a mathematical model to explain these patterns. Our theoretical analysis suggests that technological progress drives resource use beyond sustainable levels. At the same time, technological progress paves the way for the introduction of resource use regulation by fostering structural change and thereby lowering regulatory costs. Our analysis suggests further that a temporal use of a natural resource beyond sustainable levels may be economically optimal.

Whether a pattern of resource use beyond sustainable levels and the subsequent recovery is economically optimal depends on the cost structure of resource use regulation, which is difficult to observe empirically. In addition, it also depends on the objectives of fishery management. In our model, fish is only valued for its consumptive value. Fish, or a renewable resource more generally, may have an additional existence value, and fishery management may have goals related to ecosystem health. An early introduction of regulation may therefore be optimal despite its negative impact on overall resource rents from resource harvesting, i.e. on those rents that include regulatory costs.

In any case, reducing regulatory costs supports resource conservation. While we focus on different types of regulatory costs in this article, we ignore the direct impact of technological progress on the regulatory costs (e.g. through technological progress

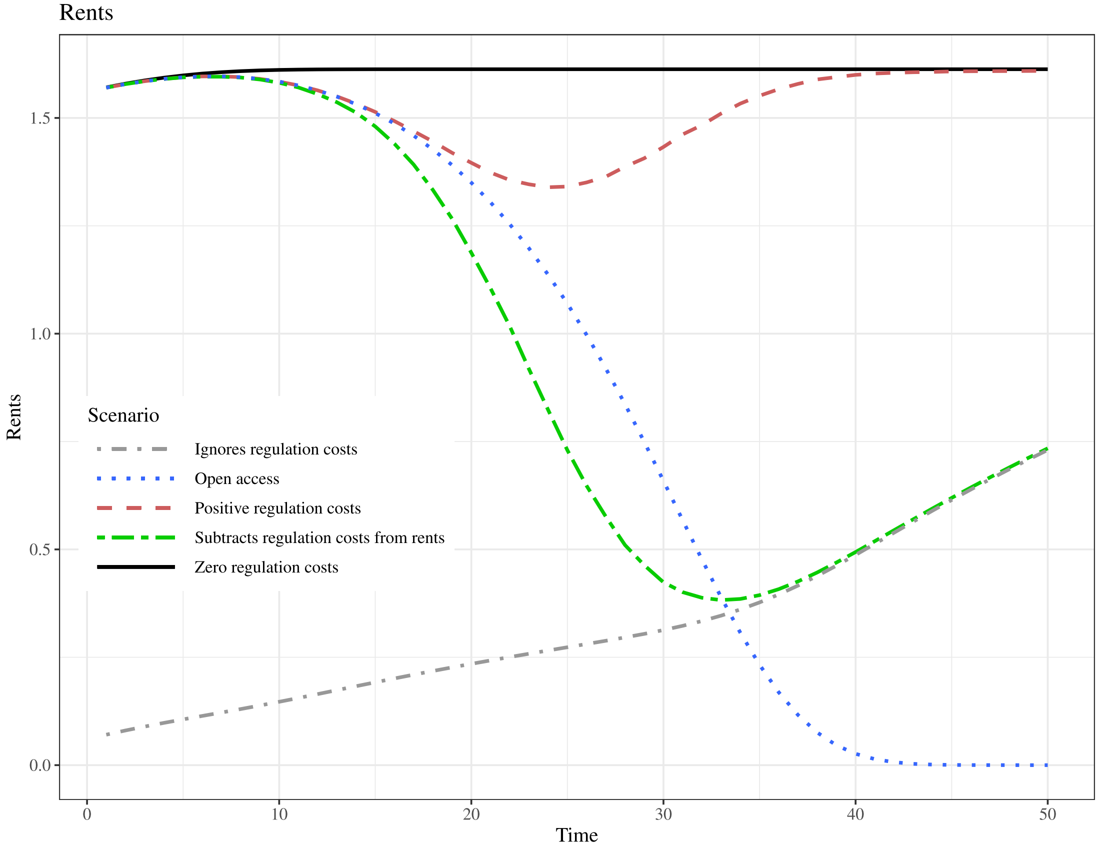

Fig. 11. Costs and benefits from regulation.
Notes: The figure shows the means from 5000 model runs. The dotted blue line relates to resource rents under open access, the black solid line refers to the case of zero regulatory costs, the red dashed line refers to a situation with costly regulation when regulatory costs are covered by another entity, and the green line shows the case with costly regulation when regulatory costs are subtracted from the rents. The grey line depicts the case in which a stock is managed as if there were no regulatory costs, but where the enactment of the regulation (enforcement and monitoring) in reality creates costs which are subtracted from the rents.

in monitoring and enforcement). Introducing technological progress in regulation may change our results, especially in cases when fixed costs exceed regulatory benefits and no regulation will be introduced in the long-run. Then, technological progress in regulation may make regulation for those stocks eventually optimal.

Resource regulation may become more challenging if resources take a long time to recover. In our analysis, we focus on fast resource dynamics such that the resource stock reaches its steady-state level within a period. We therefore abstract from spill-overs of resource use between different periods and between different economies. Even in this setting, we find that relatively slower-growing resources are more prone to overuse: a lower intrinsic growth rate leads to stricter regulation, but the introduction of regulation is independent of the intrinsic growth rate or, in the case of fixed regulatory costs, even negatively affected. Thus, no mechanisms exist that ensure regulation in the case of slower-growing resources. With slow-growing resources that do not match the set-up of our model, two aspects need to be considered. First, as the stock remains low initially when resource regulation is enacted, the value of regulation in terms of income in a given period is smaller compared to fast-growing resources. Second, the impact of regulation would now impact several periods, such that gains from regulation in subsequent periods as well as discounting, need to be taken into account.

Finally, while this paper focuses on the timing and costs of regulation in a single species setting, some insights can be gained related to the role of the ecosystem and on strategic interaction between different agents. Our model shows that changes in the environment's carrying capacity will influence whether and at which level regulation is introduced, but we leave the examination of interacting species, regime shifts, and uncertainty to future research.[17] Our model also gives an explanation why resource stocks managed by the same country may be in different conditions: With costly regulation, regulation depends on economic and ecological

[17] While uncertainty related to tipping points may influence the introduction of regulation, it may be less of an issue once regulation is implemented to recover the stock to sustainable levels, as the knowledge on critical thresholds has already been gained during the phase of resource depletion (see e.g. Diekert, 2017).

parameters. With international trade, spill-overs between countries related to resource use occur (Riekhof et al., 2018). Last, in the long-run when structural change has advanced and only a few resource users are left, strategic behavior may become more relevant. Fewer resource users make coordination between players easier (Olson, 1971) such that they may form a cartel, ask for regulation to maintain this cartel, and split the benefit accordingly. The impact on the resource would be as before, as the cartel will still maximize income in the resource sector. The difference from the previous setting is that effort reduction is along the intensive margin instead of the extensive margin. Interestingly, with a cartel of size $P_M A_M(0)/(0.5\kappa P_R A_R(0))$, individual incomes in both sectors would be identical, such that this may be a likely outcome in the long-run. We leave further examinations for the future.

6. Conclusion

We present a dynamic model of a dual economy with a manufacturing and a renewable resource sector in which regulatory costs decline with development. The model generates resource use paths similar to the empirical pattern in which resources are used beyond sustainable levels and subsequently recovered. In our model, this pattern is driven by technological progress, structural change, and costly regulation. Technological progress leads to resource use beyond long-run levels in the first place, and the declining productivity of the resource fosters structural change. This reduces regulatory costs. The exemption is fixed costs. If they are too high, regulatory benefits will remain below regulatory benefits. It will not be efficient to introduce regulation. Our results suggest that assigning a resource manager, reducing regulatory costs as well as fostering income alternatives support natural resource conservation. In addition, further research is needed to understand the drivers of introducing and enforcing resource use regulations in more detail.

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Declaration of competing interest

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

Appendix

A.1. Notation

Symbol	Meaning
n^r	individuals in resource harvesting
n^*	individuals in resource harvesting under optimal management
n^{OA}	individuals in resource harvesting under open access
n^Z	individuals in resource harvesting under zero regulatory costs

A.2. Regulatory costs

Here, we describe how a more complex setting of regulatory costs can be reduced to our relatively simple setting used in our main analysis. We consider again three costs types.

First, fixed costs $\tilde{C}_f$ occur, e.g. from stock assessment. Second, we consider monitoring costs $\tilde{C}_m(n^*(t))$ that depend on the allowed number of resource users $n^*(t)$ under regulation. In order to manage a resource successfully, the actions of the resource harvesters need to be observed. Third, we distinguish between two sub-types of enforcement costs. One type, $\tilde{C}^e_e(\bar{n} - n^*(t))$, depends on the number of resource users that would like to enter the fishery.[18] The other type depends on the number of individuals that have to leave the fishery, $\tilde{C}^l_e(n^{OA}(t) - n^*(t))$ when regulation is introduced. Especially when resource regulation generate rents, further individuals would like to enter the sector, such that a given regulation needs to be enforced. In addition, over time and especially when regulation is introduced for the first time, resource harvesters have to be forced or incentivized to leave the resource sector.[19]

[18] Here, we implicitly assume that each non-resource user tries to enter.

[19] We focus on the costs related to the introduction of regulation and abstract from costs related to reducing capacity over time.

We assume that enforcement and monitoring costs are linear in the respective number of resource users with marginal costs $\tilde{c}_m$, $\tilde{c}_e^e$, and $\tilde{c}_e^l$ respectively. Regulatory costs C_R would thus read $C_R = \tilde{c}_m n^* + \tilde{c}_e^e(\bar{n} - n^*) + \tilde{c}_e^l(n^{OA} - n^*) + \tilde{C}_f$. We can reformulate regulatory costs to obtain

$$C_R = \underbrace{(\tilde{c}_m - \tilde{c}_e^e - \tilde{c}_e^l)}_{=:c_m} n^* + \tilde{c}_e^l n^{OA} + \underbrace{\tilde{c}_e^e \bar{n} + \tilde{C}_f}_{=:C_f}$$
$$= c_m n^* + c_e n^{OA} + C_f,$$

with $\tilde{c}_e^l = c_e$, and assuming $c_m > 0$.

Enforcement costs related to capacity reduction when regulation is introduced only occur once, such that in principle, c_m would be higher when considering the level of regulation over time (as $\tilde{c}_e^l = 0$). In a real case study, this would have to be taken into account.

In addition, one could also assume that individuals coordinate before they try to enter the rent-generating resource sector, as a rent will only result for $n^r < n^{OA}$, such that only $n^{OA} - n^*$ individuals have to be kept out. This case can also be incorporated in the given setting, similar to the cases illustrated above.

A.3. Other assumptions on technological progress and price growth

Let prices depend on time and grow with the rates γ_{PR} and γ_{PM} in the resource and the manufacturing sector, respectively. To consider the impact from relative stronger growth in manufacturing prices or productivity, write individual income in the resource sector as

$$Y_R(t) = P_R(0)(1+\gamma_{PR})^t A_R(0)(1+\gamma_{AR})^t \kappa \left(1 - \frac{n^r(t) A_R(0)(1+\gamma_{AR})^t}{\rho}\right), \tag{22}$$

and income in the manufacturing sector as

$$Y_M(t) = P_M(0)(1+\gamma_{PM})^t A_M(0)(1+\gamma_{AM})^t. \tag{23}$$

With $1 - \frac{n^r(t) A_R(0)(1+\gamma_{AR})^t}{\rho}$ bounded from above, the combination $\gamma_{AM} = \gamma_{AR}$ and $\gamma_{PM} > \gamma_{PR}$ or the combination $\gamma_{AM} > \gamma_{AR}$ and $\gamma_{PM} = \gamma_{PR}$ lead to $Y_M(t) > Y_R(t)$ as $t \to \infty$.

In our simple model, $\gamma_{PM} > \gamma_{PR}$ depicts the case that the manufacturing good is relatively scarce, leading to a relative stronger growth in prices. The case $\gamma_{AM} > \gamma_{AR}$ depicts faster technological progress in the manufacturing sector. In both cases, incomes will be lower in resource harvesting such that all individuals leave the sector or would have to be forced – or compensated – to stay. If all individuals leave the natural resource sector, the resource will not be used anymore in the long(er) run, in our view an unlikely outcome for most natural resources.

The situation $\gamma_{AR} = \gamma_{AM}$ and $\gamma_{PM} = \gamma_{PR}$ is qualitatively identical to $\gamma_{PM} = \gamma_{PR} = 0$ and $\gamma_{AR} = \gamma_{AM} > 0$, the case discussed in the main body of the paper.

When either price or productivity growth rates are higher in the resource sector, under open access, the stock level will be driven to zero in the long-run. Consider

$$n^{OA}(t) = \frac{\rho}{A_R(0)(1+\gamma_{AR})^t}\left(1 - \frac{P_M(0)(1+\gamma_{PM})^t A_M(0)}{P_R(0)(1+\gamma_{PR})^t A_R(0)\kappa}\right)$$
$$\bar{S}(t) = \frac{P_M(0)(1+\gamma_{PM})^t A_M(0)}{P_R(0)(1+\gamma_{PR})^t A_R(0)},$$

with n^{OA} plugged into (4) to obtain the expression for $\bar{S}(t)$. For example, it can be easily seen that if $\gamma_{PR} > \gamma_{PM}$, $\bar{S}(t) \Rightarrow 0$ as $t \Rightarrow \infty$.

A.4. Proofs

Proof of Lemma 1. Based on (9), it could be that

$$P_R A_R \kappa \left(1 - \frac{n^{OA} A_R}{\rho}\right) > P_M A_M > P_R A_R \kappa \left(1 - \frac{(n^{OA}+1) A_R}{\rho}\right),$$

i.e. individual income in the resource sector is higher, but if an additional user enters, incomes would fall below the income in the manufacturing sector. In this situation, no individual has an incentive to switch the sector and n^{OA} results. Let π denote the income difference such that

$$P_R A_R \kappa \left(1 - \frac{n^{OA} A_R}{\rho}\right) = P_M A_M + \pi,$$
$$\frac{\rho}{A_R}\left(1 - \frac{P_M A_M + \pi}{P_R A_R \kappa}\right) = n^{OA}.$$

Then, the number of resource users in period t is described by

$$n^{OA}(t) = \begin{cases} \bar{n} \text{ for } P_R A_R(t)\kappa\left(1 - \frac{\bar{n}A_R(t)}{\rho}\right) > P_M A_M(t) \\ 0 \text{ for } P_R A_R(t)\kappa < P_M A_M(t) \\ \frac{\rho}{A_R(t)}\left(1 - \frac{P_M A_M(t)+\pi(t)}{P_R A_R(t)\kappa}\right) \text{ else.} \end{cases} \quad (24)$$

The steady state resource stock in a given period is obtained by plugging (24) into (4), which gives

$$\bar{S}(t) = \begin{cases} \kappa\left(1 - \frac{\bar{n}A_R(t)}{\rho}\right) \text{ for } n^{OA}(t) = \bar{n} \\ \kappa \text{ for } n^{OA}(t) = 0 \\ \frac{P_M A_M(0)(1+\gamma_{AM})^t+\pi(t)}{P_R A_R(0)(1+\gamma_{AR})^t} \text{ else.} \end{cases} \quad (25)$$

As $\pi(t)$ is small, we will assume $\pi(t) = 0$.

Initially, based on Assumption 1, $n^{OA}(0) = \bar{n}$ and $\bar{S}(0) = \kappa\left(1 - \frac{\bar{n}A_R(0)}{\rho}\right) > S^{MSY}$. With technological progress, the resource stock decreases over time, such that eventually individuals start to leave the resource sector according to

$$n^{OA}(t) = \frac{\rho}{A_R(t)}\left(1 - \frac{P_M A_M(0)(1+\gamma_{AM})^t}{P_R A_R(0)(1+\gamma_{AR})^t\kappa}\right).$$
$$= \frac{\rho}{A_R(t)}\left(1 - \frac{P_M A_M(0)}{P_R A_R(0)\kappa}\right).$$

The resulting resource stock for $t \to \infty$ is

$$\bar{S}(t) = \frac{P_M A_M(0)}{P_R A_R(0)}. \quad \square$$

With Assumption 1, the middle lines in (24) and (25) will never be realized as $\gamma_{AR} = \gamma_{AM}$ and $P_R A_R(0)\bar{S}(0) > P_M A_M(0)$.

Proof of Lemma 2. In a given period,

$$\max_{n^r} n^r\left(P_R A_R\kappa\left(1 - \frac{n^r A_R}{\rho}\right) - P_M A_M\right), \quad \text{and}$$
$$P_R A_R\kappa(1 - \frac{2n^Z A_R}{\rho}) - P_M A_M = 0$$

such that

$$n^Z = \frac{\rho}{2A_R}\left(1 - \frac{P_M A_M}{P_R A_R\kappa}\right) = n^{MEY}.$$

Taking Assumption 1 and restriction on resource users into account, (14) results. Plugging into (4) leads to (15). Given $n^Z(0) > \bar{n}$ (from Assumption 2), eventually $n^Z(t) < \bar{n}$ and S^{MEY} results. $\square$

Proof of Proposition 1. To find n^*, the manager considers

$$\max_{n^r} n^r\left(P_R A_R\kappa\left(1 - \frac{n^r A_R}{\rho}\right) - P_M A_M\right) - c_m n^r - c_e n^{OA} - C_f$$

in each period. Based on the first-order condition,

$$P_R A_R\kappa\left(1 - \frac{n^* A_R}{\rho}\right) - n^* P_R A_R\kappa\frac{A_R}{\rho} - c_m - P_M A_M = 0.$$

Together with Assumptions 1 and 2, one obtains (18).

Using that $Y_R(n^{OA}) = P_M A_M$ and

$$Y_R(n^*) = P_R A_R(t)\kappa\left(1 - \frac{\frac{\rho}{2A_R(t)}\left(1 - \frac{c_m+P_M A_M(t)}{P_R A_R(t)\kappa}\right)A_R(t)}{\rho}\right)$$
$$= P_R A_R(t)\kappa\left(0.5 + \frac{0.5(c_m + P_M A_M(t))}{P_R A_R(t)\kappa}\right)$$
$$= \frac{P_R A_R(t)\kappa + c_m + P_M A_M(t)}{2}$$

in (8), one obtains

$$n^* Y_R(n^*) - c_m n^* - P_M A_M n^* - c_e n^{OA} - C_f > n^{OA} Y_R(n^{OA}) - P_M A_M n^{OA},$$

$$n^*\left(\frac{P_RA_R\kappa - c_m - P_MA_M}{2}\right) > n^{OA}c_e + C_f,$$

$$\frac{\rho}{2A_R}\left(1-\frac{c_m+P_MA_M}{P_RA_R\kappa}\right)\left(\frac{P_RA_R\kappa - c_m - P_MA_M}{2}\right) > \frac{\rho}{A_R}\left(1-\frac{P_MA_M}{P_RA_R\kappa}\right)c_e + C_f,$$

$$\left(P_RA_R\kappa - c_m - P_MA_M\right)^2 > 4\left(P_RA_R\kappa - P_MA_M\right)c_e + C_f\frac{4A_R^2P_R\kappa}{\rho}. \tag{26}$$

Regulation is introduced when (26) holds. In the proposition, Condition (17) implies that Condition (26) is not fulfilled at $t = \tilde{t}$. Rewriting the condition to explicitly include time gives

$$\left(P_RA_R(0)\kappa - \frac{c_m}{(1+\gamma_{AR})^t} - P_MA_M(0)\frac{(1+\gamma_{AM})^t}{(1+\gamma_{AR})^t}\right)^2$$
$$>4\left(\frac{P_RA_R(0)\kappa}{(1+\gamma_{AR})^t} - P_MA_M(0)\frac{(1+\gamma_{AM})^t}{(1+\gamma_{AR})^{2t}}\right)c_e + C_f\frac{4A_R(0)^2P_R\kappa}{\rho}. \tag{27}$$

For $\gamma_{AM} = \gamma_{AR}$, the first term increases, the second term decreases, and the third term stays constant over time. Regulation will eventually be introduced (see second inequality of Condition (17)). For $C_f = 0$, regulation will always be introduced in the long-run, independent of the second inequality in Condition (17). □

A.5. Resource incomes

Using the optimal number of resource harvesters from Eq. (18), the open access resource user from Eq. (12)(ignoring the corner solutions) and assuming further that $A_R = A_M$ as well as $P_M = 1$ (i.e. resource prices are relative prices) resource incomes can be expressed as

$$n^{OA}Y_R(n^{OA}) = \rho\left(1-\frac{1}{P_R\kappa}\right)$$

and

$$n^*Y_R(n^*) = \frac{\rho P_R\kappa}{4}\left(1-\left(\frac{c_m}{P_RA_R\kappa}\right)^2\right).$$

These equations state that open access aggregate resource income is constant (as long as resource prices are constant) and that aggregate optimal resource income is constant unless there are monitoring costs. The reason for the latter effect is that monitoring becomes relatively less costly with technological progress. A higher technological level allows a number of resource users closer to the level of optimal resource users in the case of zero regulatory costs. Using (20) and (21), changes in opportunity costs $(n^{OA} - n^*)P_MA_M$ can be written as

$$\frac{\rho}{A_R}(1 - 1/P_K - 1/2 + c_M/(2P_RA_R\kappa) + 1/(2P_R\kappa)),$$

showing that they decrease over time as resource users decline in general. Changes in the incentives to regulate are mainly driven by changes in regulatory costs relating to the number of optimal and open access resource users.

A.6. Comparative statics

In the following, we derive some comparative statics results, i.e. we ask: how does a variable impact the introduction of regulation and its strictness, keeping everything else equal?

We assume that $c_m + P_MA_M(0) < P_RA_R(0)\kappa$ holds. We find

$$\frac{\partial n^*}{\partial \rho} = \frac{1}{2A_R}\left(1-\frac{c_m+P_MA_M}{P_RA_R\kappa}\right) > 0;$$

$$\frac{\partial n^*}{\partial A_R} = -\frac{\rho}{2A_R^2} + \frac{2\rho(c_m+P_MA_M)}{2P_RA_R^3\kappa}$$

$$= \frac{\rho}{2A_R^2}\left(\frac{2(c_m+P_MA_M)}{P_RA_R\kappa} - 1\right)\begin{cases} < 0 \text{ for } 2(c_m+P_MA_M) < P_RA_R\kappa \\ > 0 \text{ for } 2(c_m+P_MA_M) > P_RA_R\kappa,\end{cases}$$

$$\frac{\partial n^*}{\partial P_R} = \frac{\rho}{2A_R}\frac{c_m+P_MA_M}{P_R^2A_R\kappa} > 0,$$

$$\frac{\partial n^*}{\partial \kappa} = \frac{\rho}{2A_R}\frac{c_m+P_MA_M}{P_RA_R\kappa^2} > 0,$$

$$\frac{\partial n^*}{\partial c_m} = -\frac{\rho}{2A_R^2P_R\kappa} < 0,$$

$$\frac{\partial n^*}{\partial P_MA_M} = -\frac{\rho}{2A_R^2P_R\kappa} < 0.$$

Table 1
Resource extraction and GDP.

Model:	Costello et al. (2016) data			RAM data
	(1)	(2)	(3)	(4)
log(GDP)	211.7***	478.5***	460.6***	2.55***
	(56.4)	(139.0)	(115.3)	(0.901)
log(GDP)^2	−10.9***	−26.9***	−25.1***	−0.152***
	(3.10)	(7.84)	(6.73)	(0.056)
Year fixed-effects		Yes	Yes	Yes
Country fixed-effects		Yes	Yes	Yes
Stock fixed-effects			Yes	Yes
Observations	56,429	56,429	56,429	17,015
R^2	0.008	0.029	0.631	0.652
Within R^2		0.002	0.005	0.009

Notes: Standard errors are clustered at the year, country, and species level. Significance levels are ***: 0.01, **: 0.05, *: 0.1.

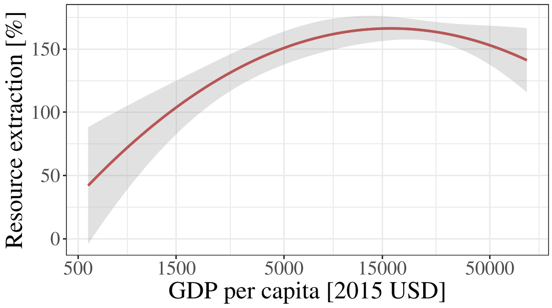

Fig. 12. Resource extraction and GDP.
Notes: Resource extractions are measured as resource extraction rates relative to extraction rates that maximize long-run harvest (maximum sustainable yield) and are expressed in percent. GDP per capita is measured in constant 2015 USD. The line shows the conditional mean and 95% confidence intervals of specification (1) in Table 1.

Regulation is stricter if the resource price is smaller or the carrying capacity is lower. When $c_m = P_M A_M = 0$, there is no impact. A less productive resource (a lower regeneration rate) leads to stricter regulation.

The impact from the technological level on the strictness of regulation depends on the level of monitoring and opportunity costs: for no or low monitoring and opportunity costs, a higher technological level leads to stricter regulation, everything else equal. The relation changes for higher monitoring and opportunity costs: then, a higher technological level leads to a less strict regulation. To understand this result, on has to keep in mind that a less strict regulation in the case of positive monitoring costs brings regulation closer to its long-run level.

To consider when a regulation is introduced, consider Condition (27). Higher regulatory costs (c_m, c_e, C_f), a lower intrinsic growth rate ρ and lower (identical) rates of technological progress – the latter translating into lower income levels – delay the introduction of regulation, everything else equal.

A.7. Data

To measure resource extraction, we use the data of Costello et al. (2016). The data comprise the majority of the commercial fisheries worldwide from 1960 to 2012. The catches are matched with data on resource stock sizes based on stock assessments, when available, and estimated stock sizes based on observed catch histories otherwise. We follow Costello et al. (2016) in normalizing the resource extraction rate (share of the extracted resource stock) by the fish stock-specific resource extraction rate that would maximize sustainable harvest (i.e. the MSY harvest). After this normalization, extraction rates above 100 % imply harvesting beyond biologically sustainable levels independent of the biological characteristics of the resource. This extraction rate is called fishing mortality in the context of fisheries, and we use both terms interchangeably. The dataset also contains catches, profits, prices, and biological growth parameters. The distribution of fishing mortality is highly skewed and contains some outliers, possibly due to measurement error. We, therefore, exclude the 99th percentile of the distribution.

We merge these data with GDP and population data from the World Bank World Development Indicators. After merging and filtering, we remain with an unbalanced panel of 5846 fish stocks in 151 countries over 53 years.

As a robustness test, we use the RAM Legacy Stock Assessment Database (Ricard et al., 2012) version 4-495 (RAM data henceforward) to measure resource extraction. The database contains data from stock assessments of 529 stocks starting in the 19th century. We restrict the data to the time period between 1960 and 2020 to match our GDP data. Although the quality of the

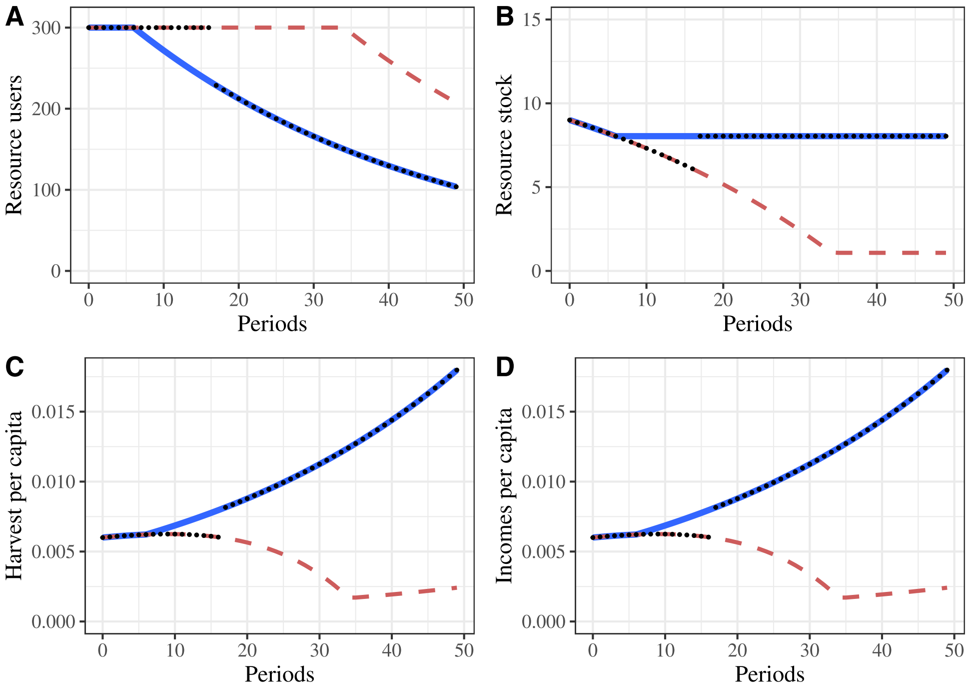

Fig. 13. Development in a dual economy when only enforcement of a regulation is costly.
Notes: The figure shows the dynamics of key variables enforcement costs with dotted black lines. In addition, results under open access (dashed red lines) and zero regulatory costs (blue solid lines) are depicted. Parameter values are $\kappa = 15$; $\rho = 0.5$, $P_R(0) = 1$, $P_M(0) = 1.2$, $A_R(0) = 0.00067$, $A_M(0) = 0.0006$, $\gamma_{AR} = \gamma_{AM} = 0.025$; $\bar{n} = 300$; $c_e = 0.0035$, $c_m = C_f = 0$.

data is higher than the data of Costello et al. (2016) it is also restricted to fish stocks with formal stock assessments. Because formal stock assessments are costly and require high levels of resources such as research vessels etc., the database mainly contains stocks in developed countries. Further, agencies conduct stock assessments mainly with the intention to regulate the stocks. The RAM data may, therefore, be affected by a strong selection bias towards stocks that were regulated early. We, therefore, only use the RAM data for robustness tests and focus throughout the text on the data of Costello et al. (2016). To avoid the impact of influential outliers, we exclude the 99th percentile of the distribution in the RAM data.

A.8. Resource extraction and economic growth

In this section, we report the results of a regression that relates resource extraction to economic growth i.e. we estimate

$$\text{Resource extraction}_{ijt} = \alpha + \beta_1 \log(\text{GDP}_{jt}) + \beta_2 \log(\text{GDP}_{jt})^2 + \varepsilon_{ijt}$$

where Resource extraction$_{ijt}$ is the resource extraction rate relative to the extraction rate that maximizes long-term harvest of stock i in country j in year t, GDP$_{jt}$ is per capita GDP in constant 2015 USD and ε_{ijt} is the error term. We add country, year, and resource stock fixed effects in the subsequent specifications. Columns (1) to (3) of Table 1 report the main results. The results suggest that resource extraction initially increases with GDP levels and then declines again after an inflection point between $ 7200 (Specification 2) and $ 16,100 (Specification 1). Column (4) reports robustness tests based on the RAM data (see Appendix A.7). Although the inflection point is reduced ($ 4300 in Specification (4)), the results are qualitatively similar to the main results. The lower inflection point is possibly a result of the selection bias of the RAM data that mainly contains early regulated stocks (see Appendix A.7).

Fig. 12 predicts the results of Specification (1). The relationship is an inverted U similar to Fig. 2.

A.9. Additional figures

See Fig. 13.

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