Environment and Development Economics 9: 455–472 © 2004 Cambridge University Press
DOI: 10.1017/S1355770X04001597 Printed in the United Kingdom

Sharing rules and the commons: evidence from Ha'apai, Tonga

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ABSTRACT. This paper argues that sharing rules have served to reduce the inefficiency caused by common pool externalities in many developing societies. To this end, a two-sector model of renewable resource use is employed where sharing rules are interpreted as implicit resource taxes. The model is applied to the island economy of Lofanga in the Kingdom of Tonga. The model generates a growth pattern which is consistent with the observed time paths of population and the resource stock. Cyclical fluctuations are weak even in the absence of resource taxation because the intrinsic growth rate of the resource is high.

1. Introduction

The problem of the commons arises whenever an economic resource is jointly used by a group of individuals who inflict negative technological externalities on each other. An important example is the extraction (appropriation) of resource units from a renewable resource stock such as fish, rangelands, groundwater aquifers, or forests. In the absence of adequate rules, individual appropriators determine their harvesting effort by considering only the private marginal cost of extraction, which is lower than the social marginal cost. As a consequence, aggregate harvest is above the efficient level (Gordon, 1954; Dasgupta and Heal, 1979). Experimental evidence has confirmed this (non-cooperative) outcome in a variety of settings (Walker, Gardner, and Ostrom, 1990; Walker and Gardner, 1992; Herr, Gardner, and Walker, 1997).

The resulting inefficiency can be eliminated if appropriators establish a set of rules which restrict access to the resource system directly or indirectly. Direct restrictions define who is allowed to enter the resource system at what times. Indirect restrictions include systems of harvest quotas and the specification of harvesting technologies or harvesting seasons. These restrictions are called *access restrictions* here. Empirical research has shown that access restrictions existed (or have continued to exist) in many past and contemporary societies (Guha, 1989; Ostrom, 1990; Baland and Platteau, 1996).

This paper is published posthumously, due to the tragic death of the author on 1 December 2002.

https://doi.org/10.1017/S1355770X04001597 Published online by Cambridge University Press

This paper focuses on *sharing rules* as another class of rules which reduce inefficiency in the commons. Sharing rules are rules which prescribe that each resource user give part of his or her harvest to other individuals as a gift. Sharing rules have existed in several agrarian societies and are still widespread in contemporary Oceania. In a recent paper, Bender, Kägi, and Mohr (2002) have argued that *sharing rules can be a substitute for access rules*. The authors compare coastal subsistence fisheries around two islands in the Ha'apai region in the Kingdom of Tonga where access restrictions are virtually absent. While fish stocks are lower in the fishing areas of the island of 'Uiha, stocks are larger around the other island, Lofanga. At the same time, the authors find sharing rules to be stronger among the population of Lofanga than on 'Uiha. Sharing rules can be interpreted as an informal insurance system that protects fishermen against random fluctuations in fishing yields (Bender, Kägi, and Mohr, 2002; Chakraborty, 2002).

This paper presents an alternative interpretation of sharing rules as an *implicit resource tax*. To this end, a dynamic general equilibrium model is applied to the commons problem on Lofanga island. The model, which has been developed elsewhere (Chakraborty, 2001), considers an economy where fisheries yields are certain, both the resource stock and population are endogenous, and where no human-made capital is accumulated. It is assumed that sharing rules are symmetric, i.e. they require each resource user to share the same fraction of her harvest with all others. The effects of sharing rules are then identical to those of a uniform resource tax, the proceeds of which are redistributed across appropriators on a per capita basis.

As the tax reduces the private marginal return to harvesting effort, users expend less effort than they would if sharing rules were absent. Consequently, the aggregate harvest can be reduced to its efficient level by choice of a sufficiently high tax rate (sharing rate) even when access restrictions do not exist. Simulations reveal that the resource tax raises the equilibrium level of the resource stock by up to 49 per cent and individual welfare by up to 13 per cent. Cyclical fluctuations of population and the resource stock are weak even in the absence of a resource tax, which is due to the high intrinsic growth rate of the local fish stocks.

Earlier work on sharing rules in fisheries has focused on contractual choices between boat owners, captains, and crew members (e.g. Platteau and Nugent, 1992). This paper, in contrast, analyzes sharing rules as an implicit contract among independent entrepreneurs in fisheries. The effects of resource taxation in the commons were studied by Dasgupta and Heal (1979) in a static partial equilibrium framework. The model employed in this paper extends their analysis to a dynamic general equilibrium context where both the population (and, hence, the number of users) and the resource stock are endogenous.

The paper is organized as follows. Section 2 presents the model and describes its equilibrium, stability, and adjustment properties. Section 3 contains the application to Tonga, while section 4 concludes.

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2. Resource taxation in a dynamic general equilibrium model

The model presented in this section was developed in Chakraborty (2001). It extends an earlier model by Brander and Taylor (1998) to a resource tax.

2.1. The model

Consider an agrarian two-sector economy without capital accumulation or technological change. Labour and the stock of a renewable (Gordon–Schaefer) resource are the only factors of production. In the first sector, labour produces a manufactured good with constant returns to scale. The second sector comprises resource harvesting, which is undertaken with constant returns to scale to labour and to the resource stock. The population growth rate is endogenous; it is assumed to respond positively to the per capita consumption of the resource. Consumers maximize instantaneous utility, which is increasing in the resource harvest (equals consumption) per capita and manufacturing output. Perfect competition in the labour market ensures that all labour is allocated to resource harvesting or manufacturing. As goods markets are also perfectly competitive and the resource is harvested under open access, the resource price equals the labour cost of harvesting plus the resource tax.

The model aims to analyze sharing in societies where symmetric sharing rules prevail: each resource user is required to share the same fraction of her harvest with all other users. As was mentioned in the introduction, sharing rules can then be interpreted as a resource tax, the proceeds of which are redistributed equally among all taxpayers. In principle, the sharing rule can be modelled as a quantity tax or as an *ad valorem* tax on resource harvesting. The former corresponds to a system of sharing rules that prescribe constant sharing rates, e.g. constant percentages of the quantity harvested to be given away. The latter corresponds to a system of rules where the sharing rate varies as the resource price varies. The following analysis assumes an implicit *ad valorem* tax where the tax rate is fixed in terms of units of the manufactured good per unit of harvest. The tax proceeds are redistributed equally to all consumers on a per capita basis.

This specification implies that the tax rate, measured as a percentage of the resource units harvested, declines as the resource becomes scarcer (i.e. as the relative price of the resource increases), which appears plausible on the following grounds. In non-industrial societies, sharing rules rarely specify the precise quantities to be shared. Neither is sharing legitimized by resource conservation objectives (Ruddle, 1996a). Instead, sharing rules are defined by a set of social obligations to share with family members, local dignitaries, and other members of the community. These obligations, which may be more or less demanding, are motivated by solidarity (extending support to the poor, the aged, the sick, and to children), extended reciprocity, and prestige. In other words, what is shared when resource users give part of their harvests to others is primarily economic value. It is then reasonable to expect that less resource units are shared when the value of the resource increases. Section 3.2 discusses the issue with regard to Lofanga island.

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The resource tax generates two effects in the model. First, it induces a static reallocation of labour from harvesting to manufacturing, because it reduces the private marginal net return to harvesting. As all individuals expend less effort on harvesting, the resource stock is higher than without a tax at the long-run equilibrium. At the same time, the population size adjusts in such a way that harvest (equals consumption) per capita remains the same as before. However, the amount of labour allocated to manufacturing is higher, which results in an unambiguous increase in individual welfare.

Second, the model is able to generate cyclical behaviour, as population size and the resource stock may adjust cyclically to their long-run equilibrium values. However, both variables adjust monotonically to long-run equilibrium if the tax rate is sufficiently high. The remainder of this section describes the formal structure of the model.

The dynamics of the natural resource stock S are assumed to follow a logistic growth function (Clark, 1976/1990)

$$\dot{S} = rS\left(1 - \frac{S}{K}\right) - H \tag{1}$$

The first term on the right-hand side of (1) represents the own rate of growth of the resource, i.e. the rate at which the resource regenerates if it is undisturbed by human intervention. The speed of regeneration depends on the resource stock S and a parameter $r > 0$, which is called the 'intrinsic growth rate' of the resource. The second term represents the harvest rate $H > 0$. The growth rate $\dot{S}$ of the resource stock per unit of time becomes negative if S exceeds K, which implies that K is the maximum possible resource stock ('carrying capacity').

It is assumed that the harvest rate supplied by producers H^P rises as the resource stock or the amount of labour L_H allocated to resource harvesting increases

$$H^P = \alpha S L_H \tag{2}$$

$\alpha > 0$ is a parameter. Apart from the resource harvest, the economy produces a manufactured good (denoted M), which can be interpreted as an index of agricultural or artisanal goods and reproductive activities. Good M is produced with a fixed coefficient technology that uses only labour. One unit of labor is assumed to produce one unit of M. As both labour and goods markets are assumed to be perfectly competitive, the price of M equals one, and so does the wage rate w if manufactures are produced.

The resource is harvested under open access, which implies that resource rents are zero. It is assumed that an environmental tax is levied on resource harvesting. As was discussed above, the model considers an *ad valorem* tax where the marginal tax rate is assumed to be constant in terms of the manufactured good. As perfect competition prevails in the goods market, the supply price p^P of one resource unit harvested must equal its marginal (= average) labour cost, $w/(\alpha S)$ at the prevailing wage rate w, plus the tax rate t

$$p^P = \frac{w}{\alpha S} + t \tag{3}$$

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The tax rate t is measured in units of the manufactured good per unit of the resource harvested. Hence, the marginal tax rate, measured in terms of renewable resource units, varies as the resource price varies.

Labour is allocated between resource harvesting and the production of manufactures according to the following labourforce constraint

$$\frac{H^P}{\alpha S} + M = L \tag{4}$$

The labourforce L is assumed to be equal to the population size. The allocation of labour is determined by utility maximization of a representative consumer who is endowed with one unit of labour. Her utility function is assumed to have the following form

$$u = h^{\beta} m^{1-\beta} \quad with \quad 0 < \beta < 1 \tag{5}$$

h and m are the individual consumption of the resource harvest and the manufactured good, respectively. The proceeds from the environmental tax are distributed equally among all consumers. Measured in units of the manufactured good, the individual consumer's budget constraint is then

$$ph + m = w + \frac{tH^P}{L} \tag{6}$$

Utility maximization yields the following aggregate demand quantities of the two goods (details see Full mathematical workings)

$$H^D = \frac{L\beta}{p}\left(w + \frac{tH^P}{L}\right) \tag{7}$$

$$M^D = L(1-\beta)\left(w + \frac{tH^P}{L}\right) \tag{8}$$

From (7), the demand price p^D for the resource can be calculated as

$$p^D = L\beta\left(\frac{w}{H^D} + \frac{tH^P}{LH^D}\right) \tag{9}$$

At short-run equilibrium (where the resource stock and the population are considered as given), the demand price must equal the supply price, $p^D = p^P = p$, and the quantity demanded must equal the quantity supplied, $H^P = H^D = H$. Setting (3) and (9) equal yields

$$\begin{aligned} \frac{w}{\alpha S} + t &= \frac{L\beta w}{H} + \beta t \\ H &= \frac{L\beta w}{\frac{w}{\alpha S} + (1-\beta)t} \\ &= \frac{L\beta\alpha S}{1 + \frac{\alpha S}{w}(1-\beta)t} \end{aligned} \tag{10}$$

Equation (10) shows that the equilibrium harvest with environmental taxation is lower than without taxation for any positive tax rate if the

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resource stock is given. According to (4), the output of manufactures is

$$M = L - \frac{H}{\alpha S} = L - \frac{L\beta}{1 + \frac{\alpha S}{w}(1-\beta)t}$$

$$= L\left(1 - \frac{\beta}{1 + \frac{\alpha S}{w}(1-\beta)t}\right) \tag{11}$$

The equilibrium output of manufactures is higher with environmental taxation than without taxation for any positive tax rate. As expected, the tax shifts the composition of output towards manufactures.

Inserting (10) into (1) gives the change in the level of the resource stock per unit of time

$$\dot{S} = rS\left(1 - \frac{S}{K}\right) - \frac{L\beta\alpha S}{1 + \frac{\alpha S}{w}(1-\beta)t} \tag{12}$$

The population growth rate positively depends on the difference between the birth rate b and the death rate d, which is assumed to be negative, $b - d < 0$. It also positively depends on the resource harvest per capita H/L. $\phi > 0$ is a parameter that measures the responsiveness of population growth to resource harvest income per capita. The change in population per unit of time is then

$$\dot{L} = L\left(b - d + \phi\frac{H}{L}\right)$$

$$\dot{L} = L\left(b - d + \phi\frac{\beta\alpha S}{1 + \frac{\alpha S}{w}(1-\beta)t}\right) \tag{13}$$

2.2. Equilibrium, stability, and adjustment patterns

This section provides an overview of the equilibrium, stability, and adjustment properties of the model.[1] As in the Brander–Taylor model without taxation, two obvious solutions for a long-run equilibrium are ($S = L = 0$) and ($S = K$, $L = 0$). Setting $\dot{S} = \dot{L} = 0$ in (12) and (13) and solving for S and L gives the interior solution (S^*, L^*)

$$S^* = \frac{d - b}{\phi\beta\alpha - (d-b)\frac{\alpha}{w}(1-\beta)t} \tag{14}$$

$$L^* = \frac{r}{\beta\alpha}\left(1 - \frac{S^*}{K}\right)\left[1 + \frac{\alpha S^*}{w}(1-\beta)t\right] \tag{15}$$

An interior solution exists if the equilibrium resource stock is smaller than the carrying capacity, K. This is the case if the tax rate satisfies the following condition (see Full mathematical workings for details)

$$0 < t < \frac{\phi\beta w}{(d-b)(1-\beta)} - \frac{w}{\alpha K(1-\beta)} := t^K \tag{16}$$

[1] A more detailed analysis is contained in Chakraborty (2001).

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It can be seen by inspection of (14) that S^* rises as the tax rate increases. Furthermore, it can be shown that the equilibrium is locally stable for all tax rates $t \in [0, t^K[$ if $-1 < (b-d)/(\alpha\beta K\phi) < -3+2\sqrt{2}$ (details see Full mathematical workings).

The system (12) and (13) adjusts monotonically to its long-run equilibrium if the characteristic equation to the system linearized at (S^*, L^*) has complex roots. This is the case if the intrinsic growth rate of the resource, r, satisfies the following condition (see attached Mathematica file for details)

$$r > \frac{4\alpha\beta K\phi w[(1-\beta)(d-b)t-\beta\phi w]^2[-\alpha(1-\beta)(d-b)Kt+(b-d+\alpha\beta K\phi)w]}{(d-b)[\alpha(-1+\beta)^2(d-b)Kt^2+(-1+\beta)(b-d+\alpha\beta K\phi)wt+\beta\phi w^2]^2}$$
$$:= f(t) \tag{17}$$

As the right-hand side of (17) is a function of the tax rate, $f(t)$, it depends on the tax rate whether adjustment is cyclical or monotonous. As condition (17) cannot easily be solved for the tax rate, the set of tax rates which generate monotonous adjustment paths is identified by means of simulation in the next section.

3. An application to Tonga

This section applies the model to the island economy of Lofanga, which is situated in the Ha'apai region of Tonga. Section 3.1 presents a brief overview of the structure of property rights over fishing areas in the Kingdom of Tonga. Section 3.2 describes the system of sharing rules that prevails on Lofanga island and derives empirical estimates of the implicit resource tax rate. Section 3.3 discusses the choice of parameter values. The data on catch rates and sharing behaviour on Lofanga island were taken from the results of a field study published by Bender (2001) and Bender, Kägi, and Mohr (2002). Section 3.4 presents simulation results.

3.1. Marine tenure

Territorial rights to fishing grounds (marine tenure) existed in the Kingdom of Tonga in earlier times (Gifford, 1929: 146–147, 177). These rights were related to land rights in the following way. Local rulers were given land by the king in the form of hereditary fiefs. The subjects of local rulers who lived in fiefs that included parts of the coastline were allowed to fish in the waters adjacent to their waterfront. Inhabitants of the interior tracts had to obtain seafood through exchange against horticultural and other inland products. Transgressions were sanctioned by the local rulers. Furthermore, Johannes (1978: 352) notes the existence of closed fishing seasons, bans on fishing during spawning periods, and the practice of allowing a portion of the catch to escape. Little is known about the precise formulation of these rules and their impact on resource conservation, however.

The system of marine tenure was abolished by the Tongan constitution, which was enacted in 1875 and guaranteed the right of every Tongan citizen to catch fish anywhere in the Kingdom (Bender, 2001: 118). This change of rules was part of the king's strategy to weaken the position of local rulers. Formally, all fishing grounds in the Kingdom of Tonga have been under

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open access since then. Furthermore, many other traditional restrictions on fishing seem to have disappeared in the region (Johannes, 1978).

In the Ha'apai region, a remainder of the historic marine tenure systems exists in that certain fishing grounds have customarily been used by the residents of particular islands. The entry of fishing vessels from the island of Uiha into Lofangan fishing grounds occasionally leads to conflicts; however, it is tolerated by the Lofangan population in most cases (Bender, 2001: 209–213). The Fisheries Act of 1989 and the Fisheries Regulations (1994) impose restrictions on harvest times, technology, and fish size for certain species; however, these rules are rarely observed and practically not enforced on Lofanga (Bender, 2001: 132 and 136). Among the island population of Lofanga, no other formal or informal rules exist at present, which put binding restrictions on catch rates, the fishing technology, the fishing season, or other indicators of effort (Bender, Kägi, and Mohr, 2002).

It is likely that the traditional rules described above had a positive impact on resource conservation. The impact of sharing rules would then have been additional. As the traditional system of marine tenure was abolished and other traditional restrictions apparently eroded on Lofanga, the conservation impact of traditional rules has been reduced to the impact of the sharing rules. In principle, it is possible to model the impact of marine tenure and other traditional access restrictions during the early history of the island. An equivalent tax rate could be defined which generates an impact on harvesting identical to the access restrictions just mentioned. To the best of the author's knowledge, however, no data exist which would permit an estimate of the equivalent tax rate. The following analysis, therefore, makes the extreme assumption that resource conservation relied exclusively on sharing rules at all times, i.e. it treats the Lofangan fishery as being open access. This serves to identify the maximum impact that could have been attained by sharing rules in the Lofangan setting.

3.2. Sharing rules

Informal sharing rules (locally known as *fetokoni'aki*) exist on Lofanga island which prescribe that each fisherman give part of his catch to others without immediate compensation. As in many other non-industrial societies, these rules do not specify precise quantities to be shared. Rather, sharing rules represent a set of social obligations which can, in principle, place 'stronger' or 'weaker' demands on each fisherman to share his catch with others. Bender (2001) reports that the aged, the sick, and close family members are among the beneficiaries of sharing on Lofanga island. Furthermore, sharing includes individuals whom a returning fisherman meets more or less incidentally on the beach or on his way home. Sharing also has a demand component, as interested individuals deliberately visit the house of a fisherman who just returned from his trip.

In the perception of the members of the community, sharing is motivated by solidarity and prestige. Solidarity requires to support those who cannot catch fish themselves. Prestige is an important motivation because sharing raises the social status of those who share: it is prestigious to be a productive fisherman who is able to give considerable amounts of fish to others. Furthermore, sharing serves to reinforce social relationships with family

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Table 1. *Lofanga: catch data*

Class	*Number of fishermen*	*Weekly average catch [kg/week/person]*	*Donors*
commercial	6	188	6
semi-commercial	23	71	9
predom. subsistence	12	20	3

Source: Bender, 2001: 195 and 201.

members, friends, and office-bearers (Bender, 2001; Bender, Kägi, and Mohr, 2002).

Catch levels and sharing behaviour are not identical across Lofangan fishermen. Catch levels differ because capabilities and effort levels differ. Bender (2001) divides the fishermen into three classes: commercial, semi-commercial, and predominantly subsistence. She presents data for average weekly catches for each of the three classes, which are based on interviews with fishermen. Moreover, she presents data on the number of members of each class who give fish to others than close relatives (donors). Table 1 summarizes this information. It can be seen that the weekly average catch rate of commercial fishermen strongly exceeds that of semi-commercial fishermen, which in turn is approximately three and a half times that of the subsistence fishermen. The first two classes of fishermen set aside only a small fraction ($< 1/2$) of their catch for self-consumption; the remainder is either shared with others or sold on Lofanga island or (through a trader) to the national market in Tongatapu. The third class does not share at all, but receives shared catch from the other two classes because their fishing yields are smaller than the minimum quantity of fish that people choose to consume themselves (minimum consumption requirement).

The implicit resource tax How can the empirical evidence on sharing be related to the model of section 2? The distribution of resources that results from the sharing process can be treated *as if* it had been generated by an equivalent *ad valorem* tax which is uniform and constant. It is reasonable to assume an *ad valorem* tax in the Lofangan setting because anecdotal evidence indicates that people share less if fish become scarcer. The uniform tax rate in the model then corresponds to an *average* tax rate in the empirical setting. In the following analysis, the data in table 1 will be used to derive two estimates for the average implicit tax rate.[2]

The first estimate concerns the maximum implicit tax rate which is consistent with the data. To this end, it is assumed that all fishermen distribute the part of their harvest which is above their minimum consumption requirement to all others. Although this assumption is unrealistic (if the

[2] A more accurate analytical representation of the sharing rules encountered on Lofanga island would account for an unequal distribution of capabilities and (possibly) preferences among agents and would consider a marginal tax rate which is nonlinear in the quantity harvested. However, it would then not be possible to solve the model analytically.

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commercial and semi-commercial fishermen shared all their surplus, they would not be (semi-)commercial in the first place), it serves to identify an upper bound on the implicit tax rate. The fishermen's minimum consumption requirement is 25 kg/week/person, which is to cover the subsistence needs of the fisherman himself and all other (at an average five to six) members of his household (Bender, 2001: 196). The implicit resource tax rate T can then be computed as

$$T = \frac{\sum_{i=1}^{2}(\text{catch} - \text{subsistence requirement})_i \cdot (\text{number of donors})_i}{\text{aggregate catch}} \tag{18}$$

with the summation taken over the first and second class of fishermen because the third class (predominantly subsistence) catches less than their minimum consumption requirement. The average implicit tax rate is then

$$T = \frac{(188 - 25) \cdot 6 + (71 - 25) \cdot 9}{188 \cdot 6 + 71 \cdot 23 + 20 \cdot 12} = 0.46 \tag{19}$$

It needs to be emphasized that the average tax rate of $T = 46$ per cent conceals strong differences among the two classes of fishermen who catch more than their minimum consumption requirement. The implicit tax rate for the commercial fishermen is (188–25)/188 = 87 per cent, while the implicit tax rate for the semi-commercial fishermen is only (71–25) · 9/(71 · 23) = 25 per cent.

The second estimate is based on the assumption that the commercial fishermen sell 50 per cent of their catch and the semi-commercial fishermen sell 25 per cent of their catch. Given the anecdotal evidence on sharing, the assumption defines a lower bound on the average tax rate, which now becomes

$$T = \frac{(188 \cdot 0.5 - 25) \cdot 6 + (71 \cdot 0.75 - 25) \cdot 9}{188 \cdot 6 + 71 \cdot 23 + 20 \cdot 12} = 0.22 \tag{20}$$

It appears plausible that the actual tax rate lies between 22 and 46 per cent. Note that the tax rate T is measured in resource units per unit of resource harvest whereas the tax rate t in (3) was fixed in manufactured goods per unit of resource harvest. T varies with the resource stock in the model, as $T = t/p = t/(t + \frac{w}{\alpha S})$.

The history of sharing rules Little is known about the specific history of sharing rules on Lofanga island. However, sharing rules have been common in the Kingdom of Tonga and in Oceania in general since ancient times (Alkire, 1977; Gerber, 1985; Lutz, 1982; Mauss, 1923/1954; Ruddle, 1996b; Ruddle, 1996c: 157–159). The available archaeological evidence is consistent with the hypothesis that sharing rules and access restrictions reduced pressure on finfish stocks in the region. In a survey on the history of coastal fisheries in the Pacific, Dalzell (1997: 1) concludes with regard to finfish capture: 'There is no firm evidence from the archaeological record to suggest that long-term subsistence exploitation of reef fish populations has had any serious negative effects on abundance or structure of reef fish communities.'

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The fact that sharing rules have existed in different regions of Oceania for a long time suggests that sharing rules stem from a common source which probably pre-dates the ancestral Polynesians who lived in the region of today's eastern Indonesia and the Philippines in the third millenium BC. This is corroborated by anthropological studies which reveal that sharing rules have been common in many hunter-gatherer societies (Woodburn, 1982). This again indicates that sharing rules, where they exist, have been in force for a long time.

3.3. Other parameters

Section 3.3.1 derives measurable parameters such as maximum sustainable yield or catch per unit of effort from the resource dynamics component of the model. Section 3.3.2 describes the choice of other parameters than the tax rate for the simulation experiments.

3.3.1. The derivation of yield parameters in the logistic growth model

From (1) and (2), the dynamics of the natural resource stock can be described as follows

$$\dot{S} = rS\left(1 - \frac{S}{K}\right) - \alpha S L_H \tag{21}$$

As $\dot{S} = 0$ at equilibrium, the equilibrium harvest and effort levels H^0 and L_H^0 can be computed as follows

$$rS^0\left(1 - \frac{S^0}{K}\right) - \alpha S^0 L_H^0 = 0 \tag{22}$$

$$L_H^0 = \frac{r}{\alpha}\left(1 - \frac{S^0}{K}\right) \tag{23}$$

$$H^0 = rS^0\left(1 - \frac{S^0}{K}\right) \tag{24}$$

Catch per unit of effort (CPUE) at equilibrium is then

$$CPUE = \frac{H^0}{L_H^0} = \alpha S^0 \tag{25}$$

From (24), the resource stock that generates the maximum equilibrium harvest ('maximum sustainable yield', MSY) can be computed by

$$\frac{dH^0}{dS^0} = r\left(1 - \frac{2S^0}{K}\right) = 0 \tag{26}$$

$$\overline{S^0} = \frac{K}{2} \tag{27}$$

$$MSY = H^0(\overline{S^0}) = r\frac{K}{2}\left(1 - \frac{1}{2}\right) = \frac{1}{4}rK \tag{28}$$

Pezzey *et al.* (2000) employ a modified version of the Gordon–Schaefer model to a coral reef ecosystem in order to assess the impact of a marine

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Table 2. *Fishing grounds of the Lofangan fishermen*

Island	*Land area* $[km^2]$	*Estimated reef area* $[km^2]$
Lofanga	1.46	7.99
Niniva	0.49	4.63
Nukupule	0.03	1.15
Meama	0.00	0.00
Hakauata	0.02	0.94
$\sum$	2.00	14.71

reserve on fish yields. With a reserve size of zero and a fixed carrying capacity of the reef, their model is identical to the specification employed here if α is set to $\alpha := \overline{\alpha}/K$ with $\overline{\alpha}$ being a parameter.

3.3.2. Parameters

Reef area The area of the coral reefs that represent the fishing grounds of the Lofangan fishermen is unknown. The following calculation estimates the size of their fishing area. From Bender (2001: 161) and UNEP and IUCN (1988: 293–296), the islands listed in table 2 are known to be their most important fishing grounds.[3]

Reef area is known for Tongatapu – the island on which the national capital is located. The sum of reef flats and reef slopes amounts to 106.4 km^2 (Felfoldy-Ferguson, 1988: 4) while the land area of the island is 257 km^2 (UNEP and IUCN, 1988: 293–296). For estimating the reef areas around the islands listed in table 2, it was assumed that islands are circular and reefs form a circular ring around an island. An island's reef area is then estimated by the following formula

$$\text{island's reef area} = \text{Tongatapu reef area} \cdot \sqrt{\frac{\text{island's land area}}{\text{Tongatapu land area}}} \qquad (29)$$

Sustainable yields Archaeological evidence suggests that island populations in Polynesia heavily relied on molluscs during the initial phase of settlement. Molluscs were gathered in the lagoons and in the intertidal reef zones. However, growing shellfish scarcity set incentives to expand horticulture and finfish fisheries in later centuries (Dalzell, 1997). Finfish caught by artisanal coastal fisheries has been a resource central to the survival of the populations since then. The following analysis therefore focuses on finfish yields. It simplifies by assuming that the population exclusively relied on finfish and the manufactured good from the time of settlement. As it will become clear in the next section, this assumption is not critical.

[3] Besides these islands, Lofangan fishing grounds include the reef area of Hakau Eiho and the shoals of Lua Fakatele and Lua Faha Lalo. As no data exist on the size of these locations, they are not included in the table.

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The maximum standing reef finfish biomass per unit of reef area is estimated by Dalzell, Adams, and Polunin (1996: 427) as being in the range of 50–100 t/km^2 for coral reef ecosystems in the South Pacific. With the maximum standing biomass in the reef area around Lofanga being assumed to be 100 t/km^2, the carrying capacity of the resource is

$$K = 14.71\,km^2 \cdot 100\,t/km^2 = 1471\,t \tag{30}$$

Dalzell, Adams, and Polunin (1996: 428) estimate sustainable reef finfish yields in the South Pacific to range from 5–20 t/km^2/yr and to represent 5–40 per cent of the standing biomass stock. Therefore, a value of 15 t/km^2/yr is assumed for maximum sustainable yield (MSY) in Lofanga. For a reef area of 14.71 km^2, the intrinsic growth rate of the resource can be computed from (28) as

$$r = \frac{4 \cdot MSY}{K} \cdot 14.71 = \frac{4 \cdot 15}{100} = 0.6\ [\mathrm{yr}^{-1}] \tag{31}$$

Catch–effort relationship According to Bender (2001: 195), 41 Lofangan fishermen catch 3001 kg of fish per week, which amounts to 156 t/yr. Catch per unit of effort (*CPUE*) is then

$$CPUE = \frac{156}{41}\,\mathrm{t/person/yr} = 3.8\,\mathrm{t/person/yr} \tag{32}$$

It is assumed that the standing biomass is 60 per cent of the maximum standing biomass. From (25), the productivity of harvesting is then

$$\alpha = \frac{CPUE}{S^0} = \frac{CPUE}{0.6 \cdot K} = \frac{3.8}{0.6 \cdot 1471} = 4.31 \cdot 10^{-3} \left[\frac{1}{\mathrm{person} \cdot \mathrm{yr}}\right] \tag{33}$$

Three qualifications are in order. First, equation (25) strictly applies only when the resource stock is in equilibrium, which was not necessarily the case when the CPUE data were collected. Second, Bender's catch data are based on estimates the fishermen made in interviews and not on the physical determination of catch weight. Third, the data may give higher weights to harvest rates that prevailed at the time of the interviews, which was from October, 1997 to February, 1998. As this period falls into the 'high season', the values represent an upper bound for average annual catch rates.

Population growth Available archaeological evidence indicates that the islands of Tonga were settled around 1500 BC (Bellwood, 1987). The settlers came in small groups who travelled in canoes from Melanesia. Hence, it is assumed that the initial population on Lofanga was approximately 50 individuals and that settlement occurred in 1500 BC.

The population growth responsiveness parameter ϕ was set to 0.1, which appears to be plausible on the following grounds. Harvest per capita is 156 t/250 persons = 0.624 t/person. With $\phi = 0.1$, an increase in harvest per capita by 25 per cent raises the annual population growth rate by $0.624 \cdot 0.25 \cdot 0.1 = 0.0156$, i.e. by 1.56 percentage points. The crude birth and death rates b and d were set at 2 and 2.1, respectively.

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Table 3. *Parameter values for simulation*

Parameter	r	K	α	β	b	d	ϕ	t
Value	0.6	1471	$4.31 \cdot 10^{-3}$	0.4	2.0	2.1	0.1	0.22

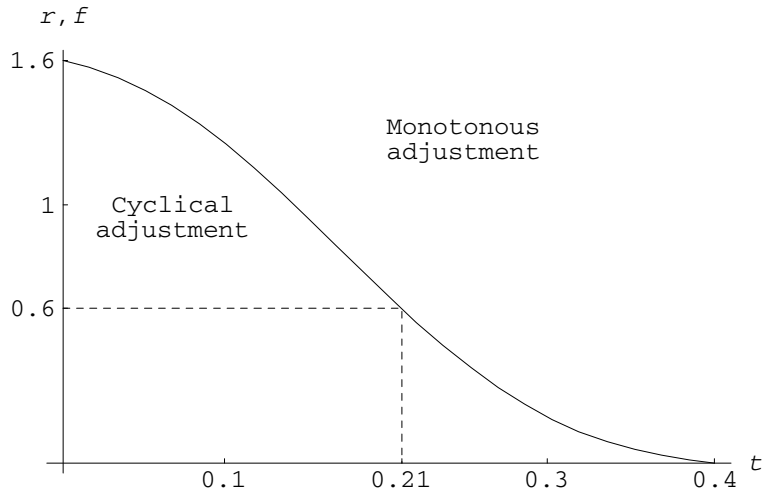


Figure 1. *Adjustment to long-run equilibrium under alternative tax rates t*

Other parameters For other parameters, the specification of Brander and Taylor (1998) has been used. The wage rate w is normalized to one, while the preference parameter (the elasticity of utility of consumption of the resource) β is set at 0.4. Table 3 summarizes the data set used for the simulation experiments.

3.4. Simulation results

As was mentioned in section 2.2, the long-run equilibrium of the model is locally stable for all permissible tax rates if $-1 < (b-d)/\alpha\beta K\phi < -3+2\sqrt{2}$, which is indeed the case as $-1 < -0.39 < -3+2\sqrt{2}$ under the parameter values for Lofanga. Furthmore, it was shown that the dynamic system (12)–(13) adjusts monotonically (cyclically) to its equilibrium at a given tax rate t if the intrinsic growth rate, r, exceeds (is smaller than) the value of the function $f(t)$. Figure 1 shows that, with $r = 0.6$, a tax rate of $t > 0.21$ is required to shift the dynamics from cyclical to monotonous adjustment. However, simulations reveal that cyclical behaviour is not very strong, as the cyclical decline in population at a tax rate of zero is less than 1 per cent of the equilibrium value.

The reason is that the intrinsic growth rate, r, of the resource is high compared with the Easter Island case (see Brander and Taylor, 1998; Chakraborty, 2001). Simulation experiments with lower values of r generate stronger cycles. At the same time, they generate an equilibrium population level that is inconsistent with observed historical patterns (see below).

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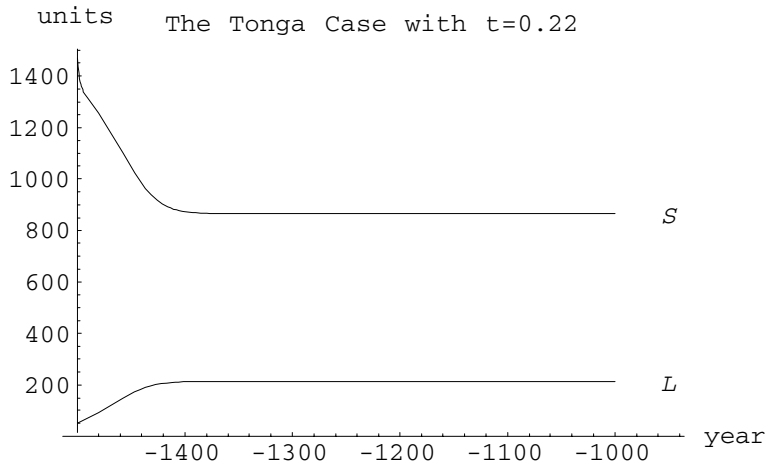


Figure 2. *Evolution of population L and resource stock S at an equilibrium tax rate of T = 45% (negative years are BC)*

Figure 2 shows the evolution of the timepaths of the population and the resource stock at a tax rate of $t = 0.22$, which corresponds to a tax rate of $T = 45$ per cent at the long-run equilibrium. It was assumed that the resource stock was equal to its maximum value, K, at the time of settlement (1500 BC). The equilibrium tax rate of $T = 45$ per cent is consistent with the empirical estimate of the maximum average tax rate of 46 per cent, which was derived in section 3.2.

The model generates an equilibrium population size of 214, which is roughly consistent with the estimated present population of 250 (Bender, 2001: 153). However, it appears to be more useful to compare the equilibrium population size with the population size in the beginning of the twentieth century, which was approximately 200 persons. For population increased subsequently as a result of improved medical and hygienic conditions (Wiemer, 1985: 95). It attained a peak value of 428 in 1976 and has been declining since then as a result of outmigration to Tongatapu (the island where the capital of Tonga is located) and to other countries. At the same time, the income of the present population is augmented by remittances from the migrants, which is not reflected in the model.

It therefore appears to be reasonable to conclude that the model can explain the evolution of the population and the resource stock from the time of settlement until the beginning of the twentieth century. If the implicit tax rate observed at present has been stable for a long time, the model predicts an equilibrium population which is in the same order of magnitude as the estimated historic population size in 1900. The tax rate raises the equilibrium population marginally from 211 to 214. Moreover, it raises the equilibrium resource stock by 49 per cent from 580 *t* to 866 *t* of finfish biomass. According to (5), this corresponds to an increase in individual welfare by 13 per cent. An implicit tax rate that is close to the lower bound derived in section

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3.2, e.g. $T = 23$ per cent, would raise the resource stock by 18 per cent and individual welfare by 6 per cent.

4. Conclusion

This paper has applied a two-sector model of renewable resource use to the island economy of Lofanga in the Kingdom of Tonga. Given the choice of parameters, the model generates a growth pattern which is roughly consistent with the observed patterns of historic population growth and contemporary implicit resource taxation. The implicit resource tax raises both the long-run level of the resource stock and individual welfare. Its impact on the dynamics of adjustment to long-run equilibrium is small however, because cyclical behaviour is weak even in the absence of resource taxation. The reason is that the intrinsic growth rate of the resource is comparatively high.

The simulation was conducted with data that treated Pacific coral reef finfish as a homogenous resource, the dynamics of which can be adequately described by the Gordon–Schaefer model. In this context, three qualifications are appropriate.[4] First, coral reef ecosystems are complex multispecies systems. The specification adopted above ignores changes in catch composition which have a strong impact on the economic value of the catch. Second, is was implicitly assumed that no biological linkages exist between the fishing grounds of the Lofangan fishermen and other coral reef ecosystems. This is not necessarily the case because certain fish species may migrate over large distances during their larval stadium. However, recent research suggests that this effect is not very strong (Cowen *et al.*, 2000). Third, it had to be assumed that the Lofangan fishery was in equilibrium at the time of catch data collection, which is difficult to verify in practice.

Can the results from Lofanga be generalized? As was discussed in section 3.2, sharing rules have been common in the Pacific region for a long time. However, systems of marine tenure and other access restrictions existed as well in earlier times. They were abolished by colonial rulers and national governments or have eroded since the time of first European contact (Johannes, 1978; Ruddle, 1996a). As far as contemporary Tonga is concerned, a case study by Tonga, Naqasima-Sobey, and Quinn (1997) on the island of Hihifo notes the absence of access restrictions, which is indicative of the situation in the country.

In summary, the available evidence indicates that sharing rules coexisted with access restrictions in Oceania for a long period of time and enhanced the resource conserving impact of the latter. Since the time of European contact in Polynesia, however, the burden of marine resource conservation has fallen almost entirely on sharing rules in many locations.

Sharing rules are part of a wider class of rules which may be called consumption rules. In contrast to access restrictions, consumption rules alter the pattern of resource consumption, while leaving access to the resource system and to the resource as such unrestricted. It appears to be a

[4] See Pezzey *et al.* (2000) and Polunin and Roberts (1996) for an overview of problems in modeling coral reef ecosystems.

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promising direction of research to investigate to what extent the exploitation of common pool resources has been regulated by consumption rules.

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