FISH and FISHERIES

Effort rights-based management

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Abstract

Effort rights-based fisheries management (RBM) is less widely used than catch rights, whether for groups or individuals. Because RBM on catch or effort necessarily requires a total allowable catch (TAC) or total allowable effort (TAE), RBM is discussed in conjunction with issues in assessing fish populations and providing TACs or TAEs. Both approaches have advantages and disadvantages, and there are trade-offs between the two approaches. In a narrow economic sense, catch rights are superior because of the type of incentives created, but once the costs of research to improve stock assessments and the associated risks of determining the TAC and costs of monitoring, control, surveillance and enforcement are taken into consideration, the choice between catch or effort RBM becomes more complex and less clear. The results will be case specific. Hybrid systems based on both catch and effort are increasingly employed to manage marine fisheries to capture the advantages of both approaches. In hybrid systems, catch or effort RBM dominates and

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controls on the other supplements. RBM using either catch or effort by itself addresses only the target species stock externality and not the remaining externalities associated with by-catch and the ecosystem.

Keywords Catch rights, effort rights, fisheries management, total allowable catch, total allowable effort

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> It doesn't matter if a cat is black or white, so long as it catches mice.Deng Xiaoping

Introduction

Effort rights-based fisheries management (RBM), an input control, is an important form of fisheries management, even if less widely used than the more broadly employed catch rights, an output control, for groups or individuals (e.g. individual transferable quotas or ITQs). [Note that throughout this document the word 'quota' refers to an allocation to a rights holder from an overall limit, whether total allowable catch (TAC) or total allowable effort (TAE), and not to the limit itself.] Both rights systems were established to address the problems that arise with target species, notably the resource stock externality and accompanying over-capacity and overcapitalization, overfishing, and overfished stocks. (An externality is an unintended and uncompensated consequence of one economic agent's actions upon another economic agent's wellbeing or profitability. The resource stock externality, due to absent or incomplete property rights, leads to overfished stocks and economic inefficiency, Gordon 1954)

The results of this paper, while focused upon effort RBM, should largely hold for other cap-and-trade approaches, such as effort credit systems. Credit systems, arising out of pollution control, are quotas made flexible, and not property rights (Nentjes and Woerdman 2012).

Neither output nor effort RBM was established for the broader goal of ecosystem-based fisheries management (EBFM) or biodiversity conservation, although they both have potential in this regard.

As raised by Emery *et al.* (2012) and as we also discuss in this paper, combined catch and effort hybrid systems, sometimes coupled with area specifications of rights, are emerging to address the multiple externalities associated with EBFM and biodiversity conservation.

Effort RBM has received considerably less conceptual or empirical attention in the literature than transferable catch quota approaches, and the intent of this paper is to close this gap. This paper is the outcome of a workshop held at the University of the Basque Country, September 17–20, 2013, and background papers, published in General Principles and Case Studies from Around the World (2016). We synthesis the workshop results, summarized by Squires and Maunder (2016), conceptual papers (Del Valle and Astorkiza 2016; Hannesson 2016a,b; Segerson 2016; Squires *et al.* 2016b) and case-studies (Caballero-Miguez *et al.* 2016; Clarke *et al.* 2016; Ellefsen 2016; Havice 2016; Hoydal 2016; Maharaj 2016; Sidique *et al.* 2016; Thunberg 2016; Thunberg and Lee 2016) and relevant existing literature, notably Shepherd (2003, n.d.). Specific references to this literature are not, in general, made in this synthesis paper. Many surveys of catch-based RBM abound, notably ITQs, introduced by Christy (1973) and given economic rigour by Moloney and Pearse (1979) (see e.g. Copes 1986; Squires *et al.* 1995; Shotten 2000, 2001; Hannesson 2004; Grafton *et al.* 2006; MRAG 2007 Scott 2008; Chu 2009; Branch 2009; Allen *et al.* 2010; Jardine and Sanchirico 2012; Squires *et al.* 2013; Del Valle and Astorkiza 2016), and of group catch rights (Ostrom 1990; Baland and Platteau 1996; Deacon 2012; Zhou and Segerson 2016; Segerson 2016). This paper does not make specific references to these reviews. RBM, whether through catch or effort and private or group property, may or may not be through comanagement (Jentoft *et al.* 2010), a feature we do not develop further. (Comanagement is a fishery in which the resource user group and governing body share responsibility and authority over the fishery).

The main focus of the workshop was effort RBM for 'target' species, although by-catch, associated ecosystem and biodiversity issues necessarily entered into the discussion. The workshop also did not consider the characteristics and design of a particular property right, such as duration, divisibility, transferability, or methods of allocation, or other issues that arise in the design of rights-based management (see Scott 2008). The workshop also did not explicitly consider RBM in international fisheries, although the results should hold (see Allen *et al.* 2010; Squires *et al.* 2013). The workshop surveyed the practice of, and discussed issues associated with, transferable effort RBM and effort management in general. Strauss and Harte (2013) extensively discuss effort RBM design issues that are especially germane to an actual programme.

All forms of RBM reorient the economic incentives motivating fisher behaviour from the open access, perverse 'race to fish' incentives to incentives that more closely align the private behaviour of fishers with society's desired social–economic–ecological objectives of harvests satisfying a sustainable yield or effort target and sustainable social and economic benefits. Some forms of RBM perform more effectively than others under different conditions, and some forms are more effective in resolving some issues than others. The workshop aimed to compare catch and effort forms of RBM, evaluating their strengths, weaknesses, trade-offs and the conditions under which each might be preferred to the others. Although limited access, including licence limitation and limited entry, is a widely used form of effort management (see Wilen 1988; Townsend 1990 for domestic fisheries and Hallman *et al.* 2010 for international fisheries), this workshop focused upon some unit of time or gear as effort.

Effort RBM programmes represent a major progression from open access and limited entry by providing a more completely structured right through stronger exclusive use of the right by individual firms, vessels or groups. Effort RBM programmes set an annual TAE for the fishery, typically denominated in nominal units of effort such as days at sea, or number of sets of gear, or number of gear, such as pots, traps or hooks. When the TAE is allocated to individuals and explicit transferability of effort rights is allowed between individuals, giving individual transferable effort (ITE), flexibility and economic efficiency increases. Group rights with effective management can give comparable efficiency gains, depending upon their intragroup coordination and organization and upon other factors (see Ostrom 1990; Baland and Platteau 1996; Zhou and Segerson 2016; Segerson 2016). The workshop did not favour individual or group rights for effort or catch, recognizing that the choice between the two depends upon the circumstances.

Effort can be area-denominated (as in the Faroe Islands (í Jákupsstovu *et al.* 2007; Ellefsen 2016; Hoydal 2016), or Malaysia (Sidique *et al.* 2016) to preclude local stock depletion, to protect sensitive areas or to protect particular groups such as artisanal fishers in Malaysia). Area denomination can lead to economic–ecological–social gains through more spatially efficient allocation of effort. Area denomination allows for area closures. Effort can be further denominated and allocated across species and/or gear combinations to realize efficiency gains, and stock and biodiversity conservation, by reducing unwanted by-catch, or by separating different methods of fishing or different groups, or in some instances by preventing localized overharvesting. Effort rights can also be supplemented by technology standards, such as restrictions on gear or fishing practices.

Fisheries management by-catch or effort property rights simultaneously requires estimation of, and management under, a TAC or TAE. Nonetheless, fisheries might simply be managed by TACs or TAEs without catch or effort property rights. When considering catch and effort management under TACs or TAEs as general approaches, RBM can in one sense be viewed as special cases of these two approaches.

Both effort and catch RBM have strengths and weaknesses, and both have the potential to be applied in different circumstances as well as in conjunction with one another through hybrid programmes. Providing an indication of the limitations of pure effort and catch systems, hybrid programmes are increasingly found (Emery *et al.* 2012). The property and use rights are focused on either catch or effort, but they are accompanied by supplementary catch or effort limits. The choice between catch, effort and hybrid approaches to managing a fishery is likely to be best determined on a case-by-case basis. This paper is intended to guide informed choices between catch and effort RBM systems, and to evaluate the trade-offs involved.

Transferability, when allowed, is explicit with individual rights, and is often conducted through secondary markets but also through informal bilateral exchanges. Transferability with group rights can be allowed between groups or occurs solely within the group, with a number of arrangements ranging from informal exchanges to formal exchanges with legally binding contracts.

The balance of this paper is organized as follows. Global effort programmes briefly surveys global effort programmes. Microeconomics of vessel harvesting, economic incentives, law and economics of property rights discusses the microeconomics of a vessel's harvesting process, economic incentives and law and economics of property rights with their implications for catch and effort rights. Technical change and effort productivity differences: 'effort creep' and effective effort considers technical change, catchability and effort productivity (fishing power) differences. By-catch briefly discusses by-catch. Denomination of catch and effort rights considers denomination of catch and effort rights. Allocation and 'over-allocation' discusses allocation. Transition from one system to another and hybrid systems discusses the transition from one system to another and hybrid systems. Nationality restrictions considers nationality restrictions. Multispecies and protected species issues considers multispecies and protected species issues. Spatial management discusses spatial management. Management costs considers management costs. Political economy discusses issues of political economy. Estimating fish stocks, total allowable catch and total allowable effort considers stock assessments and estimation of TACs and TAEs. Formal bioeconomic modelling perspective summarizes implications from formal bioeconomic modelling. Finally, Conclusions provides summary conclusions. The conceptual and case-study chapters in General Principles and Case Studies from Around the World (2016) contain many more details about effort management and associated references.

Global effort programmes

Individual non-transferable effort (hereafter individual effort, IE) and ITE programmes have been applied around the world from the United States and Australia to Estonia and the Falkland Islands on species ranging from groundfish and large pelagic species to squid, scallops and especially shellfish (Table 1). Limits have been applied to a variety of effort measures ranging from days fishing and fleet capacity to traps, and some have been transferable, but others not. Some of these fisheries transitioned to ITQs, although the pot-and-trap fisheries retained many of their ITE features. More details are given in Andersen *et al.* (2016), Caballero-Miguez *et al.* (2016), Clarke *et al.* (2016), Havice (2016), Hoydal (2016), Sidique *et al.* (2016), Squires *et al.* (2016b) (which also gives references to case-studies not

Table 1 Global effort rights-based management programmes.

Fishery	Type of effort	Additional features	Sources
U.S. New England Groundfish	Vessel fishing days	ITE, initial over-allocation of effort, eventually exchanges limited within specified intervals based on horsepower and length, limits to vessel upgrades and effort holdings, indirect effort controls (e.g. trip limits, gear restrictions, time/area closures), majority of fleet transitioned to sector allocation catch share programme	Demarest (2002), Thunberg and Lee (2016)
Faroe Island Demersal Gadoid	Vessel fishing days	ITE combined with area management and mesh size regulations, transitioned from catch quotas to effort quotas	Reinert (n.d.), Thomsen (2005), Nielsen *et al.* (2006), Baudron (2007), Løkkegaard *et al.* (2007), Baudron *et al.* (2010), Ellefsen (2016), Hoydal (2016)
European Union traditional TAC fleet capacity restrictions with sea-day restrictions	Vessel sea days	Hybrid programme of output and effort controls, transferability allowed in some countries and to varying degrees and formality	Daan and Rijnsdorp (2006), Nielsen *et al.* (2006), MRAG *et al.* (2009), Cotter (2010), Khalilian *et al.* (2010)
Iceland Demersal Trawl	Vessel fishing days	ITE introduced in 1977 and employed alongside and as an alternative to ITQs until 1990. No limited entry, annual reductions in each vessel's days	Runolfsson and Arnason (2001), Pascoe *et al.* (2002)
Australian Queensland East Coast Otter Trawl Fishery	Vessel fishing and steaming days	ITE, total effort cap at 1996 less 5% and allocation, limited entry, vessel and gear restrictions, temporal and permanent closures, by-catch controls, no effort banking to the following year. Mandatory Turtle Excluder Devices and Bycatch Reduction Devices. Surrender provisions if replace vessels or licence or transfer effort units. Demersal otter trawl nets, VMS	Commonwealth of Australia (2004c), Government of Queensland (2010), Strauss and Harte (2013)
Spanish Trawl and Longline Vessels (the Spanish '300' Fleet)	Vessel days at sea	ITE, transitioned to hybrid individual transferable quota-days programme in 2007 that is *de facto* largely a group catch right organized around regionally oriented vessel associations	MRAG *et al.* (2009), Caballero-Miguez *et al.* (2014, 2016)
Estonia Coastal Fishery	Number of gear (gear-use rights) per vessel	ITE, plaice, perch, salmon and herring, fyke net and gillnet gear, formal duration of right for 1 year but in practice in perpetuity	Vetemaa *et al.* (2002), MRAG *et al.* (2009), OECD (2009)
Latvian Coastal Fishery	Vessel days at sea	Supplement individual quotas, in principle non-transferable effort, but in practice limited transferability	MRAG *et al.* (2009)
U.S. Atlantic Sea Scallop	Vessel fishing days	IE combined with area management	Georgiana and Shrader (2008), Thunberg and Lee (2016)
Australian Eastern Tuna and Billfish	Number of hooks per vessel	ITE, available effort units based on hooks and location fished, five species allowed for harvesting, gear and closure controls to limit by-catch of sea turtles and sea birds, transitioned to individual transferable quotas in 2011–2012 fishing season	Pascoe *et al.* (2013), Strauss and Harte (2013)
U.S. Hawaiian Pelagic Shallow Set Longline Swordfish	Number of sets per vessel	IE, sea turtle by-catch oriented, non-transferable effort; recently disbanded, and now regulated by sea turtle by-catch limits	Gilman *et al.* (2007), Clarke *et al.* (2016)

Table 1 Continued.

Fishery	Type of effort	Additional features	Sources
Western and Central Pacific Ocean Purse Seine Tuna Fishery	Vessel days	IE, within EEZs of parties to the Nauru Agreement countries for yellowfin, bigeye and skipjack tunas. Resource rent collection and stock conservation primary goals. Vessel days transferable between countries. VMS. To access EEZ, foreign vessels must purchase vessel days	Aqorau (2009), Shanks (2010), Havice (2013, 2016)
Falkland/Malvinas Islands Squid	Vessel days	IE combined with vessel licence limitation programme. Annual holdings adjusted by vessel horsepower and length. Vessel-specific catchability coefficient, *q* used to adjust annual catch entitlements to vessel days for productivity growth. Resource rent collection is primary goal through auctioning and rental fees	Barton (2002), Harte and Barton (2007a,b), MRAG (2007), Maharaj (2016)
Australian Southern Squid Jig Fishery	Gear per vessel	IE, limited entry, 4000 t catch trigger for squid catch, Bycatch Action Plan, effort is squid jig gear	Commonwealth of Australia (2004b), Strauss and Harte (2013)
U.K. Salmon Netting		ITE, net mesh and size restrictions, seasonal closures	MRAG *et al.* (2009)
Canada Area H Johnson Strait Chum Salmon Demonstration	Vessel days	ITE between vessels within a block but not between blocks and only between Area H vessels. Up to one-third unused vessel days could be carried from Block One to Block Two. Since 2008, effort quota stacking, unused effort banking to following year	Pinfold (2009), DFO Canada (2012)
Swedish Gullmarsfjord Shrimp Trawl	Vessel days	IE, 100 days per year per trawler, licence limitation, informal comanagement and local management (allocation) of fishing days to avoid crowding and early fishery closure, combined with TURF	MRAG *et al.* (2009)
Australian Torres Straight Prawns	Hybrid effort per vessel	ITE, limited within season transferable effort, formerly effort was fishing days and now form of effort units and access is as a proportion of TAE in any season, ongoing access rights in the form of units of fishing capacity. Input controls restrict the type of gear and vessel. Mandatory Turtle Excluder Devices and Bycatch Reduction Devices	Commonwealth of Australia (2009)
Australian Northern Prawn	Hybrid individual gear units (headrope & footrope length) per vessel	Limited entry, vessel classes based on vessel volume and engine power, restrictive vessel replacement, vessel buybacks and compulsorily surrendering of vessels. From 1984 to 2000, effort based on engine and vessel capacity. Under effort control, spatial and temporal closures protect habitats, juveniles and pre-spawning animals. Transitioned to ITQs based on maximum economic yield	Kompas *et al.* (2004), Nielsen *et al.* (2006), MRAG (2007), Dichmont *et al.* (2012)
U.S. Outer Cape Cod and Southern New England Lobster	Number of traps per vessel	ITE, commercial lobster fishery in Lobster Conservation Management Areas	Massachusetts Division of Marine Fisheries (2010), Thunberg (2016)

Table 1 Continued.

Fishery	Type of effort	Additional features	Sources
U.S. New England American Lobster	Number of traps per vessel	ITE, federal waters (beyond 3 nm), no leasing, limits on number of licence and traps per person, passive reductions in total traps by levying 'conservation tax' on all trap transfers, limits on transferability	Thunberg (2016)
U.S. Florida Commercial Spiny Lobster Trap	Number of traps per vessel	Two fisheries, ITE, Trap Certificate Program capping total effort, 25% effort reduction with transfers, minimum size, seasons, prohibition on harvest of gravid females and trap size and construction limits	Matthews (1995), Larkin and Milon (2000), Ehrhardt and Deleveaux (2009), EDF (2010), Vondruska (2010), Thunberg (2016)
U.S. Florida Stone Crab Fishery	Number of traps per vessel	ITE, Trap Certificate Program capping total effort, gradual effort reduction, no leasing, biological and input controls for conservation	Matthews and Larkin (2002), Thunberg (2016)
Australian Southern and Northern Zones Rock Lobster	Number of traps per vessel	ITE, effort quota stacking, unused effort banked to following year, subdivided into northern and southern management zones, south transitioned to hybrid ITQ-effort system in 1994 and north transitioned to hybrid ITQ effort in 2003, hybrid systems since ITQs denominated in traps (total quota/total traps), upper limits on ITQ-trap holdings	Borg and Metzner (2001), Morgan (2001c), Sloan and Crosthwaite (2007a,b), Thunberg (2016)
Western Australia Pilbara Trap	Number of traps per vessel	ITE, limited entry, defined fishery area, biological conservation controls, high-value demersal scalefish	Borg and Metzner (2001), Commonwealth of Australia (2004a)
Western Australia Rock Lobster	Number of pots per vessel	ITE, started in 1960s, transitioned to ITQs in 2010 due to economic inefficiency, gear and area restrictions, upper limit on number of traps per person	Morgan (2001a,b), Fletcher *et al.* (2005), de Lestang *et al.* (2008), de Lestang and Barker (2009), Reid *et al.* (2013), Thunberg (2016)
Australian Tasmanian Rock Lobster	Number of traps per vessel	ITE, started in 1972, transitioned to ITQs in 1998 due to effort creep. Under ITQ programme, quota units still enumerated in terms of traps by dividing total quota by number of traps, biological conservation controls	Bradshaw *et al.* (2000), Phillips *et al.* (2002), Bradshaw (2004), Hamon *et al.* (2009), Van Putten and Gardner (2010), Strauss and Harte (2013), Thunberg (2016)
Danish Blue Mussels	Formal vessel licence (Permit), Voluntary fishing days per vessel	Licence limitation, limits on engine power and gross registered tonnage, weekly and daily quotas per vessel, minimum mussel sizes, fishers decide number of fishing days and season start and end	Andersen *et al.* (2015)

ITE, individual transferable effort; ITQ, individual transferable quotas.

explicitly referenced here), Thunberg (2016) and Thunberg and Lee (2016). Table 1 lists the fishery, the type of effort, other notable details and references for the source information. It excludes the hybrid systems of individual quotas (IQs) and ITQs coupled with individual days at limitations found in many Northern European fisheries and increasingly elsewhere and further discussed in Emery *et al.* (2012).

Microeconomics of vessel harvesting, economic incentives, law and economics of property rights

Catch rights programmes are largely preferred from the perspective of the microeconomics of a vessel's production process and the law and economics of property rights, due to catch rights programmes' more comprehensive and stronger characteristics as a right (see Scott 2008 for characteristics) and the superior economic incentives that are created. These factors lead to economic efficiency, minimizing effort usage and costs and matching catches with TACs (but recognizing that the match is not perfect due to discards of quota overages and high grading, whereby higher valued catch replaces lower valued catch). ITQs and group catch rights within the context of TAC management, reflecting their antecedents in the environmental economics literature aimed at controlling pollution externalities, were explicitly designed to overcome the common resource stock externality.

Effort is less well defined and homogenous as an input than catch is as an output. (Here, we discuss effort as nominal and effective effort, rather than fishing mortality.) Effort is ideally a consistent composite input, comprised of all the various components such as various capital stocks, labour, fuel or fishing time, skipper skill, and that satisfies specific conditions (Hannesson 1983). Effort in practice is typically defined as just one of these components and a proxy variable. Effort is often denominated as a measure of fishing time such as days, or one element of the capital stock, usually the vessel or gear such as pots or traps. On rare occasions, effort might be defined as a composite of two inputs such as headrope and footrope length in the Northern Prawn Fishery before transitioning to ITQs (MRAG 2007; Dichmont *et al.* 2012). Controlling a single dimension of effort, say days, leaves unregulated dimensions that can be expanded to increase catch (Pearce and Wilen 1979). The input days is also not homogeneous, with effectiveness varying by vessel according to vessel size, levels of investment, productivity (fishing power) and skipper skill that varies between vessels and other factors (Shepherd 2003; Maunder and Punt 2004). The Faroe Islands addressed this issue as follows (Hoydal 2016, section 5), 'Fishing effort is traditionally estimated by combining available physical measurements of fishing capacity (fixed production inputs) and of fishing activity (variable production inputs). In the Faroese case vessels with similar physical characteristics and fishing patterns were grouped in 11 fleet categories and the partial fishing mortalities were estimated and subsequently the relationship between fishing days and fishing mortality. The number of categories has since been reduced to 7'.

The length of time actually fished during a day can also vary considerably, giving variations in capacity and capital utilization (Kirkley and Squires 1998). This issue affects the parties to the Nauru Agreement (PNA) Vessel Day Scheme (VDS), for example (Havice 2013, 2016). Pot and trap size and design, number and frequency of hauls and soak time are also heterogeneous, so that simply regulating the number of pots or traps does not control effort fully, again due to differences in utilization of capacity and capital. Furthermore, skipper skill can be viewed as one of other unmeasurable inputs that cannot be regulated in effort management (Kirkley *et al.* 1998).

Economic incentives

Effort rights (both individual and group) are weaker than catch rights from the perspective of the law and economics and microeconomics, as effort is less clearly defined. Effort is an input with possibilities for substitution between inputs that are and are not denominated and regulated in the effort definition ('capital stuffing') (Pearce and Wilen 1979). There are also possibilities for increasing effectiveness of effort due to technological progress and investment in physical capital, both leading to increases in effective effort or 'effort creep' (Shepherd 2003).

Effort RBM, in contrast to catch rights, creates incentives to increase input use and costs in an attempt to maximize individual vessel catches and revenues. Given effort (one or more individual inputs), the individual vessel's simple incentive (under certainty) lies in the direction of maximizing catch or revenue. The point is that the incentive is far stronger towards maximizing output and revenue than towards minimizing effort and costs. Adding in uncertainty, skipper preferences, etc., may complicate the incentive, but the major thrust of the incentive created by effort RBM remains towards maximizing catch and revenue. This incentive in turn raises, rather than minimizes, input usage and costs, at least collectively for a fleet as a whole.

In contrast to catch rights, effort RBM does not create incentives to overcome biological overfishing or to minimize costs. For many vessels, trading through markets, or informal exchanges with ITEs or within a group for rights commonly held, can be expected to lead to increases in effective effort (productivity). This in turn leads to increased catches and fishing mortality, as rights gravitate towards more efficient vessels and less efficient vessels drop out of the fishery or fish less. Particularly under conditions favouring effort approaches to management, such as when effort and fishing mortality are proportional, fish stocks can be maintained at desired levels, but weaker incentives are created to maximize economic resource rents compared with catch rights programmes.

In contrast to effort rights, catch rights generate stronger incentives to reduce effort and costs and to increase price. Catch rights thereby increase revenue through improved quality or smoothing out seasonality of production (as there is a limited catch). This was the case in the British Columbia ITQ fishery for halibut, where the key efficiency gains were a more than doubling of ex-vessel price as the fishery shifted from an extremely short season and frozen product to a much expanded fishing season and fresh, higher quality product (Grafton *et al.* 2000).

The effectiveness of economic incentives depends not just on whether the right is defined as effort or catch, but the composition of the rights holders. RBM will align incentives, but in practice the incentives depend on who holds the rights, who the harvesters are and who establishes the rules. For instance, PNA VDS property rights holders are multiple governments, and use rights holders are multiple fishing nations who hold the use right for limited duration (Havice 2016). All PNA parties' interests are to stretch vessel days and to create or maintain over-capacity to increase the derived demand for vessel days. Receipts from this programme are often major sources of government revenues. In contrast, use rights in the Falklands/Malvinas squid fishery are held by a limited number of vessels (individuals or companies), a single government holds the property right, and all parties have the incentive to maximize profits, and in the process maximize the fishery's resource rent (Barton 2002; Baudron 2007; MRAG 2007; Baudron *et al.* 2010; Maharaj 2016).

Substitution of unregulated for regulated inputs

Effort rights create incentives to increase input use by expanding along unregulated dimensions of effort through substituting unregulated inputs for regulated inputs ('capital stuffing'), increasing input utilization (fishing time), replacing inefficient vessels with efficient ones and investment that augments the capital stock (such as more effective gear, electronics) that raise productivity (fishing power) and catchability (Pearce and Wilen 1979; Hannesson 2004, Shepherd 2003). Innovations embodied in the physical capital stock, such as electronics to find fish or gear, are especially important. Comparable incentives exist to expand catches of unregulated species or to discard under catch quotas (catch is not homogeneous over species, sizes, ages, locations, susceptibility to different gears, etc., and consequently neither as regards revenue generation). Incentives are also created for high grading (discarding lower value for higher value fish). Nonetheless, programmes have been developed to create incentives for landing these otherwise discarded fish (Squires *et al.* 1995, 1998; Sanchirico *et al.* 2006).

An effort programme may require limits on vessel size and other forms of capital stock (e.g. gear) to limit input usage, to accommodate replacement of old by new vessels or gear and other upgrades, and transfers of effort rights across gear types. An effort programme limiting time (e.g. days) restricts utilization of capital and capacity. Supplementary restrictions on gear types used, vessel numbers for each gear type, and real-time seasonal and area closures may also be required to maintain fishing mortality levels and species mixes. For example, the United States Atlantic sea scallop fishery has been comparatively successful, not solely due to an ITE system, but also because it is area based (Thunberg and Lee 2016). Over time, restrictions on one or more dimensions of effort can induce a long-term response through technical change, which may be biased towards particular inputs comprising effort.

Technical change and effort productivity differences: 'effort creep' and effective effort

Technical change increases the productivity (fishing power) of nominal effort and thereby increases effective effort and fishing mortality ('effort creep'), compounding the difficulties associated with effort management. Technical change can be implemented through investment that augments the capital stock (i.e. embodied technical change) or technical change can be disembodied (technical change not embodied in the capital stock) through learning by doing (LBD) and using (Solow 1957, 1960; Arrow 1962). (LBD – describes how unit production costs tend to fall and efficiency rises as producers gain production experience. Learning by using, a concept closely related to LBD, occurs during utilization of a product.) Controlling expanding effort due to technical progress is made more difficult because rates of technical progress vary across rights holders depending upon their rates of adoption and diffusion. Accounting for increases in effective effort due to technical progress can therefore penalize those who have not been as effective in adopting new technology and becoming more productive.

Effective effort also varies by the state of technology, where changes in technology are not typically smooth and constant, but instead occur in fits and starts and depend upon the current state of technology. The effectiveness (productivity/fishing power) of effort grows under technological change ('effort creep', increases in catchability), even though the nominal units of effort (e.g. days, number of pots) may remain constant.

When effort rights are defined as levels or nominal units (days, number of gear) rather than shares or proportions of TAE, programme design requires a built-in way to reduce nominal units of effort to match effort holdings with the TAE. When effort is denominated in days, progressive reductions in TAE lead to a growing excess capacity problem, in which there are progressively fewer days available for existing vessels that grow increasingly productive over time through technical progress, increases in technical efficiency and substituting unregulated for regulated inputs. Across-the-board reductions differentially affect vessels, as vessels differ by their state of technology, effectiveness of effort and productivity growth ('effort creep').

In contrast, catch rights systems allow vessels to more directly address increasingly productive effort. A vessel's economic incentive is to reduce costs when utilizing a quota allocated to it. That vessel then has the economic incentive not only to adopt new technology, but also to concomitantly shed variable inputs or even to exit the fishery, thereby reducing variable and/or fixed costs (Moloney and Pearse 1979; Scott 2008). The reduction in fixed costs through smaller fleet size is often the single largest source of cost efficiency gain, rather than gains in economic efficiency through economies of scale, reduction in costs through changes in catch mix (scope economies), improved capacity utilization that lowers unit variable costs and equating marginal costs across vessels (the equi-marginal principle) (Squires *et al.* 2016a,b).

Catch rights and TAC management are not immune from the effects of technical change, however. Technical change does not manifest directly as with effort. Rather, it indirectly shows up in stock assessments (e.g. if catch per unit of effort is used as an index of relative abundance) and TAC forecasts. There is thus 'no free lunch' with technical change, which pops up somewhere, and must be explicitly taken into account at some point. Estimates of the TAE and TAC both require accounting for increases in catchability from technological progress (growth in fishing power/productivity, which manifests as time-varying catchability; Wilberg *et al.* 2010).

TAC and TAE both require acquisition of additional quota as fishing effort becomes more efficient. However, they differ in that with TAC, the need for additional quota is related to the increase in efficiency of the individual vessel. That is, as the vessel more quickly catches its portion of the TAC, the vessel needs more quota, which enables it to more fully utilize the vessel's capacity. In contrast with TAE, the need for additional quota is related to the efficiency of all the vessels as a group. As the group of vessels increases their efficiency, the total amount of effort required to meet the TAE is reduced. The amount of an individual vessel's nominal effort to reach a specified level of catch also decreases, so that the vessel has to obtain more quota to fully utilize its capital stock and capacity.

Effort regulation faces the difficulty in different productivities (fishing power), effectiveness of effort and fishing mortalities by gear, vessel class, area fished, etc. This problem becomes more acute when fishing time, rather than the number of pots or traps, defines nominal effort. Clearly, a day fished by a vessel of one gear type can vary considerably in effectiveness from another gear type, or even within a vessel size-class and gear type. Different levels of fishing technology then lead to different effectiveness between vessels. The PNA VDS distinguishes purse seine vessel days by vessel size-class, and effective effort between gears can be standardized (Havice 2013, 2016). Units of exchange different than one to one can be imposed between different gears–vessel size-classes. Exchange can also be prohibited, although the latter runs the risk of creating a limited number of buyers and sellers, or thin effort markets and monopoly powers, or lower gains from trade, thereby increasing economic inefficiency.

By-catch

Both catch and effort rights systems can address 'by-catch'/incidental catch and ecosystem issues. Transferable by-catch rights or broad-based ITQ programmes directly address by-catch issues. Transferable effort through a limit on sets was part of an integrated package, along with caps on total turtle takes for leatherback and loggerhead sea turtles, in the Hawaiian shallow set pelagic longline fishery for swordfish (Segerson 2011; Clarke *et al.* 2016). The effort limit was eventually dropped, after it was considered redundant to the turtle caps.

Hybrid programmes of effort and by-catch catch rights or effort and area rights or time–area restrictions are possible (Emery *et al.* 2012). By-catch rights become more complex when the by-catch is a rare event, such as some species of sea turtles (Segerson 2011). By-catch may become more influential when the target catch rates are low (e.g. for high-value species such as bluefin tuna). In this case, effort limits may need to be added in addition to target species catch limits to limit by-catch, forming a hybrid programme. As with quota overages, programmes have been developed, which create incentives to land by-catch, such as deemed values in New Zealand (a two-part policy instrument, comprised of the quota and a payment to fishers in principle equal to their marginal costs to incentivize landing catches that exceed the allowed quota, rather than discarding the quota overages at sea) (Squires *et al.* 1995).

Denomination of catch and effort rights

Both catch and effort rights systems can specify rights as shares (proportions) of the TAC or TAE rather than in nominal units, such as kilograms or metric tonnes of allowable catch or kilowatt-days of allowable effort. When catch and effort are denominated in shares, multiplying each right holder's TAC or TAE share by the TAC or TAE gives the catch or effort quota in nominal units. Changes in TAC or TAE then automatically lead to changes in each rights holder's amount of catch that can be landed or nominal effort that can be applied in each time period. When rights are denominated in nominal units rather than shares or proportions of TAC or TAE, the total catch or effort rights sum to the TAC or TAE. When the TAC or TAE is reduced, the total amount of excess rights must be bought or by some other means reduced to match the decrease in TAC or TAE. When the TAC or TAE is expanded, additional rights must be created and allocated.

Catch rights programmes are now universally defined as shares of the TAC, to allow automatic adjustments in individual vessel or group levels of catches with changes in the TAC and because units of catch are readily defined and divisible into small units. There are a few exceptions, such as the South African west coast rock lobster fisheries, which is area and individual quota based with rights durations of 4 years (RSP 2001, 2016). Here, through a buffering system for holders of smaller shares, catch quotas are changed less frequently than for the larger commercial companies as the TAC changes in response to resource trends.

Effort RBM programmes have always been denominated in nominal units. The reason may in part be limited divisibility of nominal units of effort, where units of capital, such as pots or traps, are lumpy and heterogeneous in effectiveness. In this case, effort is inherently defined in terms of units of the lumpy, heterogeneous capital. In contrast, effort defined as days or number of sets lends itself to a right defined as a share due to the divisibility of such effort. Effort defined not as shares, but instead as nominal units, is susceptible to continual increases in effective effort and initial 'over-allocation', a topic to which we turn next.

Allocation and 'over-allocation'

Both effort and catch rights programmes face the issue of 'over-allocating' individual or group rights. The tendency is to assign each right's recipient the share that corresponds to that recipient's maximum catch or effort, as long as: (i) rights are denominated in shares; (ii) the rights programme is entered into cooperatively rather than imposed from above; and (iii) rights are allocated on the basis of the usual approach of historical participation ('grandfathering'). Such an allocation helps achieve cooperation among all the participants, since in the early time periods during which the agreement is made, all parties are better off and no individual party (individual or group) or coalition of parties is made worse off (Barrett 2003). This is particularly important in international RBM, where (i) the catch or effort right is coupled with the right to fish in national Exclusive Economic Zones (EEZs) and the high seas under the auspices of a flag state that is a member or cooperating non-member of a Regional Fisheries Management Organization, and (ii) agreements are inherently voluntary and self-enforcing (Barrett 2003; Allen *et al.* 2010; Squires *et al.* 2013). Moreover, grandfathering rights to local users, when the allocated right matches the TAC or TAE, can be more efficient over time than auctions of such rights by raising expected rates of return for investment, lowering the cost of capital and providing incentives for collective action (Anderson *et al.* 2011).

When nominal units of effort, not shares, are allocated through grandfathering, the conditions for cooperation can potentially lead to an actual 'over-allocation' of effort, in which the allocated total amount of nominal effort exceeds the optimal TAE based upon mortality. This 'over-allocation' arises because in a fishery that initially has overcapacity, the only way that all parties and coalitions of parties can gain and none lose is to borrow fish from the future. Higher discount rates aggravate the problem, as the future is valued less than the present. 'Over-allocation' of catch is potentially more detrimental to the stock than over-allocation of effort, as for the later, the catch will reduce with the population size.

Transition from one system to another and hybrid systems

A rights system may start out as an effort right and transition into a catch right or vice versa, or transition into a hybrid system. The Australian Northern Prawn Fishery has examined and could shift to an ITQ programme from a limited entry programme with vessel size limits, but has not yet made the transition. The United States New England groundfishery is transitioning from a vessel day effort system to a catch quota system that includes group rights (sector allocations) (Thunberg and Lee 2016). Four Australian rock lobster fisheries transitioned from tradable traps to an ITQ system (Strauss and Harte 2013; Thunberg 2016).

The tendency in the Australian tradable trap systems was for the quota unit to be denominated on a per trap basis (by dividing total quota by total number of traps) (Thunberg 2016). With this denomination, the system became a hybrid ITQ-effort system that retained a legacy of the ITE system. The transition to an ITQ system in the Australian rock lobster fisheries was intended to reduce the economic inefficiencies associated with the mounting number of input restrictions needed to maintain objectives of biological sustainability, rather than inability to control total effort or achieve sustainable harvest levels (Strauss and Harte 2013; Thunberg 2016). The Spanish '300 fleet' harvesting groundfish on the Gran Sol fishing grounds transitioned from an individual days-at-sea programme with limited transferability to a hybrid ITQ-days programme, with effort denominated in kilowatt-days, that is *de facto* largely a group catch right organized around regionally oriented vessel associations (Caballero-Miguez *et al.* 2014, 2016). The Faroe Islands effort rights systems voluntarily transitioned from a catch rights system, due in part to difficulties in forecasting TACs and managing a multispecies fishery by-catch quotas for individual species (Hoydal 2016).

Hybrid systems are individual or group rights complemented by effort restrictions and vice versa, that is effort rights systems supplemented by-catch quotas, notably for by-catch, or catch rights systems supplemented by effort limits (Emery *et al.* 2012). An example is the South African south coast rock lobster fishery, which combines a TAC, individual quotas, and a TAE in the form of limited number of fishing days in a season (OLRAC 2014). A number of the transferable effort programmes that transitioned to ITQs, notably the Australian pot-and-trap programmes, effectively became hybrid systems by retaining elements of previous effort management regimes or even denominating quotas on a per unit of effort basis.

A single policy instrument, such as catch or effort quotas, may be insufficient to address all policy concerns. Multiple externalities, such as the common resource stock externality (Gordon 1954), gear/mesh size externalities (Turvey 1964), the crowding externality (Smith 1968) and ecosystem externalities (Finnoff and Tschirhart 2003), imply multiple market failures, which in turn require multiple policy instruments to correct the externalities, as long as these the externalities are not linked (Tinbergen 1952). As noted, catch rights developed as a response to the resource stock externality that arises from absent or incomplete property rights, and as such, they do not solve growth or biodiversity and ecosystem externalities. Effort restrictions have been introduced as a complementary measure to limit by-catch, discarding and quota overages, creating hybrid systems. Effort rights, while not addressing the resource stock externality as directly as catch rights, may, by their very bluntness and focus upon fishing mortality, be superior (even if not precise) at addressing part of the ecosystem externalities. Nonetheless, neither right is designed as an instrument of conservation *per se*. The complexity of EBFM may also lead to hybrid systems of catch and effort, perhaps denominated by area, with either catch or effort the paramount approach. This is supplemented by the other, and complemented by command-and-control measures such as time–area closures, technological change that is by-catch reducing or habitat preserving, technology standards such as mandated gear and operating procedures and other measures. Habitat rights might also be added to the mix (Holland and Schnier 2006). Emery *et al.* (2012) provide further discussion and examples.

Effort rights may also be combined with territorial rights to form a hybrid system. In some sense, the VDS is such a system, in which shares of overall Western and Central Pacific Ocean tuna TAE are allocated to PNA states, where TAE share amounts are a weighted combination of historical catch and the biomass in the individual PNA EEZs (Havice 2013, 2016). The PNA states in turn lease vessel day use rights to distant water fishing nations. Hybrid effort–area rights systems are also found for pot, trap and shellfish fisheries, such as management of lobster pots and traps in the Northeast United States, where informal territorial units emerged (Acheson 1975). The Atlantic scallop days-at-sea programme was combined with area management (Thunberg and Lee 2016), as was the Faroe Islands groundfish effort programme (Ellefsen 2016; Hoydal 2016).

Nationality restrictions

Common to virtually all RBM programmes is some type of nationality restriction. When RBM is extended to the international arena, the issue of sovereign rights that can be obtained by nonnationals becomes important (Allen *et al.* 2010; Squires *et al.* 2013). The catch or effort right is implicitly bundled with a national right of access to an EEZ and to the high seas. The PNA VDS, even though an effort RBM programme in an international fishery, still allocates effort to national EEZs, where the TAE shares are allocated to PNA states and in turn to individual vessels, sometimes mediated through their flag state's government, the standard form of allocation with international fisheries (Grafton *et al.* 2010; Squires *et al.* 2013, Havice 2016). In the Falklands/Malvinas squid fishery, effort rights are allocated to companies owned by Falkland/Malvinas residents (Maharaj 2016).

Multispecies and protected species issues

Both effort and catch quota management become more complicated and difficult in multispecies fisheries (where catch is not homogeneous). Multispecies fisheries under multiple quotas face the well-known problem of matching TACs with stock productivities, and the potential for under- or overharvesting one or more species, discards at sea, and misreporting. ITQ programmes, as noted, have developed a number of approaches to address this issue (Squires *et al.* 1995, 1998; Sanchirico *et al.* 2006). ITEs, such as transferable days, face difficulties in matching overall TAE with sustainable catch rates, again with the potential for under- or overharvesting one or more species, leading to supplementary regulations such as area management, gear restrictions, as discussed elsewhere.

By-catch of protected species such as sea turtles, birds and sharks is likely to be independent of either system, and is one reason why hybrid systems are emerging.

Spatial management

Although time–area restrictions and closures or spatial management can contribute to both catch and effort RBM, they may be especially important in effort management when there are not any direct controls upon catches. Area management can be important to separate gear types and vessel classes, to preclude local stock depletion, to protect sensitive habitat, to protect or favour groups of fishers deemed socially desirable and to protect species for both target catch and by-catch and effort management. Area management may be even more important in effort RBM compared with catch RBM, as the control over catch species is more indirect and hence less sure.

Both the Atlantic sea scallop and the Faroe Islands programmes combine days with area management (Ellefsen 2016; Hoydal 2016; Thunberg and Lee 2016). Incentives could also be applied to attract effort to particular areas. The Faroe Islands' ITE quota system provides incentives for vessels to fish in offshore areas by allowing each quota day to equal three fishing days in these areas (Jakupsstovu *et al.* 2007). Variable penalty systems, such as a series of differential hook penalties, can provide incentives for fishers to redirect their effort away from problem areas (Pascoe *et al.* 2013).

Management costs

Management costs need to be factored into the overall benefit–cost equation for choice between catch or effort systems to determine whether the net benefits favour catch or effort RBM. There may be fisheries where catch quota management is preferred on biological and economic efficiency grounds (at the vessel level), yielding the greatest economic net benefits compared with controlling fishing mortality at the desired level. The overall net benefits include the overall costs of monitoring, control and surveillance (MCS) of catches or effort, enforcement, data collection, stock assessments and other governance issues. Including these costs in any overall assessment of catch vs. effort RBM could either reinforce or tip the balance of the net benefits between the two systems. These additional costs are less readily apparent or tend to be borne by the public rather than harvesters. As such, they are typically overlooked or downplayed and are not factored into the choice between effort and catch rights-based management.

Catch can sometimes be more challenging to monitor than effort, especially if it is landed under 'informal' circumstances, to say nothing of discards at sea. More complex multispecies and/or transboundary fisheries can be costly to monitor. In contrast, effort is sometimes easier and cheaper to monitor, through counting vessels, tracking vessels through electronic vessel monitoring systems, use of logbooks, etc. rather than at-sea observers and reconciling landings with observer records.

Stock assessments in catch-based programmes can be costly and for a variety of reasons. For example, stock assessments in which fishery-independent data, collected by at-sea sampling on cruises, coupled with supporting life-history laboratory work, are expensive and require considerable costly scientific and logistical infrastructure.

In sum, when overall net benefits that include costs of management and governance are factored into the overall net benefits in choosing between effort and catch RBM, the greater economic efficiency at the vessel level for catch systems may (or may not) be countered. The overall net benefits between catch and effort RBM should factor in all costs and benefits and are not always clear.

Political economy

There may be fisheries in which either effort or catch quota management is more suitable on the basis of biology, economic efficiency and management costs. Nonetheless, the political economy of reaching and sustaining agreement among participants, and governance of the fishery, might favour the alternative RBM approach. Governance is likely to be easier and less expensive in effort RBM, as there are generally fewer detailed and/or less expensive management restrictions. For example, ITQs require more comprehensive and generally expensive MCS and stock assessment requirements for each TAC-regulated species, and may require at-sea observers and onshore catch-and-quota balancing. In contrast, effort MCS is more readily confined to inspections of gear and/or electronic vessel monitoring systems.

One reason for effort rights in the Falklands/Malvinas squid fishery is trans-shipment at sea, which can be difficult and costly to monitor and police (Maharaj 2016). A number of ITQ programmes that transitioned from ITE programmes retained many features of the ITE programmes, reflecting the dependency of current and future events upon the past, that is upon path dependency.

Estimating fish stocks, total allowable catch and total allowable effort

Under the objective of controlling fishing mortality, the aim is to keep the stock at a productive level. Effort management then directly relates to fishing mortality, whereas catch management less directly relates to fishing mortality. On this point, Shepherd (2003, p. 2) observes, '…in adopting effort control we would be accepting that fine-tuning the management of individual stocks in a fishery is impossible, and that effective but broad-brush control would be preferable to the apparent (but actually ineffective) precision management using TACs and quotas'. We now discuss this point in more detail.

Unless there are mechanisms present that introduce nonlinearities into the relationship, effort management defaults to a constant fishing mortality rate. In the case of constant effort quotas, as the biomass fluctuates the catch realized from the effort will also change (catch increases when biomass increases and vice versa), giving automatic feedback control. Hence, when the abundance declines or increases, the catch will correspondingly decrease or increase. However, in the case of constant TACs, as the biomass declines (perhaps due to an environmentally reduced series of recruitments) fishing mortality will increase, which is not desirable, as it may result in a highly depleted stock. Thus, the within-the-period self-correcting mechanism of the effort quota management reduces the risks of both underutilization and over-exploitation. On this point, Shepherd (2003, p. 1) summarizes: 'Under an effort control system it is no longer necessary to predict the fishable stock size accurately every year to fix a TAC, as the level of fishing mortality is restrained directly, irrespective of the continual fluctuations of stock size, by controlling the level of fishing effort, which need only be adjusted occasionally and progressively in order to achieve medium-term management objectives. The landings would of course continue to vary with the natural fluctuations of stock size, but this would occur automatically and they would not need to be predicted in advance'. Conversely, some form of harvest control rule, which may involve estimating the abundance, is needed to modify the catch to avoid endangering the stock in the catch quota approach. There may be delays in implementing the new catch quota. These concerns strengthen with increasing stochastic variation in the stock size.

Both effort and catch-based quotas require the estimation of TAC or TAE, so that issues arising with estimation of biomass and TACs or TAEs, and management by TAC or TAE, are an important consideration in the choice between the two RBM approaches. As we shall see, catch RBM under a TAC requires an estimate of the absolute level of biomass, while effort rights-based management under a TAE requires an estimate of the catchability coefficient. These differences can be illustrated by the simple equation that relates catch (C) to effort (E) and biomass (B) through the catchability coefficient (q):

$$C = qEB.$$

Here, fishing mortality (F) is equal to the product of q and E (in this case, F is used as an exploitation rate rather than an instantaneous fishing mortality to simplify the illustration).

Take a hypothetical case where the TAC is set using the fishing mortality corresponding to maximum sustainable yield (F_{msy}) such that $C = F_{msy} \times B$. In this case, both F_{msy} and B need to be determined. These are generally estimated using a stock assessment model.

F_{msy} is determined from the assumptions about the population (e.g. form of the growth and stock–recruitment curves) and fishery (e.g. form of the selectivity curves) dynamics and the predetermined or estimated parameters (e.g. natural mortality, growth rate, stock–recruitment steepness, selectivity) and is typically independent of absolute abundance. (The steepness of a stock–recruitment curve is the fraction of the average recruitment at pristine spawning stock biomass that occurs when abundance is reduced to 20% of that pristine level.) It may not be necessary to accurately estimate F_{msy} for use in management. For many species, the stock–recruitment relationship is weak (the steepness of the Beverton–Holt stock–recruitment relationship is high and recruitment is virtually independent of stock size). This means that the yield curve is similar to the yield-per-recruit (YPR) curve. It is well established that the YPR curve is rather flat as a function of fishing mortality for many species, so that fishing at a rate somewhat less than (or greater than) F_{msy} will produce similar equilibrium yields. However, dynamic yields may be very different.

Estimates of both TAC ($C = F_{msy} \times B$) and TAE ($E = F_{msy}/q$) require estimation of F_{msy}, and therefore, the difference between the two approaches lies in the accuracy of estimating the absolute level of biomass B (for catch quotas) vs. the catchability coefficient q (for effort quotas). In reality, both B and q are not known exactly. Measures of absolute B are required for catch quotas and q is required for effort quotas.

The absolute level of abundance B (the 'scaling' of the stock assessment model) is notoriously difficult in many assessments (Maunder and Piner

2015), where we note that absolute levels of biomass are more difficult to estimate than depletion relative to some target level, that is relative changes. Biomass estimates are a function of all the model assumptions and data, but are generally driven by the influence catch has on abundance indices and how many old fish are in the catch. In contrast, an effort quota based on F_{msy} is calculated as $E = F_{msy}/q$ and, when applied to the stock, automatically takes the true B into account resulting in the C. The evaluation of effort-based quotas can be implemented by estimating F/F_{msy} in a stock assessment model, which may be more robust to the scaling issue. In equilibrium, error in F/F_{msy} is more robust than error in C/MSY in terms of catch due to the flat yield curve and less risky in terms of unintended depletion.

Difficulties arise in estimation of biomass and TACs. B and q are seldom known with great certainty. The catchability coefficient q may change over time randomly (e.g. due to environmental influences) or systematically (e.g. due to improvements in technology, giving time-varying catchability) or both. Failing to account for improvements in technology will cause the fishing mortality to increase over time. Catch may be a nonlinear function of effort or biomass, $C = qE^aB^b$, and may stay high even if the biomass declines because the fishery can find schools of fish ($b < 1$). Competition among effort (crowding external cost) may cause increased effort to not produce the same proportional increase in catch ($a < 1$) (Hannesson 1983). Conversely, with investment in physical capital that embodies new technology, there can be non-trivial knowledge external benefit as fishers learn about new technology and how to use it, which leads to increasing returns ($a > 1$) (see Arrow 1962; Romer 1986).

There are several other reasons why a stock assessment may not be accurate:

1. Estimation uncertainty (low sample size, not the right data)
2. Process variability and uncertainty (e.g. in recent recruitment)
3. Model misspecification (incorrect fixed parameter values or model structure)
4. Biased data (e.g. under-reported catch)
5. Programming/logic errors.

The factors above can introduce bias or variance into the biomass B and F_{msy} estimates and hence TAC estimates. If the variance is accurately estimated, it can be taken into consideration when setting the TAC. However, some of the sources of variance are often ignored (e.g. when influential parameters such as natural mortality are pre-specified). In addition, there are errors in implementing the catch or effort limits. For example, catch may be misreported or vessels could add additional catching capacity.

Effort management may be more effective at managing fishing mortality when there is (i) a clear and direct link between effort and fishing mortality as a result of minimal uncertainty or stochastic variation in q, and a TAE may be more effective by directly acting on F; (ii) high unpredictable annual recruitment variation and a short-lived species (i.e. few cohorts comprising the population), leading to stochastic variation in the fish stock B; (iii) low availability or low quality of data that relatively affects estimation of B more than q; (iv) uncertainty in the estimates of biomass B and the TAC is more important than uncertainty in the estimates of the catchability coefficient q and the TAE; and (v) there are relatively infrequent stock assessments (relatively frequent, if not annual, assessments are required for TACs), or there are difficulties in conducting rapid, within season, stock assessments for short-lived species such as squid. These conclusions are some of the key results of the workshop.

TAC and catch RBM may be favoured when there are a high number of age classes and/or low recruitment variability in the fishery, as stochastic variation and uncertainty together with annual changes in the biomass are minimized. In this case, the biomass and hence TAC are comparatively stable, and there is substantially reduced uncertainty in stock assessments. TAC and catch RBM are also favoured when there is more uncertainty in q or the catch–effort relationship. TAC and catch quota management may also be favoured (if all other factors are held constant) when quotas are transferable across disparate gear types, thereby reducing the problems of standardizing effort and finding a stable unit of account for effort. These conclusions are also some of the key results of the workshop.

The size composition of the catch can change the effectiveness of the TAC and TAE. Catching the same tonnage of small fish has a different impact on the population than catching that tonnage of large fish. Similarly, the same effort on small fish has a different impact on the population than that effort directed at large fish. TAE has the additional complication that small and large fish may have different catchabilities. Measures that relate the catch to its impact on the population, such as spawning biomass per recruit, might be needed to transfer catch among vessels, gears or errors. In essence, catch is not homogeneous.

Formal bioeconomic modelling perspective

From the formal bioeconomic modelling perspective, no clear advantage exists for either TAC or TAE approaches that always hold under all conditions (Danielsson 2002; MRAG 2007; Kompas *et al.* 2008; Yamazaki *et al.* 2009). Rather, the use of TAE or a TAC depends critically on the source of uncertainty in these models. If there is a good deal of environmental uncertainty in abundance, an MEY target will be best achieved with a TAE. If most of the relative uncertainty is in the harvest function, a TAC is preferred.

Both approaches maximize economic rents, although the TAC optimum may exceed the TAE optimum if the latter's bioeconomic model accounts for the growing economic inefficiency due to 'effort creep'. The sources and extent of uncertainty determine which is more advantageous. The principal causes of uncertainty are (i) unexpected realizations in terms of the stock size (including the stock–recruitment relationship), such that the TAC is set at too high or too low a level and (ii) unexpected realizations in terms of the catch–effort relationship, such that the TAE is set at an inappropriate level. On this point, MRAG (2007) states, 'If environmental uncertainty is high, (or, in some contexts, where there is large variance in the stock-recruitment relationship), compared to the variance in catchability, then input controls will be preferred. If the reverse holds, output controls are the better choice (although it should be noted that this conclusion ignores the increase in estimation/implementation error that is likely with output controls)…If there is a good deal of environmental uncertainly, setting catch will likely miss the target, with lost profitability in years when abundance is especially high…'.

Conclusions

In sum, the choice between catch or effort RBM essentially comes down to three factors: economics, biology and the political and policy climate. Table 2 summarizes the advantages and disadvantages of catch and effort systems, with some repetition due to fleshing out some of the more general conclusions, that is the specific conditions under which more general conclusions hold. The following discussion provides details.

Effort RBM may be more effective at managing fishing mortality when there is uncertainty in the estimates of biomass and TAC, and catch RBM is more effective when there is uncertainty in the catchability coefficient estimate and the relationship between catch and effort (Danielsson 2002; MRAG 2007; Kompas *et al.* 2008; Yamazaki *et al.* 2009). Catch rights generate stronger incentives to reduce effort and costs and to increase price and thereby revenue through improved quality or smoothing out seasonality of production (as there is a limited catch and season length can be extended as in the British Columbia ITQ for halibut; Grafton *et al.* 2000). Effort rights create incentives to maximize revenue and catch, and in the process create incentives to expand input use and costs and adopt new technology to increase productivity.

Effort RBM may therefore require continued adjustment in the TAE and input controls to counter ongoing increases in uncontrolled inputs, including vessel size, increased productivity (fishing power) due to technological change, and more efficient fishers replacing less efficient ones, and monitoring increases in productivity. Effort RBM creates weak incentives to shed capacity. Catch RBM requires monitoring the population and catches, control of catches and dealing with catches in excess of quotas (e.g. through high grading and discards).

In a narrow economic sense, catch RBM is superior due to the incentives it creates at the vessel level. However, once the costs of research to improve stock assessments, the associated risks of error in determining the TAC, and costs of monitoring, control, surveillance and enforcement are taken into consideration, the choice between catch and effort controls and rights becomes more complex and less clear. The results will be case specific and depend upon the political economy and governance of the situation, including who gains and losses.

Hybrid systems comprised of both catch and effort rights and controls, and in some cases combined with area management, are increasingly

Table 2 Advantages and disadvantages of catch- and effort-based management systems.

	Catch	Effort
Economic advantages		
Incentive to minimize effort and harvest costs	✓	
Incentive to maximize catch price through catch quality	✓	
Costs of MCS, stock assessments, management		✓
Economic disadvantages		
Incentive to increase effective effort and costs		✓
Effort creep through technological progress		✓
Effort creep through substituting unregulated inputs for regulated inputs		✓
High grading and quota overage discards	✓	
Continued adjustment in the TAE and input controls to counter ongoing increases productivity (fishing power), i.e. 'effort creep'		✓
Greater monitoring of the population and catches and control of catches are required	✓	
Incentive to maximize catch without regard to sustainability		✓
Biological advantages		
Complex multispecies fisheries in developing countries		✓
Artisanal fisheries		✓
General uncertainty over biomass and TAC estimates		✓
Highly variable stock–recruitment relationships and subsequent high stochastic variation and uncertainty in resource stock		✓
Uncertainty about catchability coefficient value	✓	
Escapement is important		✓
Automatic feedback with respect to changes in abundance		✓
Data for stock assessments and close monitoring of catches are largely unavailable or of low quality		✓
Estimates of F/F_{msy} are more robust than those of C/MSY		✓
High number of age classes and/or low recruitment variability in fishery	✓	
Quotas are transferable across disparate gear types	✓	
Heterogeneity in size composition of catch		✓
Environmental uncertainty is high compared with variance in catchability		✓
Biological disadvantages		
Harvest control rules are required	✓	
Estimates of absolute biomass abundance needed	✓	
Catch may be a nonlinear function of effort or biomass	✓	
Highly unpredictable annual recruitment variation and short-lived species leading to stochastic variation in the fish stock	✓	
Relatively infrequent stock assessments	✓	

MCS, monitoring, control and surveillance; TAC, total allowable catch; TAE, total allowable effort.

employed to manage marine fisheries to capture the advantages of both approaches (Emery *et al.* 2012). These also address the multiple externalities emanating from multiple species, biodiversity conservation and EBFM, with one approach forming the dominant management system. The form of rights-based management cannot be separated from the choice of TAC or TAE management, which is a key conclusion of the workshop and this paper.

Effort rights-based management has clear advantages for (i) complex multispecies fisheries in developing countries (especially with complex tropical multispecies ecosystems); (ii) artisanal fisheries; (iii) when TAC-based management is more difficult and expensive, and stock assessments are difficult; (iv) data for stock assessments are largely unavailable or of low quality and close monitoring of catches is problematic or costly; (v) MCS costs for catch systems are prohibitive; and (vi) uncertainty over biomass estimates is paramount.

Effort management is widely applied in pot-and-trap fisheries, where the link between effort (number of pots and soak time) and mortality is relatively direct, managing pots and traps can be more cost-effective than managing catches, and incentives can be clear to fishers given the importance of territoriality where fishers deploy their pots and traps. Pot-and-trap fisheries are typically used for benthic and demersal species. Even when pot-and-trap fisheries have transitioned to ITQs, the ITQs are often denominated in units of pots and traps, so these ITQ programmes are still closely linked to, and path dependent upon, ITE programmes. There may also be elements of fisher territoriality in these fisheries, which favours effort management, as fishers can readily monitor and control the numbers and locations of pots and traps, and the relatively clear spatial dimension and number of gear confer a relatively strong sense of exclusivity of the right. In this case, there can be a close relationship between effort management and territorial use rights for fisheries (TURFs) (See Christy 1982 for TURFs and Acheson 1975 for a nice example of informal area rights). Effort management, perhaps in a hybrid system with territorial rights, may also be favoured for shellfish fisheries, such as molluscs, for the same fundamental reasons as for pot-and-trap fisheries.

Effort management has advantages in fisheries on short-lived species with highly variable stock–recruitment relationships and subsequent high stochastic variation and uncertainty in resource abundance, such as for shrimp, squid and some small pelagic species. Effort management is typically applied when escapement is important, such as for salmon. With such fisheries, where the river of origin is important, effort can be targeted at specific rivers and regions. In contrast, catch at sea is difficult to directly relate to the river of origin – unless catch quotas are allocated and applied to each river or to areas and quotas are enforced at this point.

In some situations, it may not be possible to calculate MSY-related quantities or the current stock status, so that optimal management may not be possible. In these cases, if all stakeholders are satisfied with the current state of the fishery, it may be reasonable to keep things as they are. The use of TAEs would be less risky as they have automatic feedback with respect to changes in abundance. Management may only need to keep an eye on ‘effort creep’ or monitor relative fishing mortality, which is easier to estimate than absolute fishing mortality.

Catch rights programmes provide advantages from the perspective of the microeconomics of the vessel’s production process and the law and economics of property rights. These advantages are due to the superior economic incentives they create for greater economic efficiency from vessels minimizing costs and effort and to match catches with TACs. A related factor is the difficulty in defining and measuring effort compared with catch that contributes to ‘effort creep’, in which effective effort expands due to substitution of unregulated inputs for regulated inputs and disembodied and embodied technological change, boosted by the knowledge externality. Catch rights programmes do not face the need for continued reductions in TAE and tightening of input controls, or even implementation of new input controls, to counter increased input usage and technological progress. TAC and catch rights-based management can provide advantages when there are a high number of age classes and/or low recruitment variability in the fishery for a number of reasons: (i) stochastic variation, uncertainty and annual changes in the biomass are minimized; (ii) the biomass and hence TAC are consequently comparatively stable; and (iii) there is substantially reduced uncertainty in stock assessments and TAC forecasts.

The critical effort management issues for other fisheries outside of MCS, enforcement, stock assessment costs and political economy include the following: (i) a standardized and agreed upon measure for the relationship between fishing effort and fishing mortality. This in turn reflects the two principal sources of uncertainty: (i.a) unexpected realizations in terms of the stock size, such that the TAC is set at too high or too low a level and (ii.b) unexpected realizations in terms of the catch–effort relationship such that the TAE is set at an inappropriate level), including technical change, and for effort itself; (ii) the greater difficulty in effort systems to inherently address overcapacity growing through investment, input substitution, increased input utilization (fishing time) due to substantially weaker effective incentives to minimize effort and costs than catch quota systems, and increasingly productive capital and effort due to disembodied and embodied technical change and knowledge externalities; (iii) discards of target species under catch quotas; (iv) the feasibility of fine-tuning the management of individual stocks in a fishery and the validity; and (v) the possibility that effective but broad-brush control could be preferable to the apparent precision of management using TACs and quotas.

Maintaining an underlying licence limitation scheme can safeguard against pressures to expand the TAE or TAC in either effort- or catch-based management systems.

Both individual and group effort or catch rights can achieve target fishing mortality, can improve economic efficiency, are clear improvements over open access and simple limited entry, but can raise associated issues of political economy and governance. Transferability of either catch or effort rights enhances economic efficiency, allows matching quota holdings with catches and reduction of discarding in catch quota systems and confers flexibility to vessels to respond to changes in environmental and market conditions. Nonetheless, several types of problems can arise. There can be concerns over quota concentration, monopoly power over pricing and the distribution among groups in society of the net benefits over time for both systems. There can also be issues of transferability among different gears and areas and duration of the right that might lead to concentration or create barriers to entry into the fishery.

The emergence of a catch or effort rights programme is also path dependent. Path dependency means that the particular initial conditions, political economy and history can play an important and ultimately idiosyncratic role in the choice and even success of one approach over another. Successful catch or effort rights programmes require that the TAC and possibly also the TAE be set according to the stock status.

The choice of effort or catch rights-based management depends upon the specific fishery. Many fisheries transitioning from ITEs to ITQs rights still retain many effort programme features, forming hybrid systems. In general, hybrid systems that address emerging ecosystems and biodiversity issues (multiple externalities) and limitations inherent in either approach to rights-based management are emerging. These hybrid programmes combine features of catch and effort rights and/or area rights.

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