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Designing hunting regulation under population uncertainty and self-reporting☆

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ABSTRACT

A number of methods exist for estimating the size of animal populations. All methods generate an uncertain estimate of population size, and have different properties, which can be taken into account when designing regulation. We consider hunting regulation when the population size is uncertain and when the self-reported bag is used to estimate the population size. The properties of a population tax and a tax on self-reported bag are analyzed and we begin by considering a baseline situation with full certainty and no use of self-reporting for population size estimation. Here individual hunters self-report a bag on zero and a population tax alone can secure an optimum. Next we show that when facing uncertain population size, a risk-averse hunter will self-report part of the bag to reduce the uncertain population tax payment, making both tax instruments necessary for reaching an optimum. Finally, when self-reported bag is used to estimate population size, we also show that it is optimal for hunters to report a part of the bag and both instruments are again necessary for reaching an optimum.

Introduction

Economists normally assume that individual hunters are interested in their own returns from the activity while a social objective must include the well-being for all actors deriving utility from both hunting and game populations.[1] Thus, a market failure arises due to differences in objectives implying that a private hunter optimum does not maximize total welfare (e.g. Schuhmann and Schwabe,

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[1] As examples a social planner may include recreational values for non-hunters and damage on either farm crops or forest regeneration (see Ritz and Ready, 2000).

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2000). Consequently regulation of the hunting activity is needed but to regulate in an efficient way, information on population size is required (Skonhoft, 2005). The existing economic literature on regulation of hunting is based on the assumption that population size is perfectly known (e.g. Zivin et al., 2000; Rondeau and Conrad, 2003; Horan and Bulte, 2004) and a number of methods for estimating the population size exist including aerial surveys, winter surveys, mortality counts, disease die-offs, accidental deaths, and self-reported bag.[2] However, all these methods lead to highly uncertain population estimates, or even strategically biased measures, if the hunters do not have an incentive to report the true observation. Therefore, it is important to take into account both population uncertainty and the method of estimating population size when designing regulation.

The purpose of this paper is to analyze the properties of a population tax and a tax on self-reported bags for regulating hunting when population size is uncertain and when self-reported bag is used to estimate the population size. We investigate the properties of the self-reported bag as method for measuring the population size because this allows us to consider regulatory mechanism that reach socially optimal solutions.

Regulation of hunting in practice

The choice of a population tax and a tax on self-reported bag is inspired by the economic literature on fisheries and non-point pollution and now we discuss the possibilities for implementing such instruments in an actual hunting situation by using two cases from Western Europe. In Denmark hunting season restriction is the main regulation instrument (Sunde and Hougaard, 2014), based on an assumption that the time available for hunting affects the aggregated bag size and, thereby, the population size.[3] The annual bag has to be reported to the authorities to renew an annual hunting license, but the self-reported bag is not used directly for regulatory purposes.[4] However, imposing a tax on self-reported bags is practically feasible and for the following analysis the relationship between the self-reported bag and the actual bags is important. Based on both case studies and model assessments, Hansen (2000), Kanstrup (2013) and Sunde and Hougaard (2014) all show that for red deer in Denmark the average self-reported bag constitute between 75% and 85% of the estimated average actual bag. So even though hunters do not report the full bag, a relationship between the actual bag and the self-reported bag can be estimated and in this paper we rely on such a relation in this paper. In France the hunting regulation is much more complex and involves use of taxation, hunting licenses, compensation to landowners from hunter's for crop damages and other administrative regulations (Abildtrup and Jensen, 2014). Crop damage compensation from hunters may be seen as a population tax, since a larger population size implies more damage and more compensation claims.[5] Thus, a population tax would also be possible to implement in practical regulation.

Next we discuss the structure of most actual regulatory systems for hunting in Western Europe. As pointed out by Rollins and Briggs (1996) and Horan and Bulte (2004), a social planner, landowners and hunters are all actors in most privately owned hunting areas. Each of these actors has a different set of objectives and should, in principle, be included in a regulatory model for hunting. However, in the economic hunting literature it is common to only analyze the link between two of the involved actors. Skonhoft and Olaussen (2005) study the link between a social planner and landowners while Zivin et al. (2000) investigate the relationship between landowners and hunters. We follow Keith and Lyon (1985) and focus on the relation between a social planner and hunters, and, thereby, disregarding the landowners. Three arguments may justify this choice: (1) in France many landowners transfer hunting rights to municipalities implying that the landowners can be disregarded (Hasenkamp, 1995), (2) in some countries in Western Europe a part or all rights to hunting is public owned which implies that landowners can be disregarded (Keith and Lyon, 1985), (3) a social planner may regulate the landowners to provide incentives for them to regulate the hunters in an optimal way (Abildtrup and Jensen, 2014). If a well-functioning market for hunting rights exists, this market may be used as regulation instrument (Lundhede et al., 2015).

Related economic literature

A point of departure for the regulatory system analyzed here is the non-point pollution literature. The basic statement in this literature is that individual pollution cannot be measured while aggregate pollution at a given geographical point can be identified and, therefore, an asymmetric information problem arises (moral hazard). The non-point pollution literature normally investigates a flow externality problem, and, therefore, static models are used. Segerson (1988) suggest a tax based on the ambient concentration level in a region, assuming that the taxes can vary between individual polluters. Assuming uncertainty about the ambient concentration level, Xepapadeas (1995) extend the analysis by Segerson (1988) and propose to combine a tax on the ambient concentration level and a tax on self-reported pollution. Unregulated hunting is similar to a non-point pollution problem as the individual bag cannot be observed, while the aggregated bag can be estimated through the population size. Consequently, in this paper we apply the mechanism proposed by Xepapadeas (1995) to hunting but we make two extensions: (1) in the case of hunting a dynamic model must be constructed because a hunting population is a renewable resource, (2) we include a case where the self-reported bag is used not only for taxation but also for measuring the population size.

The literature on taxes on stock size within fisheries[6] is also relevant for this paper. In this literature individual harvest is assumed to be unobservable due to illegal landings and discard, while the aggregate harvest may be identified through stock size. This structure is similar to a non-point pollution problem. By using Segerson (1988), Jensen and Vestergaard (2002) propose a pure stock tax assuming perfectly measureable stock size while Jensen and Vestergaard (2007) include stock uncertainty and suggest combining a stock tax and a tax on self-reported harvest in line with Xepapadeas (1995). However, when finding the optimal taxes, Jensen and Vestergaard (2002), Jensen and Vestergaard (2007) assume that changes in stock size enter the objective function of both the fisherman and the social

[2] Bag is the number of shot animals and corresponds to harvest as used in the general resource economic literature.

[3] Hunting season restrictions are also based on a need for undisturbed periods during migration, breeding or nesting periods.

[4] Within groups of hunters (e.g. a group of hunters sharing the hunting right on a property), an internal bag fee is sometimes applied, but in the context of co-management (i.e. a private agreement).

[5] A theoretical foundation for damage based compensation is given by Rakotoarison et al. (2009).

[6] In fisheries the term "stock" is used instead of "population", and "harvest" or "landings" instead of "bag".

planner. This is not consistent with traditional natural resource economics (see e.g. Neher, 1990), and in this paper only the current population size enter in the objective functions. Furthermore, we include the possibility that the self-reported bag is used to measure the population size.

By using the approach from Segerson (1988) and Jensen and Vestergaard (2002), Abildtrup and Jensen (2014) analyze hunting and suggest a pure population tax to replace the existing regulation in France (see "Regulation of hunting in practice" section). However, three important assumptions is made: (1) The population size is perfectly observable; (2) The self-reported bag is not used for measuring population size; (3) The population is in a steady-state equilibrium. In this paper these three assumptions are relaxed making the regulatory recommendations for hunting more relevant for practical policy.

The rest of the paper is organized as follows. In "The model" section we set-up a model to be used as a baseline for the rest of the paper. This baseline model is analyzed in "Full certainty" section assuming full certainty about the population size and no use of self-reported bags for measuring population size. "Population uncertainty" section contains an analysis of uncertain population size, and we consider the use of self-reported bag for measuring the population size in "Self-reports affect the measure of population size" section. A discussion and conclusion is placed in "Conclusion and discussion" section.

The model

We assume that n hunters exploit one population of game.[7] For each time period, t, we assume that a social planner define a target population size, x_t^* (Skonhoft, 2005) according to economic objectives (e.g. Kanstrup et al., 2014). A social planner may be interested in other population characteristics than x_t^* such as a target sex ratio and we discuss this issue in "Conclusion and discussion" section. Based on x_t^* we assume that the social planner calculate a total target on the bag size, h_t^*, and x_t^* and h_t^* are announced to the hunters at the beginning of each hunting period.

We assume that the social planner uses a population tax and a tax on self-reported bags as the only regulatory instruments. The social planner makes no attempt to measure the actual bag of hunter i at time t, h_{it}, and, therefore, h_{it} is only observable for hunter i. Thus, for the social planner h_{it} is the expected bag for hunter i while h_{it} is the actual bag from the individual hunter's point of view. The lack of observability of h_{it} for the social planner is captured by including a random variable (θ_{it}), in the bag of hunter i such that $h_{it}(\theta_{it})$ but in the following sections we suppress θ_{it} to keep the notation simple. Note that h_{it} is defined as a continuous variable but in reality a hunter can often only bag a discrete number of animals and we discuss this issue in "Conclusion and discussion" section.

We let x_t denote the actual population size at time t and s_{it} the self-reported bag by hunter i. As for h_{it}, s_{it} is assumed to be a continuous variable and we also discuss this assumption in "Conclusion and discussion" section. With a tax on the population size and the self-reported bag, the tax scheme imposed on hunter i at time t can be written as $T_{it}(x_t, s_{it})$. Note that the tax function may differ between the hunters and, therefore, $T_{it}(x_t, s_{it})$ is an individual hunter's tax. We assume that the tax is announced at the beginning of a hunting period while the tax are collected based on measuring the actual x_t and s_{it} at the end of the hunting period.

Individual hunter model

In the general economic theory on renewable resources it is common to assume that an individual extractor disregard resource conservation measures by excluding a resource restriction (Neher, 1990), and this is also common in the hunting literature (e.g. Horan and Bulte, 2004). However, Keith and Lyon (1985) and Schwabe et al. (2002) argue that there are circumstances where individual hunters may take a resource restriction into account, and we identify two arguments for this with our model: (1), following Jensen and Vestergaard (2002), Jensen and Vestergaard (2007) and Abildtrup and Jensen (2014), the hunter may react to a population tax by taking a resource restriction into account, (2) in a hunting area with a small number of hunters facing a finite game population resource conservation measures may be included.[8] Thus, we assume that the individual hunter faces a resource restriction and this restriction is given by[9]:

$$x_{t+1} - x_t = F_t(x_t) - \sum_{i=1}^{n} h_{it} \tag{1}$$

where $F_t(x_t)$ is the natural growth at time t. We assume that $F_t'(x_t) > 0$ for $x_t < x_{MSY}$ where x_{MSY} is the population size at maximum sustainable yield. Furthermore it is assumed that $F_t'(x_t) < 0$ for $x > x_{MSY}$ and that $F_t''(x_t) < 0$. A natural growth function satisfying these properties is a standard logistic function. In (1) we chose a discrete time formulation because taxation is normally imposed for discrete time intervals. Condition (1) states the change in population size between time periods is equal to the natural growth minus the total bag by all hunters (Neher, 1990).

Two additional facts may be stated in relation to (1). First, by including (1) in the hunter's optimization problem, the population externality problem is partly solved. The main externality is caused by difference in the hunter's and the social planner's objective functions (see below). Second, if hunters do not take (1) into account, the population tax would be a lump-sum transfer, which does not affect incentives to bag. Indeed including (1) is the same as assuming that a private firm must perceive to have an influence on the aggregated pollution when using an ambient tax to solve non-point pollution problems (Cabe and Herriges, 1992).

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[7] It is assumed that the number of hunters is given. Schuhmann and Schwabe (2000) and Schwabe et al. (2002) argue that most hunting areas are characterized by open-access implying that n is endogenous due to entry and exit. However, as mentioned by Hasenkamp (1995) a license to hunt must be acquired in most hunting areas and, therefore, n can be treated as constant.

[8] This argument implies that the regulatory mechanisms, we suggest, works best with small and restricted groups of hunters.

[9] Jensen and Vestergaard (2002, 2007) and Abildtrup and Jensen (2014) allow for errors in the perception of the resource restriction, but including this in our model does not change the basic results.

Each individual hunter is assumed to maximize the discounted values of current and future net benefits. In the economic literature on hunting, it is sometimes argued that hunters exclude discounting (e.g. Skonhoft, 2005) while others argue the opposite (e.g. Huffaker, 1993; Chen and Skonhoft, 2013). If an individual hunter takes (1) into account, it is also reasonable to assume that future net benefits are discounted. The net benefit function for hunter *i*, $B_{it}(h_{it}, x_t)$, is, therefore, assumed to depend on both the actual bag and the population size, and the net benefits are defined as gross benefits minus hunting costs. It is common to assume that hunter's gross benefit only depend on the bag (e.g. Horan and Bulte, 2004). At the same time the bag size affects the costs but we assume that the effect on the gross benefit dominates the effect on the costs implying that $\frac{\partial B_{it}}{\partial h_{it}} > 0$ and $\frac{\partial^2 B_{it}}{\partial h_{it}^2} < 0$ (e.g. Horan and Bulte, 2004). Turning to population size, x_t, we assume, as in general economic literature on both non-renewable and renewable resources, that a larger population size makes bagging less costly[10] implying that $\frac{\partial B_{it}}{\partial x_t} > 0$ and $\frac{\partial^2 B_{it}}{\partial x_t^2} < 0$. We also assume that an increase in the population size leads to an increase in the marginal net benefit of the bag implying that $\frac{\partial^2 B_{it}}{\partial h_{it}\partial x_t} > 0$. Last we allow for the possibility that the individual hunters are heterogeneous with respect to the net benefit function implying that an index, *i*, is included.

Given these definitions and taking the tax payment into account, the maximization problem for hunter *i* can be written as:

$$\underset{h_{it},s_{it}}{Max}\ J_{it} = \underset{h_{it},s_{it}}{Max}\left[\sum_{t=1}^{\infty}\alpha^{t-1}(B_{it}(h_{it}, x_t) - T_{it}(x_t, s_{it}))\right] \tag{2}$$

s.t.

$$x_{t+1} - x_t = F_t(x_t) - \sum_{i=1}^{n} h_{it} \tag{3}$$

In (2) α^{t-1} is the discount factor and J_{it} are the sum of the discounted net benefits for all time periods. Note that in (2) we assume infinite time horizon implying that $t\text{–}>\infty$ and for each time period, h_{it} and s_{it} are control variables while x_t is a state variable.[11] Based on the identification of control and state variables, let us briefly consider the nature of the solution to the problem in (2) and (3). At the initial time period ($t = 1$) the hunter determines an entire time path for h_{it}, s_{it} and x_t covering all future time periods and due to the resource restriction the paths for h_{it} and x_t are closely related. We will use this observation below.

Turning to the tax function we follow Xepapadeas (1995) and use the following specific functional form:

$$T_{it}(x_t, s_{it}) = g_{it}(s_{it})(x_t^* - x_t) + \tau_{it}s_{it} \tag{4}$$

In (4) the population tax faced by each hunter depends on the difference between the target population size and the actual population size. In (4) the tax function, $g_{it}(s_{it})$, depend on the self-reported bag of hunter *i*. Note that each hunter receive a population subsidy if the actual population size exceeds the target population size ($T_{it}(x_t, s_{it}) < 0$). τ_{it} is the tax rate on self-reported bag and it is assumed that the tax rate is positive. Furthermore, both $g_{it}(s_{it})$ and τ_{it} may vary between hunters and below we want to calculate the optimal values of $g_{it}(s_{it})$ and τ_{it}.

In "Regulation of hunting in practice" section we mentioned that a relation between the self-reported bag and the actual bag exist and this relation can be defined as:

$$s_{it} = f_{it}(h_{it}) \tag{5}$$

We assume that $s_{it} \geq 0$ and $f'_{it}(h_{it}) > 0$ in the interval around an optimum capturing that an increase in the actual bag will increase in the self-reported bag. $f_{it}(h_{it})$ is assumed to be perfectly known by the individual hunter but unknown to the social planner. This is captured by including a random variable, ω_{it}, in $f_{it}(h_{it})$ but in the following analysis ω_{it} is excluded to simplify the notation. (5) can be substituted into the population tax function which gives $g_{it}(s_{it}) = g_{it}(f_{it}(h_{it})) = k_{it}(h_{it})$.

Last, note that x_t enters on both the right hand side and the left-hand side in (1). Thus, the resource restriction in (1) can be solved for x_t and because $\frac{\partial B_{it}}{\partial x_t} > 0$, x_t lies to the right of x_{MSY} implying that $F'_t(x_t) < 0$ (Sunde and Hougaard, 2014). Therefore, we can concentrate on the largest root for x_t [12] and we get from (1) that:

$$x_t = M_t(x_{t+1}, h_{it}, h_{-it}) \tag{6}$$

where h_{-it} is a vector of bag by all other hunters than *i*. Condition (6) captures how the actual population size at time *t* relates to changes in x_{t+1}, h_{it} and h_{-it} and (6) is the resource restriction given by (1) expressed in an alternative way. From this it follows that an important element of $M_t(x_{t+1}, h_{it}, h_{-it})$ is the natural growth function. Note that with (6) x_t becomes a function of x_{t+1} and this formulation is possible because the individual hunter at $t = 1$ selects a whole time path for x_t. Based on (6), a biological response function, $\frac{\partial M_t}{\partial h_{it}}$, may be defined and this response function expresses how a change in the individual hunter's bag will affect the population size. Now we

[10] See Neher (1990) and Rondeau and Conrad (2003) for a justification for this assumption.

[11] In most economic literature on hunting, the bag is control variable for the hunter (e.g. Horan and Bulte, 2004) but in this paper we also use the self-reported bag as control variable.

[12] There exist a number of growth functions for which this solution procedure is not possible. However, with the assumptions about $F_t(x_t)$ mentioned in connection with (1), (6) can be defined.

have that $\frac{\partial M_t}{\partial h_{it}} < 0$ because $F_t'(x_t) < 0$ implying that a larger bag of hunter i lead to a lower population size. Furthermore, from (6) we get that $\frac{\partial^2 M_t}{\partial h_{it}\partial x_t} = 0$.

Conditions (4)–(6) can be substituted into (2) and now the maximization problem becomes:

$$\underset{h_{it},f_{it}(h_{it})}{Max} \ J_{it} = \underset{h_{it},f_{it}(h_{it})}{Max}\left[\sum_{t=1}^{\infty}\alpha^{t-1}(B_{it}(h_{it},M_t(x_{t+1},h_{it},h_{-it})) - k_{it}(h_{it})(x_t^* - M_t(x_{t+1},h_{it},h_{-it})) - \tau_{it}f_{it}(h_{it}))\right] \tag{7}$$

From (2) and (3) we have that h_{it} and s_{it} are control variables while x_t is a state variable. However, in reaching (7) we have used that $s_{it}=f_{it}(h_{it})$ so now h_{it} and $f_{it}(h_{it})$ is control variables and using a function ($f_{it}(h_{it})$) as a control is well-known in economics (see e.g. Varian, 1992). Furthermore, because (6) is substituted into (2) we now have x_{t+1} as state variable.

Note three facts in relation to the solution in (7). First, from (2) and (3) we have identified time paths for h_{it}, s_{it} and x_t while (7) imply that a time path for h_{it}, s_{it} and x_{t+1} can be found. However, it is well-known that the problem given by (2) and (3) is equivalent to the problem in (7) due to the resource restriction (Xepapadeas, 1997). Therefore, we may use (7) to find the optimal taxes. Second, in the following sections the first-order condition for x_{t+1} is excluded when solving (7) so the optimal taxes found are conditional on an optimal value for x_{t+1}. Lastly, below we only consider the first-order condition for one time period implying that the optimal taxes are conditional on optimal regulation all other time periods. These three facts are important to keep in mind when interpreting the results in "Full certainty", "Population uncertainty", "Self-reports affect the measure of population size" sections.

Social planner model

Next we turn to a model for a social planner. The objective function for the planner should incorporate that a number of other actors, apart from the hunters, receive benefits and incur costs from both hunting and the game population. Ritz and Ready (2000) mention that additional benefits include non-use values and recreational values while additional costs may be damage due to vehicle accidents and damages on forest stands and agricultural crops. Due to these additional benefits and costs to non-hunters, an externality arise making regulation of hunting is necessary. However, because we investigate hunting regulation, the net benefits of other users must be included as a part of the hunter net benefit since the objective function for the social planner and hunter must be defined over the same agents. Thus, we define the social planner's net benefit functions as $D_{it}(h_{it}, x_t)$. We assume that hunter's net benefits are also incorporated by the planner but despite this we have that $B_{it}(h_{it}, x_t)$ differ from $D_{it}(h_{it}, x_t)$ because of non-hunter benefits and cost. Because the hunter benefits are included in the net benefit function for the social planner we have that $\frac{\partial D_{it}}{\partial h_{it}} > 0$ and $\frac{\partial^2 D_{it}}{\partial h_{it}^2} < 0$. However, due to the additional costs of non-hunters we assume that $\frac{\partial B_{it}}{\partial h_{it}} > \frac{\partial D_{it}}{\partial h_{it}}$. Regarding the derivatives for x_t we follow Ritz and Ready (2000) and Abildtrup and Jensen (2014) and assume that the additional gross benefits dominates the additional costs implying that $\frac{\partial D_{it}}{\partial x_t} > 0$ and $\frac{\partial^2 D_{it}}{\partial x_t^2} < 0$. Furthermore, as in Abildtrup and Jensen (2014) we assume that the marginal net benefit of population size for the social planner is higher than the marginal net benefit of population size for the hunter from which it follows that $\frac{\partial D_{it}}{\partial x_t} > \frac{\partial B_{it}}{\partial x_t}$. It is, also, assumed that the numerical value of $\frac{\partial^2 D_{it}}{\partial x_t^2}$ is larger than the numerical value of $\frac{\partial^2 B_{it}}{\partial x_t^2}$. As in "Individual hunter model" section it is also assumed that an increase in the population size leads to an increase in the marginal net benefit of the bag implying that $\frac{\partial^2 D_{it}}{\partial h_{it}\partial x_t} > 0$ and by following the same line of reasoning we have that $\frac{\partial^2 D_{it}}{\partial h_{it}\partial x_t} > \frac{\partial^2 B_{it}}{\partial h_{it}\partial x_t}$.

In "Individual hunter model" section we mentioned that h_{it} and $f_{it}(h_{it})$ are unmeasurable for the social planner and this implies that the social planner maximizes the expected present value of current and future net benefits (welfare). However, for simplicity we disregard an expectation operator and the maximization problem may be written as:

$$\underset{h_{it},k_{it}(h_{it}),\tau_{it}}{Max} \ K_{it} = \underset{h_{it},k_{it}(h_{it}),\tau_{it}}{Max}\left[\sum_{t=1}^{\infty}\sum_{i=1}^{n}(D_{it}(h_{it},x_t))\alpha^{t-1}\right] \tag{8}$$

s.t.

$$x_{t+1} - x_t = F_t(x_t) - \sum_{i=1}^{n} h_{it} \tag{9}$$

$$h_{it}, f_{it}(h_{it}) \varepsilon \arg\max(J_{it}) \tag{10}$$

Note that h_{it}, $k_{it}(h_{it})$ and τ_{it} are control variables in (8)–(10)[13] while x_t is a state variable. h_{it} is a control variable because the social planner is interested in an optimal value for the individual bag. Furthermore, an objective for the social planner is to design the

[13] Within the hunting literature, control variables for a social planner have been the population size (e.g. Skonhoft and Olaussen, 2005), the bag (e.g. Zivin et al., 2000) or effort (e.g. Chen and Skonhoft, 2013).

hunting regulation in an optimal way and, therefore, optimal values for the population tax, $k_{it}(h_{it})$, and a self-reporting tax, τ_{it}, must be found. Note that using of regulatory instruments as control variable for a social planner is common in the literature on regulating externalities (see e.g. Baumol and Oates, 1988). Note that the resource restriction in (9) is identical to the restriction on the individual hunter problem (1) while (10) captures that the social planner must accept that the hunter that choice of h_{it} *and* $f_{it}(h_{it})$. Therefore, (10) express the individual hunter's reaction function to the regulatory instruments selected by the social planner. However, (10) can be replaced with the first-order conditions for the individual hunter's if an interior optimum for h_{it} *and* $f_{it}(h_{it})$ exist. Last, with (8)–(10) the social planner identify a whole time path for both h_{it} and x_t and these paths are closely related due to the resource restriction in (9).

Because (9) and (1) are identical we can use $x_t = M_t(x_{t+1}, h_{it}, h_{-it})$ in the social planner objective function (as in (6)) and the following problem is reached:

$$\underset{h_{it},k_{it}(h_{it}),\tau_{it}}{Max} K_{it} = \underset{h_{it},k_{it}(h_{it}),\tau_{it}}{Max} [\sum_{t=1}^{\infty}\sum_{i=1}^{n}(D_{it}(h_{it}, M_t(x_{t+1}, h_{it}, h_{-it})))\alpha^{t-1}] \tag{11}$$

s.t.

$$h_{it}, f_{it}(h_{it}) \varepsilon arg\max(J_{it}) \tag{12}$$

In (11) h_{it}, $k_{it}(h_{it})$ and τ_{it} are still control variables while x_{t+1} is a state variable. As in "Individual hunter model" section the problems in (8)–(10) and (11)–(12) are equivalent due to the inclusion of a resource restriction. Furthermore, we exclude the first-order condition for x_{t+1} below so the optimal taxes identified are conditional on an optimal selection of x_{t+1}. We also only consider the optimal values of $k_{it}(h_{it})$ and τ_{it} in one time period implying that optimal taxes are conditional on optimality in all other time periods. As in "Individual hunter model" section these characteristics of the solution must be remembered when interpreting the results in "Full certainty", "Population uncertainty", "Self-reports affect the measure of population size" sections.

In the following three sections the above models are used to analyze the optimal self-reporting and the optimal value of the tax variables under various assumptions about the measurement of the population size.

Full certainty

Now we discuss the optimal taxes and self-reported bags in a baseline situation with full certainty about the population size (measured based on winter surveys or other methods) and no use of the self-reported bag to estimate the population size. We use the results from this section to discuss the results reached in "Population uncertainty", "Self-reports affect the measure of population size" sections.

Individual hunter model

We begin by showing that it is optimal for hunter *i* to report zero bag. We do this by differentiating (7) with respect to $f_{it}(h_{it})$:

$$k'_{it}(h_{it})(x_t^* - M_t(x_{t+1}, h_{it}, h_{-it})) - \tau_{it} \leq 0, \quad f_{it}(h_{it}) \geq 0 \tag{13}$$

In deriving (13) we use that $g'_{it}(f_{it}(h_{it})) = k'_{it}(h_{it})$ and that the discount factor cancels away. By using Kuhn–Tucker conditions, we get from (13) that either $k'_{it}(h_{it})(x_t^* - M_t(x_{t+1}, h_{it}, h_{-it})) - \tau_{it} = 0$ or $f_{it}(h_{it}) = 0$. Now τ_{it} or $k'_{it}(h_{it})$ can be selected such that $x_t^* = M_t(x_{t+1}, h_{it}, h_{-it})$ and we have that $\tau_{it} > 0$. These two facts imply that:

$$-\tau_{it} < 0; \quad f_{it}(h_{it}) = 0 \tag{14}$$

From (14) we see that it is optimal for hunter *i* to report zero bag ($s_{it} = f_{it}(h_{it}) = 0$) and this result arise because the individual hunter is indifferent between paying the population tax and the tax on self-reported bag with full population certainty.

We, also, need a first-order condition for h_{it} and from (9) this condition is given as:

$$\frac{\partial B_{it}}{\partial h_{it}} + \frac{\partial B_{it}}{\partial M_t}\frac{\partial M_t}{\partial h_{it}} + k_{it}(h_{it})\frac{\partial M_t}{\partial h_{it}} = 0 \tag{15}$$

In (15) we have used that the discount factor cancels out and the tax on self-reported bag is not included in (15) as $s_{it} = f_{it}(h_{it}) = 0$. (15) represents an interior solution for the bag of hunter *i* and according to the condition the marginal private net benefit of the bag $\left(\frac{\partial B_{it}}{\partial h_{it}}\right)$ is equal to the marginal private costs. The marginal private costs consist of the marginal tax costs $\left(k_{it}(h_{it})\frac{\partial M_t}{\partial h_{it}}\right)$ and the marginal cost of the population externality as perceived by the hunter $\left(\frac{\partial B_{it}}{\partial M_t}\frac{\partial M_t}{\partial h_{it}}\right)$. The latter term express that an increase in bag of hunter *i* will affect the net benefit of the same hunter in future time periods through the population size. The marginal cost of the population externality has also been labelled the user cost of the population size or the shadow price of the resource restriction in the economic literature (e.g. Anderson, 1986; Jensen and Vestergaard, 2002).

Social planner model

From (12) we have that the social planner takes the hunter's reactions to the population tax and self-reporting tax into account and these reactions can be represented by the first-order conditions. However, for the self-reported bag a corner solution is reached ($s_{it} = f_{it}(h_{it}) = 0$) so this optimality can be excluded when replacing (12) with the first-order conditions. For h_{it} we reach an interior solution given by (15) so this condition must be included in the maximization problem for the social planner. Based on (11) and (15) the following Lagrange function can be constructed:

$$\underset{h_{it},k_{it}(h_{it}),\tau_{it}}{Max} L_{it} = \underset{h_{it},k_{it}(h_{it}),\tau_{it}}{Max}\left[\sum_{t=1}^{\infty}\sum_{i=1}^{n}(D_{it}(h_{it},M_t(x_{t+1},h_{it},h_{-it})))\alpha^{t-1}+\sum_{t=1}^{\propto}\sum_{i=1}^{n}\lambda_{it}\left(\frac{\partial B_{it}}{\partial h_{it}}+\frac{\partial B_{it}}{\partial M_t}\frac{\partial M_t}{\partial h_{it}}+k_{it}(h_{it})\frac{\partial M_t}{\partial h_{it}}\right)\right] \quad (16)$$

where λ_{it} is a Lagrange multiplier for the first-order condition for h_{it}.

Note that, as described in "Social planner model" section, h_{it}, $k_{it}(h_{it})$ and τ_{it} are control variables. However, the a first-order condition for τ_{it} is not defined so the optimality conditions are given by:

$$\frac{\partial L_{it}}{\partial h_{it}} = \left(\frac{\partial D_{it}}{\partial h_{it}}+\frac{\partial D_{it}}{\partial M_t}\frac{\partial M_t}{\partial h_{it}}+\sum_{j\neq i}\frac{\partial D_{jt}}{\partial M_t}\frac{\partial M_t}{\partial h_{it}}\right)\alpha^{t-1}+\lambda_{it}\left(\frac{\partial^2 B_{it}}{\partial h_{it}^2}+\frac{\partial B_{it}}{\partial M_t}\frac{\partial^2 M_t}{\partial h_{it}^2}+k_{it}(h_{it})\frac{\partial^2 M_t}{\partial h_{it}^2}\right)=0 \quad (17)$$

$$\frac{\partial L_{it}}{\partial k_{it}(h_{it})} = \lambda_{it}\frac{\partial M_t}{\partial h_{it}} = 0 \quad (18)$$

$$\frac{\partial L_{it}}{\partial \lambda_{it}} = \frac{\partial B_{it}}{\partial h_{it}}+\frac{\partial B_{it}}{\partial M_t}\frac{\partial M_t}{\partial h_{it}}+k_{it}(h_{it})\frac{\partial M_t}{\partial h_{it}}=0 \quad (19)$$

We have already interpreted (19) in "Individual hunter model" section (see (15)) and from (18) we get that $\lambda_{it}=0$ because $\frac{\partial M_t}{\partial h_{it}}<0$. Using this implies that (17) can be rewritten as:

$$\frac{\partial D_{it}}{\partial h_{it}}+\frac{\partial D_{it}}{\partial M_t}\frac{\partial M_t}{\partial h_{it}}+\sum_{j\neq i}\frac{\partial D_{jt}}{\partial M_t}\frac{\partial M_t}{\partial h_{it}}=0 \quad (20)$$

(20) captures that the marginal social net benefit of the bag $\left(\frac{\partial D_{it}}{\partial h_{it}}\right)$ is set equal to the marginal social costs of the bag. The marginal social cost of the bag for hunter i consist of two elements. The first element is the marginal effect of a hunter's bag on the net benefit of the same hunters throughout the population size in all future time period $\left(\frac{\partial D_{it}}{\partial M_t}\frac{\partial M_t}{\partial h_{it}}\right)$. The second element is the marginal effect of a hunter's bag on the net benefits of all other hunters throughout the population size in all future time periods $\left(\sum_{j\neq i}\frac{\partial D_{jt}}{\partial M_t}\frac{\partial M_t}{\partial h_{it}}\right)$. Comparing (15) with (20) we see an important difference between the private optimum and the social planner optimum. In the private optimum, (15), hunter i only takes his own net benefits into account while a social planner includes the net benefit of all actors $\left(\sum_{j\neq i}\frac{\partial D_{jt}}{\partial M_t}\frac{\partial M_t}{\partial h_{it}}\right)$. Thus, an externality arises because the individual hunter does not take into account that his bag has an effect on other user's net benefit.

Optimal taxes

To internalize this externality, an optimal population tax for hunter i can be found by setting (19) equal to (20):

$$k_{it}(h_{it}) = \frac{Q_{it}}{(\partial M_t/\partial h_{it})} \quad (21)$$

where $Q_{it}=\frac{\partial D_{it}}{\partial h_{it}}+\frac{\partial D_{it}}{\partial M_t}\frac{\partial M_t}{\partial h_{it}}+\sum_{j\neq i}\frac{\partial D_{jt}}{\partial M_t}\frac{\partial M_t}{\partial h_{it}}-\frac{\partial B_{it}}{\partial h_{it}}-\frac{\partial B_{it}}{\partial M_t}\frac{\partial M_t}{\partial h_{it}}$ is the difference in marginal net benefits between the social planner and the hunter.

Let us now clarify how (21) secures an optimum. From (4) the tax with $s_{it}=0$ is given by $T_{it}(x_t,s_{it})=k_{it}(h_{it})(x_t^*-x_t)$ and it can be shown that $\frac{\partial k_{it}}{\partial x_t}<0$ given the assumptions about the net benefit functions of the hunter and the social planner sketched in "Individual hunter model" and "Social planner model" sections.[14] To explain this result we consider two cases. First, assume that $x_t^*>x_t$. Now it follows that the closer x_t is to x_t^*, the lower is the value of the population tax and this may secure that $x_t\to x_t^*$. Second, assume that $x_t>x_t^*$. Now k_{it} is a subsidy and it follows that the closer x_t is to x_t^* the higher is the population subsidy. These two facts lead to the result that $x_t\to x_t^*$ and, therefore, the population tax in (21) secures an optimum.

[14] The results obtaining by differentiating the tax variables in this paper is available by contacting the authors.

Because the tax is based on Q_{it}, the individual hunter pays the full social cost of the bag and free-riding is avoided. Note, also, that Q_{it} is corrected with $\frac{\partial M_t}{\partial h_{it}}$ in (21), because we use population size as the tax base, but want to influence the bag of each hunter. From this it follows that if hunter *i* perceives that the bag does not affect population size $\left(\frac{\partial M_t}{\partial h_{it}}=0\right)$, the population tax will not influence bag incentives. Therefore, provided $\frac{\partial M_t}{\partial h_{it}}=0$ the population tax is in reality a lump-sum tax (see "Individual hunter model" section). Finally, (21) is exactly the population tax reached in Abildtrup and Jensen (2014) and here we use (21) as a baseline case for comparison with population taxes under both uncertainty and the use of the self-reported bags to estimate the population size.

Population uncertainty

In "Introduction" section we stated that several methods may be used for population estimation but that all methods generate an uncertain estimate for the population size. Therefore, we now extend the model from "The model" section to include uncertainty about the population size and we show that risk-aversion among hunters provides an argument for a self-reporting tax. We assume that the social planner and individual hunter share the same estimate for the population size, x_t, which is denoted $\bar{x}_t$.[15] Now, population uncertainty is described by ε_t which is assumed i.i.d $N(0;\sigma^2)$. We also assume that population uncertainty affects the resource restriction additively[16] and in this way σ_t^2 is included in (1). Solving the resource restriction in (1) for x_t we get that:

$$x_t = M_t(x_{t+1}, h_{it}, h_{-it}, \sigma_t{}^2) \tag{22}$$

As the social planner and the individual hunter share the same estimate for population uncertainty (22) holds for both actors.

Individual hunter model

Population uncertainty implies that we need an assumption about the risk attitude of the individual hunter and here risk-aversion is assumed. Very few studies on hunting include uncertainty but Skonhoft (2005) and Hussain and Tschirhart (2010) assume risk-neutrality for the hunters. However, within general economics solid empirical evidence document that economic agents are risk-averse (Varian, 1992 for an overview) and there is no reason to believe that hunters differ from other economic agents in this respect.

We define risk-aversion as decreasing expected marginal utility of goods or income (e.g. Varian, 1992) and in our model this implies that the hunter's expected marginal utility of the discounted net benefit is decreasing. However, for deriving analytical results we need a specific functional form for the expected utility of the net benefit and here we follow Xepapadeas (1995). We start by defining the following function:

$$\phi_{it} = \phi_{it}(x_t^* - M_t(x_{t+1}, h_{it}, h_{-it}, \sigma_t^2)) \tag{23}$$

Note that (23) is based on the difference between a certain target population size, x_t^*, and an uncertain expected population size, $M_t(x_{t+1}, h_{it}, h_{-it}, \sigma_t^2)$. A risk-averse hunter will require that the expected population size is larger than the target population size ($x_t^* < M_t(x_{t+1}, h_{it}, h_{-it}, \sigma_t^2)$) so we have that $\phi_{it}<0$, $\phi'_{it}<0$, $\phi''_{it}<0$ *and* $\phi''{}'_{it}<0$. In the following we label (23) a risk aversion function.

However, the risk aversion function in (23) is too general to reach analytic results and, therefore, we conduct a second-order Taylor approximation around the point where $x_t^* = M_t(x_{t+1}, h_{it}, h_{-it}, \sigma_t^2)$. This allows us to write the risk-aversion function as:

$$\phi_{it} = \phi_{it}(x_t^* - M_t(x_{t+1}, h_{it}, h_{-it}, \sigma_t^2)) + \frac{\sigma_t^2}{2}\phi''_{it}(x_t^* - M_t(x_{t+1}, h_{it}, h_{-it}, \sigma_t^2)) \tag{24}$$

where $\phi_{it}<0$, $\phi'_{it}<0$, $\phi''_{it}<0$ and $\phi''{}'_{it}<0$.

Based on (24) we can define a specific functional form for the expected utility function for hunter *i* as:

$$\begin{aligned}\underset{h_{it},f_{it}(h_{it})}{Max}\ J_{it} = \underset{h_{it},f_{it}(h_{it})}{Max}\Bigg[\sum_{t=1}^{\infty}\alpha^{t-1}(B_{it}(h_{it}, M_t(x_{t+1}, h_{it}, h_{-it}, \sigma_t^2)) - k_{it}(h_{it})(\phi_{it}(x_t^* - M_t(x_{t+1}, h_{it}, h_{-it}, \sigma_t^2))\\ + \frac{\sigma_t^2}{2}\phi''_{it}(x_t^* - M_t(x_{t+1}, h_{it}, h_{-it}, \sigma_t^2))) - \tau_{it}f_{it}(h_{it}))\Bigg]\end{aligned} \tag{25}$$

In (25) h_{it} and $f_{it}(h_{it})$ are still control variables while we do not have to include an optimality condition for x_{t+1}.

[15] The analysis generalizes straightforward to the case where the population size estimate differs between the social planner and the individual hunter. In this case two different biological response function are necessary, but to avoid complications we assume identical expectations over population size

[16] This approach is also used by Reed (1979) and Andersen and Sutinen (1984) in a fisheries economic model.

We can now investigate the optimal self-reported bag by hunter i and the first-order condition of (25) with respect to $s_{it} = f_{it}(h_{it})$ is given by:

$$k'_{it}(h_{it})\left(\phi_{it} + \frac{\sigma_t^2}{2}\phi''_{it}\right) - \tau_{it} \le 0, \quad f_{it}(h_{it}) \ge 0 \tag{26}$$

In (26) the discount factor is cancelled away and either the first or second expression is equal to zero according to the Kuhn–Tucker conditions. Now we have that $k'_{it}(h_{it}) < 0, \quad \tau_{it} > 0$ and $\phi_{it} + \frac{\sigma_t^2}{2}\phi''_{it} < 0$ and from this it follows that:

$$k'_{it}(h_{it})\left(\phi_{it} + \frac{\sigma_t^2}{2}\phi''_{it}\right) - \tau_{it} = 0, \quad f_{it}(h_{it}) > 0 \tag{27}$$

From (27) it follows that the individual hunter will report a part of the bag and the intuition for this result is that the hunter faces a trade-off between an uncertain population tax payment and a certain tax on the self-reported bag. Given risk-aversion this trade-off implies that a positive self-reported bag is chosen and this represents an interior solution for $f_{it}(h_{it})$ is found.[17] Note also that (27) express that the expected marginal cost savings of the population tax payment $\left(k'_{it}(h_{it})\left(\phi_{it} + \frac{\sigma_t^2}{2}\phi''\right)_{it}\right)$ is equal to the marginal tax on the self-reported bag (τ_{it}). Last, note that hunter i only report a part of the bag and therefore truthful revelation of the bag is not an issue in this paper contrary to the general economic theory on asymmetric information (see e.g. Laffont and Tirole, 1993).

We, also, reach an interior optimum for h_{it} and by differentiating (25) with respect to actual bag, we get:

$$\frac{\partial B_{it}}{\partial h_{it}} + \frac{\partial B_{it}}{\partial M_t}\frac{\partial M_t}{\partial h_{it}} + k_{it}(h_{it})\left(\phi'_{it}\frac{\partial M_t}{\partial h_{it}} + \frac{\sigma_t^2}{2}\phi'''_{it}\frac{\partial M_t}{\partial h_{it}}\right) - \tau_{it}f'_{it}(h_{it}) = 0 \tag{28}$$

Again α^{t-1} cancels away in (28) and the condition states that the marginal private benefit $\left(\frac{\partial B_{it}}{\partial h_{it}}\right)$ is equal to the expected marginal private costs. The expected marginal private cost consists of the marginal cost of the population externality as perceived by the individual hunter $\left(\frac{\partial B_{it}}{\partial M_t}\frac{\partial M_t}{\partial h_{it}}\right)$, the marginal tax on self-reporting bag $(\tau_{it}f'_{it}(h_{it}))$ and the expected marginal population tax payment $\left(k_{it}(h_{it})\left(\phi'_{it}\frac{\partial M_t}{\partial h_{it}} + \frac{\sigma_t^2}{2}\phi'''_{it}\frac{\partial M_t}{\partial h_{it}}\right)\right)$. Note that the expected marginal population tax payment is corrected by the marginal risk-aversion $\left(\phi'_{it}\frac{\partial M_t}{\partial h_{it}} + \frac{\sigma_t^2}{2}\phi'''_{it}\frac{\partial M_t}{\partial h_{it}}\right)$ because the population tax is uncertain from the point of view of the individual hunter.

Social planner model

Next we turn to the social planner problem under population uncertainty and from above we have that $M_t(x_{t+1}, h_{it}, h_{-it}, \sigma_t^2)$ also captures the resource restriction in this case. Thus, in (11) we may replace $M_t(x_{t+1}, h_{it}, h_{-it})$ with (22) and for (12) the interior solutions for h_{it} and $f_{it}(h_{it})$ from "Individual hunter model" section are used. Therefore, we may set-up the following expected value Lagrange-function for the social planner[18]:

$$\begin{aligned}\underset{h_{it},k_{it}(h_{it}),\tau_{it}}{Max} L_{it} = \underset{h_{it},k_{it}(h_{it}),\tau_{it}}{Max} \Bigg[&\sum_{t=1}^{\infty}\sum_{i=1}^{n}(D_{it}(h_{it}, M_t(x_{t+1}, h_{it}, h_{-it}, \sigma_t^2)))\alpha^{t-1} + \sum_{i=1}^{n}\lambda_{it}\left(B'_{it}(h_{it}) - \frac{\partial c_{it}}{\partial h_{it}} - \frac{\partial c_{it}}{\partial M_t}\frac{\partial M_t}{\partial h_{it}}\right.\\ &\left. + k_{it}(h_{it})\left(\phi'_{it}\frac{\partial M_t}{\partial h_{it}} + \frac{\sigma_t^2}{2}\phi'''_{it}\frac{\partial M_t}{\partial h_{it}}\right) - \tau_{it}f'_{it}(h_{it})\right) - \sum_{i=1}^{n}\mu_{it}(k'_{it}(h_{it})\left(\phi_{it} + \frac{\sigma_t^2}{2}\phi''_{it}\right) + \tau_{it})\Bigg]\end{aligned} \tag{29}$$

where λ_{it} and μ_{it} are shadow prices for the first-order conditions for hunter i for h_{it} and $f_{it}(h_{it})$.

As in "Social planner model" section we do not include first-order conditions for τ_{it} and x_{t+1} implying that we obtain:

$$\begin{aligned}\frac{\partial L_{it}}{\partial h_{it}} = &\left(\frac{\partial D_{it}}{\partial h_{it}} + \frac{\partial D_{it}}{\partial M_t}\frac{\partial M_t}{\partial h_{it}} + \sum_{j\neq i}\frac{\partial D_{jt}}{\partial M_t}\frac{\partial M_t}{\partial h_{it}} - \right)\alpha^{t-1} + \lambda_{it}\left(\frac{\partial^2 B_{it}}{\partial h_{it}^2} + \frac{\partial B_{it}}{\partial M_t}\frac{\partial^2 M_t}{\partial h_{it}^2} + k_{it}(h_{it})\left(\phi'_{it}\frac{\partial M_t}{\partial h_{it}} + \frac{\sigma_t^2}{2}\phi'''_{it}\frac{\partial M_t}{\partial h_{it}}\right.\right.\\ &\left.\left. + \phi'_{it}\frac{\partial^2 M_t}{\partial {h_{it}}^2} + \frac{\sigma_t^2}{2}\phi''_{it}\frac{\partial^2 M_t}{\partial {h_{it}}^2}\right)\right) + \mu_{it}\left(k'_{it}(h_{it})\left(\phi_{it} + \frac{\sigma_t^2}{2}\phi''_{it}\right) + \tau_{it}\right) = 0\end{aligned} \tag{30}$$

[17] In fact if the hunter is extremely risk-averse over-reporting of harvest may occur.

[18] As in "Individual hunter model" section we do not include an expectation operator in (29).

$$\frac{\partial L_{it}}{\partial k_{it}(h_{it})} = \lambda_{it}\left(\phi'_{it}\frac{\partial M_t}{\partial h_{it}} + \frac{\sigma_t^2}{2}\phi'''_{it}\frac{\partial M_t}{\partial h_{it}}\right) = 0 \tag{31}$$

$$\frac{\partial L_{it}}{\partial \lambda_{it}} = \frac{\partial B_{it}}{\partial h_{it}} + \frac{\partial B_{it}}{\partial M_t}\frac{\partial M_t}{\partial h_{it}} + k_{it}(h_{it})\left(\phi'_{it}\frac{\partial M_t}{\partial h_{it}} + \frac{\sigma_t^2}{2}\phi'''_{it}\frac{\partial M_t}{\partial h_{it}}\right) - \tau_{it}f'_{it}(h_{it}) = 0 \tag{32}$$

$$\frac{\partial L_{it}}{\partial \mu_{it}} = k'_{it}(h_{it})\left(\phi_{it} + \frac{\sigma_t^2}{2}\phi''_{it}\right) - \tau_{it} = 0 \tag{33}$$

We have already interpreted (32) and (33) in "Individual hunter model" section. From (33) we obtain that $\lambda_{it} = 0$ because $\phi'_{it}\frac{\partial M_t}{\partial h_{it}} + \frac{\sigma_t^2}{2}\phi'''_{it}\frac{\partial M_t}{\partial h_{it}} > 0$ and from (27) we have that $\mu_{it} = 0$. Now by using $\lambda_{it} = \mu_{it} = 0$ and the fact that the discount factor cancels away in (30) we reach:

$$\frac{\partial D_{it}}{\partial h_{it}} + \frac{\partial D_{it}}{\partial M_t}\frac{\partial M_t}{\partial h_{it}} + \sum_{j \neq i}\frac{\partial D_{jt}}{\partial M_t}\frac{\partial M_t}{\partial h_{it}} = 0 \tag{34}$$

The only difference between (34) and (20) is that we operate with expected marginal social benefit and expected marginal social cost now because of population uncertainty.

Optimal taxes

From (31)–(34) we may determine the optimal tax mechanism and by setting (34) equal to (33) we reach the following population tax rate:

$$k_{it}(h_{it}) = \frac{Q_{it} - \tau_{it}f'_{it}(h_{it})}{\phi'_{it}\frac{\partial M_t}{\partial h_{it}} + \frac{\sigma_t^2}{2}\phi'''_{it}\frac{\partial M_t}{\partial h_{it}}} \tag{35}$$

As in "Full certainty" section Q_{it} is the difference in net benefits between the social planner and the individual hunter but in (35) the net benefits are expressed in expected values. Compared to (21) (full certainty) two differences arise in (35). First, the marginal risk aversion given by $\phi'_{it}\frac{\partial M_t}{\partial h_{it}} + \frac{\sigma_t^2}{2}\phi'''_{it}\frac{\partial M_t}{\partial h_{it}}$ is included in (35) since the population size is uncertain. Second, the marginal tax cost on the self-reported bag ($\tau_{it}f'_{it}(h_{it})$) is a part of (37) because a trade-off between the population tax and the self-reporting tax is introduced. From (33) we find the optimal tax rate on self-reporting bag as:

$$\tau_{it} = k'_{it}(h_{it})\left(\phi_{it} + \frac{\sigma_t^2}{2}\phi''_{it}\right) \tag{36}$$

According to (36) τ_{it} is equal to the expected marginal value of a reduced population tax payment $k'_{it}(h_{it})\left(\phi_{it} + \frac{\sigma_t{}^2}{2}\phi''_{it}\right)$.

Now consider how (35) and (36) secure an optimum. Assume first that under population uncertainty a social planner determines the population tax by using (21) instead of (35), but that each individual hunter is risk-averse. This implies that hunter *i* will select a too low bag due to risk-aversion and, therefore, the social planner must reduce the population tax. In our model this is accomplished by correcting the population tax with the marginal tax cost on the self-reported bag.[19] The individual hunter, on the other hand, faces an uncertain population tax and a certain self-reporting tax. Thus, the population tax can be reduced by increasing the self-reported bag so we obtain that $\frac{\partial k_{it}}{\partial s_{it}} < 0$. It can also be shown that $\frac{\partial \tau_{it}}{\partial s_{it}} < 0$ implying that if s_{it} increases τ_{it} must decrease to keep the population tax rate approximately unchanged.

Furthermore, by differentiating (35) we obtain that $\frac{\partial k_{it}}{\partial x_t} < 0$ implying that the population tax rate can be designed such that $x_t = x_t^*$ is secured as in "Optimal taxes" section. Turning to the self-reporting tax rate we get that $\frac{\partial \tau_{it}}{\partial x_t} > 0$ because if x_t increases, the difference between x_t and x_t^* increases for a given k_{it}. Thus, the size of the self-reporting element in (36) must increase.

[19] This argument show that this result is not driven by the assumed relation between s_{it} and h_{it} given by $s_{it} = f_{it}(h_{it})$.

With these results we have shown that (35) and (36) represent an expected first-best optimum as claimed by Xepapadeas (1995) and Jensen and Vestergaard (2007). Furthermore, each hunter pays the full marginal social costs of non-optimal bag so free-riding is avoided. Note that in our model two market failures arise (differences in the objective functions and population uncertainty) and, therefore, two regulatory instruments (a population tax and a tax on a self-reported part of the bag) are needed to secure an expected first-best optimum.

Self-reports affect the measure of population size.

As discussed earlier many methods for estimating population size exist, but now we focus on the use of self-reported bag because this variable can be used to regulate hunting. Specifically, we show that when a self-reporting tax is used the hunter will report a part of the bag because a trade-off between the population tax and the self-reporting tax occur. This fact introduces an additional argument for a self-reporting tax and to focus as clear as possible on this argument full certainty about the population size is assumed.

Now a distinction between an actual population size, x_t, and a measure for population size constructed from the self-reported bags, $\hat{x}_t$ must be introduced. The actual population size is used to evaluate the net benefit functions of both the hunter and the social planner because the population size as perceived by the actors is relevant when evaluating these benefits. Therefore, it is the actual harvest that affects x_t.[20] However, the social planner and the hunter make no attempts to estimate the actual population size, but rely solely on a measure for population size, $\hat{x}_t$, constructed by using the self-reported bag of the hunters. We assume that $\hat{x}_t$ is used to evaluate the population tax payments and, therefore, we extend the model from "Full certainty" section to include $\hat{x}_t$. There is no guarantee that x_t and $\hat{x}_t$ are identical because hunters may choose only to report a part of the bag.

In modelling terms x_t is affected by actual bag as in "Full certainty" section and we assume that both the individual hunter and the social planner have identical perceptions of $M_t(x_{t+1}, h_{it}, h_{-it})$. In defining $\hat{x}_t$ a resource restriction is also used but now we include the aggregated self-reported bag ($\sum_{i=1}^{n} s_{it}$), instead of the aggregated actual bag as in (1). Solving this resource restriction for $\hat{x}_t$ yields the following functional relation:

$$\hat{x}_t = N_t(\hat{x}_{t+1}, s_{it}, s_{-it}) \tag{37}$$

where s_{-it} is a vector of the self-reported bag for all other hunters than hunter i. We assume that $\frac{\partial N_t}{\partial s_{it}} < 0$ and $\frac{\partial^2 N_t}{\partial s_{it}^2} < 0$ implying that a large self-reported bag decrease the population size as measured by the hunter and the social planner. Now (5) ($s_{it} = f_{it}(h_{it})$) can be inserted in (37) and this gives:

$$\hat{x}_t = N_t(\hat{x}_{t+1}, f_{it}(h_{it}), f_{-it}(h_{-it})) \tag{38}$$

where $f_{-it}(h_{-it})$ is a vector of functional relations between the self-reported bag and the actual bag for all other hunters than hunter i. From (5) we have that $\frac{\partial f_{it}(h_{it})}{\partial h_{it}} > 0$ and because $\frac{\partial N_t}{\partial s_{it}} < 0$ it follows that $\frac{\partial N_t}{\partial f_{it}(h_{it})} < 0$. As for $M_t(x_{t+1}, h_{it}, h_{-it})$ we assume that the social planner and the hunters have an identical perception of $N_t(\hat{x}_{t+1}, f_{it}(h_{it}), f_{-it}(h_{-it}))$.

Individual hunter model

Now we turn to the individual hunter model. Labelling $\hat{x}_t^*$ a target population size identified by using the self-reported bag, we begin by reformulating the net benefit function for hunter i. By using the distinction between x_t and $\hat{x}_t$ and inserting (38) in (7) the following objective function is obtained:

$$\underset{h_{it}, f_{it}(h_{it})}{Max}\; J_{it} = \underset{h_{it}, f_{it}(h_{it})}{Max} \left[\sum_{t=1}^{\infty} \alpha^{t-1} (B_{it}(h_{it}, M_t(x_{t+1}, h_{it}, h_{-it})) - k_{it}(h_{it})(\hat{x}_t^* - N_t(\hat{x}_{t+1}, f_{it}(h_{it}), f_{-it}(h_{-it}))) - \tau_{it} f_{it}(h_{it})) \right] \tag{39}$$

From (39) we see that $\hat{x}_t$ is used to evaluate the population tax while the net benefits are evaluated using x_t. As in "Full certainty" section h_{it} and $f_{it}(h_{it})$ are control variables while we do not need optimality conditions for x_{t+1} and $\hat{x}_{t+1}$.

By differentiating (39) with respect to $f_{it}(h_{it})$ we may analyze the optimal self-reported bag by hunter i:

$$k'_{it}(h_{it})(\hat{x}_t^* - N_t(\hat{x}_{t+1}, f_{it}(h_{it}), f_{-it}(h_{-it}))) + k_{it}(h_{it}) \frac{\partial N_t}{\partial f_{it}(h_{it})} - \tau_{it} \leq 0, \quad f_{it}(h_{it}) \geq 0 \tag{40}$$

As in "Full certainty" and "Population uncertainty" section the discount factor is cancelled out in (40). Now $k_{it}(h_{it})$ and τ_{it} can be selected such that $x_t^* = N_t(\hat{x}_{t+1}, h_{it}, h_{-it}, f_{it}(h_{it}))$ and this implies that (40) reduces to:

$$k_{it}(h_{it}) \frac{\partial N_t}{\partial f_{it}(h_{it})} - \tau_{it} \leq 0, \quad f_{it}(h_{it}) \geq 0 \tag{41}$$

[20] An alternative is of course to assume that the net benefits is evaluated using $\hat{x}_t$ but this will not change the main results in the paper. However, using $\hat{x}_t$ in the net benefit function complicates the first-order condition for the hunter with respect to $f_{it}(h_{it})$ so it is useful to use x_t.

In (41), either the first or the second expression is equal to zero from the Kuhn–Tucker conditions. For the first expression we note that $\frac{\partial N_t}{\partial f_{it}(h_{it})} > 0, \quad k_{it}(h_{it}) > 0 \quad \text{and} \quad k_{it}(h_{it}) > 0$ and this leads to the conclusion that:

$$k_{it}(h_{it})\frac{\partial N_t}{\partial f_{it}(h_{it})} - \tau_{it} = 0, \quad f_{it}(h_{it}) > 0 \tag{42}$$

From (42) we see that it is optimal for hunter i to report a part of the bag if the self-reported bags are used to measure the population size and the explanation for this result can be captured by considering the case where $\hat{x}_{t*} > \hat{x}_t$. Now hunter i can increase $\hat{x}_t$ by increasing the self-reported bag and this will decrease the population tax payment but also imply an increase in the tax on self-reported bag. This indicates that hunter i faces a trade-off when choosing the optimal level of the self-reported bag since the hunter must consider both the effect on the population tax and the self-reporting tax. From (42) the optimal self-reported bag occur where the marginal benefit of the reduced population tax payment $\left(k_{it}(h_{it})\frac{\partial N_t}{\partial f_{it}(h_{it})}\right)$ is equal to the marginal cost of the increased tax on self-reported bag (τ_{it}). Note, also, that (42) represents an interior solution for $f_{it}(h_{it})$ and this fact is used in "Social planner model" section.

Turning to the first-order condition of (39) with respect to h_{it}, the discount factor also cancels out and we reach an interior solution for h_{it} given by:

$$\frac{\partial B_{it}}{\partial h_{it}} + \frac{\partial B_{it}}{\partial M_t}\frac{\partial M_t}{\partial h_{it}} + k_{it}(h_{it})\frac{\partial N_t}{\partial f_{it}(h_{it})}f'_{it}(h_{it}) - \tau_{it}f'_{it}(h_{it}) = 0 \tag{43}$$

(43) can be compared with (15) and we see that two differences arises. First, the marginal population tax $\left(k_{it}(h_{it})\frac{\partial N_t}{\partial f_{it}(h_{it})}f'_{it}(h_{it})\right)$ is now included. This captures that an increase in bag for hunter i increase self-reported bag which, in turn, increase $\hat{x}_t$ and this leads to a decrease in the population tax payment. Second, the marginal tax on self-reported bag given as $\tau_{it}f'_{it}(h_{it})$ is included in (44) because $s_{it} = f_{it}(h_{it}) > 0$.

Social planner model

Next we turn to the social planner optimum and we begin with two observations. First, in "Individual hunter model" section we reached interior solutions for $f_{it}(h_{it})$ and h_{it} and this implies that (12) can be replaced with the first-order conditions in the hunter model represented by (42) and (43). Second, we use x_t to evaluate the discounted net benefit for the social planner. Thus, the Lagrange function for the social planner becomes:

$$\begin{aligned}\underset{h_{it},k_{it}(h_{it}),\tau_{it}}{Max} L_{it} = \underset{h_{it},k_{it}(h_{it}),\tau_{it}}{Max} \Bigg[& \sum_{t=1}^{\infty}\sum_{i=1}^{n}(D_{it}(h_{it}, M_t(x_{t+1}, h_{it}, h_{-it})))\alpha^{t-1} + \sum_{i=1}^{n}\lambda_{it}\left(\frac{\partial B_{it}}{\partial h_{it}} + \frac{\partial B_{it}}{\partial M_t}\frac{\partial M_t}{\partial h_{it}}\right.\\ & \left. + k_{it}(h_{it})\left(\frac{\partial N_t}{\partial f_{it}(h_{it})}\frac{\partial f_{it}(h_{it})}{\partial h_{it}}\right) - \tau_{it}f'_{it}(h_{it})\right) - \sum_{i=1}^{n}\mu_{it}\left(k_{it}(h_{it})\frac{\partial N_t}{\partial f_{it}(h_{it})} - \tau_{it}\right)\Bigg]\end{aligned} \tag{44}$$

Now we only need first-order conditions for h_{it} and $k_{it}(h_{it})$ implying that we get:

$$\begin{aligned}\frac{\partial L_{it}}{\partial h_{it}} = & \left(\frac{\partial D_{it}}{\partial h_{it}} + \frac{\partial D_{it}}{\partial M_t}\frac{\partial M_t}{\partial h_{it}} + \sum_{j\neq i}\frac{\partial D_{jt}}{\partial M_t}\frac{\partial M_t}{\partial h_{it}} - \right)\alpha^{t-1} + \lambda_{it}\left(\frac{\partial^2 B_{it}}{\partial h_{it}^2} + \frac{\partial B_{it}}{\partial M_t}\frac{\partial^2 M_t}{\partial h_{it}^2} + k_{it}(h_{it})\frac{\partial N_t}{\partial f_{it}(h_{it})}f''_{it}(h_{it}) - \tau_{it}f'_{it}(h_{it})\right)\\ & - \mu_{it}\left(k'_{it}(h_{it})\frac{\partial N_t}{\partial f_{it}(h_{it})} + k_{it}(h_{it})\frac{\partial N_t}{\partial f_{it}(h_{it})}f'_{it}(h_{it})\right) = 0\end{aligned} \tag{45}$$

$$\frac{\partial L_{it}}{\partial k_{it}(h_{it})} = \lambda_{it}\frac{\partial N_t}{\partial f_{it}(h_{it})}f'_{it}(h_{it}) + \mu_{it}k'_{it}(h_{it})\frac{\partial N_t}{\partial f_{it}(h_{it})} = 0 \tag{46}$$

$$\frac{\partial L_{it}}{\partial \lambda_{it}} = \frac{\partial B_{it}}{\partial h_{it}} + \frac{\partial B_{it}}{\partial M_t}\frac{\partial M_t}{\partial h_{it}} + +k_{it}(h_{it})\left(\frac{\partial N_t}{\partial f_{it}(h_{it})}f'_{it}(h_{it})\right) - \tau_{it}f'_{it}(h_{it}) = 0 \tag{47}$$

$$\frac{\partial L_{it}}{\partial \mu_{it}} = k_{it}(h_{it})\frac{\partial N_t}{\partial f_{it}(h_{it})} - \tau_{it} = 0 \tag{48}$$

(47) and (48) is interpreted in "Individual hunter model" section. In (46) we note that $\frac{\partial N_t}{\partial f_{it}(h_{it})} > 0, \quad \frac{\partial f_{it}(h_{it})}{\partial h_{it}} > 0 \quad \text{and} \quad k'_{it}(h_{it}) > 0$ implying that this condition can only hold if $\lambda_{it} = \mu_{it} = 0$. Using $\lambda_{it} = \mu_{it} = 0$ in (45) implies that the first-order condition for bag reduces to:

$$\frac{\partial D_{it}}{\partial h_{it}} + \frac{\partial D_{it}}{\partial M_t}\frac{\partial M_t}{\partial h_{it}} + \sum_{j\neq i}\frac{\partial D_{jt}}{\partial M_t}\frac{\partial M_t}{\partial h_{it}} = 0 \tag{49}$$

Again α^{t-1} has been reduced away and (49) is identical to the optimality condition for the social planner in "Social planner model" section (20).

Optimal taxes

We may now identify the optimal tax mechanism and we begin with the population tax rate. By setting (49) equal to (47) we reach:

$$k_{it}(h_{it}) = \frac{Q_{it} - \tau_{it} f'_{it}(h_{it})}{(\partial N_t / \partial f_{it}(h_{it})) f'_{it}(h_{it})} \tag{50}$$

where Q_{it} is the same as in "Full certainty" section. By comparing (50) and (21) we note that two differences arise. First, in (50) $\tau_{it} f'_{it}(h_{it})$ is included because there is a trade-off between the population tax and the self-reporting tax. Second, $\frac{\partial N_t}{\partial f_{it}(h_{it})} f'_{it}(h_{it})$ is included in the denominator in (50) and this term captures how the actual bag affects the self-reported bags which, in turn, affect the estimate for population size.

Concerning the tax on self-reporting bag we reach from (48) that:

$$\tau_{it} = -k_{it}(h_{it}) \frac{\partial N_t}{\partial f_{it}(h_{it})} \tag{51}$$

Condition (51) captures that the tax rate on self-reported bag has to be equal to the marginal reduction in the population tax payment.

In discussing the properties of (50) and (51) we have from (42) that it is optimal for a hunter to report a positive bag to reduce the population tax. This effect is included in (50) and it can be shown that $\frac{\partial k_{it}}{\partial f_{it}(h_{it})} < 0$ and this results captures two effects. First, increasing the self-reported bags increases $\hat{x}_t$ and, thereby, k_{it} can be reduced. Second, an increase in the self-reported bag increases the revenue from the population tax and, therefore, the population tax can be reduced if we want to reach $\hat{x}_t = \hat{x}_t^*$. For τ_{it} we get that $\frac{\partial \tau_{it}}{\partial f_{it}(h_{it})} < 0$ so a higher self-reported bag implies that a lower τ_{it} is necessary to secure that $\hat{x}_t = \hat{x}_t^*$.

For the derivatives of the tax functions with respect to population size we note that $N_t(\hat{x}_{t+1}, s_{it}, s_{-it})$, and not $M_t(x_{t+1}, h_{it}, h_{-it})$, is included in (50) but despite this fact we reach that $\frac{\partial k_{it}}{\partial \hat{x}_t} < 0$. Thus, the tax mechanism in (50) secures that $\hat{x}_t = \hat{x}_t^*$ but now we have two explanations for this result. First, as in "Full certainty" and "Population uncertainty" sections the properties of the population tax secure that $\hat{x}_t = \hat{x}_t^*$. Second, the self-reported bag will influence $\hat{x}_t$ and, thereby, the population tax. It can also be shown that $\frac{\partial \tau_{it}}{\partial \hat{x}_t} < 0$ capturing that an increase in $\hat{x}_t$ makes the self-reported tax less necessary and, therefore, τ_{it} can be reduced.

Note that the tax structure in (50) and (51) secures a first-best optimum because each hunter pays the full marginal social cost of the bag. Furthermore, we have two problems to solve (differences in objective functions and measurement of population size) and, therefore, two regulatory instruments secure an optimum.

Conclusion and discussion

In this paper we have extended the existing literature on hunting regulation by investigating both uncertainty about population size and measurement of population size by using the self-reported bag. We have investigated the properties of a population tax and a tax on self-reported bag to regulate hunting in these two situations. We show that there are two arguments for a self-reporting tax. First, under population uncertainty risk-averse hunters will report part of the bag and a self-reporting tax along with a population tax reach an optimal population size. Second, when self-reported bags are used to obtain a measure of population size, hunters will also report part of the bag because a trade-off between the population taxes and the tax on self-reported bag is introduced. In both case, there are two problems to solve so we need two instruments to secure an optimal population size.

There are several problems with our regulatory suggestion and now we discuss a few of these. We have assumed that the actual bag and the self-reported bag for each hunter are continuous variables, but for many hunting areas both variables are discrete (see e.g. Kanstrup, 2013). Despite this fact threating the bag as a continuous variable is common in the economic literature on hunting (see e.g. Abildtrup and Jensen, 2014; Hasenkamp, 1995; Rondeau and Bulte, 2007) since threating control variables as continuous provides a good approximation for discrete variables. However, allowing the self-reported bags to be a discrete variable may influence the nature of the regulatory system. If, for example, a hunter gets a license to bag one animal it is only necessary to report whether he is successful or not. However, a combination between a population tax and a tax on self-reported bag can also secure an optimum in this case. If, for example, a bag on two is optimal our mechanism can be defined such that the actual bag become two.

We have also assumed that the social planner has a target population size as objective, but instead the planner could be interested in other population characteristics, e.g. a target sex ratio. However, even though it complicates the model our analysis can be extended to cover multiple social planner objectives. Furthermore, a separate population tax on male and female game species can secure a target sex ratio, but now this tax is not without problems. A separate population tax on male and female game species requires that hunters have perfect selectivity with respect to the sex of bagged game and in reality this assumption may not be fulfilled. Finally, note that in the economic literature on hunting a target population size is a common objective (see e.g. Skonhoft and Olaussen, 2005) and this provides a justification for why we have restricted the analysis in this paper this goal.

We also note that, while we have included the size of the bag and the population size in the hunters net benefit function, hunters engage in hunting activities for a number of other reasons than killing animals (Lundhede et al., 2015). However, provided hunters select a non-optimal level of hunting related activity a properly designed tax on the activity can secure an optimum. Note, also, that wildlife regulation varies a lot between countries in Western Europe. For example, in Denmark restrictions on hunting time are used while compensation to landowners, hunting licenses, taxation and administrative regulations are combined in France. In this paper we suggest an alternative to these regulatory systems represented by a population tax and a tax on self-reported bag and we show that this two-part tax have important efficiency properties.

Turning to the acceptability of the tax mechanism, it can be argued that taxation of the population size is identical to collective punishment of hunters and this may be politically infeasible. However, under open-access (lack of inclusion of a resource restriction), the individual hunter does not take the effect on other hunters into account (Rondeau and Bulte, 2007). Thus, under open-access each hunter punishes all other hunters and this is, in principle, also collective punishment. Therefore, a population tax is in principle not different from a normal hunting situation. Furthermore, it is not uncommon that land owners apply collective punishment on hunters deviating from the agreed terms of a hunting license, including the ability to reduce population sizes (Kanstrup et al., 2014).

Our proposed mechanism requires a huge amount of information. This may imply that the tax mechanism is difficult to apply in practical regulation. However, exactly the same information requirements are raised when calculating an optimal Pigovian tax rate on actual bags with heterogeneous hunters. In addition, in a practical regulation situation hunters can be categorized into homogeneous groups facing the same tax structure and this makes implementation of our mechanism practical possible.

Last, the tax mechanism requires a given number of hunters and, therefore, an optimal number of hunters in a given area are not necessarily secured. However, the optimal amount of hunters may be reached by a lump-sum transfer from the social planner to the hunter (Hansen and Romstad, 2007). In this way our analysis can be extended to allow for free entry and exit by hunters.

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