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4

5 **Balancing public goods in agriculture through Safe Minimum Standards**

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7

8 **1. Introduction**

9 Agriculture is commonly perceived as producing public goods and/or public bads (OECD,
10 2001). It is well known that the presence of these may imply that government can use policy
11 to increase aggregate welfare above that of free-market equilibrium. We focus on public
12 goods that can be degraded beyond reversibility. An obvious example is the extinction of an
13 endangered species, which irreversibly decreases the public good agrobiodiversity. The same
14 holds true for greenhouse gas (GHG) emissions, which contribute to the public bad climate
15 change (or, equivalently, the public good emissions reductions) (IPCC, 2007). To cope with
16 the problem of degradation beyond reversibility, Bishop (1978) developed the concept of a
17 safe minimum standard (SMS). Our contribution focuses on the implications of SMS for
18 agricultural and environmental policy design when public goods are complementary to each
19 other and when public goods are in conflict with each other. We wish to explore how to
20 balance public goods and how the nature of the public goods and public bads affect the cost
21 of policy.

22 Brunstad *et al.* (2005) showed how the complementarity of public goods potentially
23 reduces the costs of their provision. We formalize their approach, and extend the analysis to
24 examine conflicting public goods. The emerging trade-offs turn out to be complex, even
25 within a rather simple welfare-theoretical model requiring numerical solutions. We illustrate

1 our findings with the help of Jordmod, a price-endogenous model of the Norwegian
2 agricultural sector to illustrate the essence of the theoretical model. By including the
3 indicators for the SMS in the model's objective function, we update and extend the model
4 used Brunstad *et al.* (2005). This enables the social costs associated with the SMS to be
5 revealed, and ensures that the SMS is achieved at minimum social cost.

6

7 **2. Safe minimum standards**

8 Agriculture is commonly perceived as being associated with market failures, such as can
9 occur in the presence of positive or negative externalities and public goods (OECD, 2001).
10 We offer three examples of public goods related to agricultural activity: (national) food
11 security, agrobiodiversity, and reductions of GHG emissions.

12 We define a *safe minimum standard* (SMS) as a requirement to maintain a public good at
13 a level robust against irreversible degradation.¹ By incorporating absolute minimum limits on
14 the level of the public good in an applied partial equilibrium model for agriculture, we have
15 assumed that the costs of complying with the SMS criterion are acceptable irrespective of the
16 public good's level. To estimate the implicit social costs of applying the SMS criterion we
17 calculate the endogenous shadow price resulting from the corresponding constraint in the
18 economic model. Simultaneously setting SMSs for several public goods permits us to
19 conduct an integrated assessment of the effects of the various public goods on social costs.

20 In a seminal paper, Bishop (1978: 13) developed the SMS concept to cope with the
21 problem of degradation beyond reversibility. The paper fostered a vast literature that aimed to
22 refine and critically discuss the SMS concept as a rule for environment policy and sustainable
23 development (e.g., Randall 1991; Rolfe, 1995; Farmer and Randall, 1998). Standard methods
24 of economic valuation, such as the contingent valuation method and travel cost method,

¹ In the general framework and the theoretical model, we turn the safe minimum standards of public goods into maximum limits to ease notation and interpretation of the corresponding shadow values.

1 involve substantial methodological and theoretical shortcomings (Nyborg, 2000). For
2 example, as they may regard it as their basic right, it would seem quite strange to ask people
3 for their willingness-to-pay for food security. Perman *et al.* (2003) claimed that, in addition to
4 scientific uncertainty about nature's threshold limits, there may also exist social and scientific
5 ignorance regarding the future usefulness and value of the public good. Hediger and Knickel
6 (2009) argued for the use of SMSs as a precautionary measure to assure that an economic
7 system does not move beyond the boundary of its "sustainability space."

8 A common criticism of the SMS criterion is that it is too conservative because it places
9 excessive weight on the potential costs from irreversible depletion and disregards the
10 potential benefits of the project it requires to cease. Any method that compares marginal costs
11 and marginal benefits, e.g., cost-benefit analysis, does not solve the principle problem of
12 irreversible depletion. If the lowest total cost of meeting the SMS constraint is deemed
13 excessive, policy makers could reject the constraint, and let the public good be at risk of
14 irreversible degradation. Policy makers need to judge what cost level is excessive to have a
15 robust level of a given public good (Perman, 2003: 462).

16 Brunstad *et al.* (2005) used an earlier version of the sector model *Jordmod* to assess the
17 complementarity between two public goods by incorporating an approach to measure
18 society's willingness to pay for cultural landscape and a food security SMS. We use an
19 illustrative welfare-theoretical model with an updated and improved version of *Jordmod* to
20 extend Brunstad *et al.*'s (2005) analysis, and illustrate trade-offs between potentially
21 conflicting public goods

22

23 **3. Theoretical model**

24 In this section, we first present a general framework for analysing the effects of policies
25 towards public goods and bads when factor and output prices are endogenous. The basic

1 insights are then illustrated in a welfare theoretical context using comparative statics to
 2 analyse the effects of a marginal change in the levels of the SMS on the welfare of different
 3 interest groups, the prices of goods, and the shadow prices of the public goods.

4

5 **3.1 General framework**

6 Consider a polity in which government uses policy to ensure that some number of public
 7 goods do not fall below their SMS levels.² For illustrative purposes, consider said
 8 government to have available two policy instruments, s_1 and s_2 , which affect the levels of two
 9 public goods G, H , each with its corresponding (SMS) level g and h . In market equilibrium,
 10 the levels of the public goods depend on the levels set for the policy instruments; we denote
 11 these functional relationships $G(s_1, s_2)$ and $H(s_1, s_2)$. The SMSs require $G(s_1, s_2) \geq g$ and $H(s_1,$
 12 $s_2) \geq h$.

13 The levels set for the policy instruments also affect social welfare derived in private
 14 markets (for example, producer and consumer surplus from buying and selling private goods,
 15 not from consuming public goods). We use $W^M(s_1, s_2)$ to denote how social welfare from
 16 market activities (that is, not including the welfare effects of the public goods G and H)
 17 depend on policy. Similarly, $W^G(G)$ and $W^H(H)$ show how social welfare is affected by the
 18 levels of the public goods G and H . For simplicity, we assume that total social welfare is
 19 separable in market activity and public goods:

$$20 \quad (1) \quad W(s_1, s_2) \circ W^M(s_1, s_2) + W^G(G(s_1, s_2)) + W^H(H(s_1, s_2)),$$

21 where $W^J \geq 0$ and $\partial W^J / \partial J > 0$, for $J = G, H$.

² It will prove notationally convenient and help with our intuitive interpretations to convert “public bads” into “public goods” by subtracting the levels of the public bads from constants. In general, if we let h' be the level of a public bad (pollution, say), then we can consider the level of the corresponding public good as $h = h^{max} - h'$, where h^{max} is just some maximum level of the public bad that can occur.

1 We assume that setting a policy instrument's level at zero implies that the instrument is
 2 not used, and that an increase in the level of the instrument implies its increased use. The
 3 policy objective is to maximize social welfare without violating the SMSs:

$$4 \quad (2) \underset{s_1, s_2 \geq 0}{Max} \left\{ \underbrace{W^M(s_1, s_2) + W^G(G(s_1, s_2)) + W^H(H(s_1, s_2))}_{W(s_1, s_2)} + g[G(s_1, s_2) - g] + h[H(s_1, s_2) - h] \right\},$$

5 where γ and η and are the Lagrangian multipliers associated with the SMSs. If the policy $(s_1^*,$
 6 $s_2^*) = \mathbf{s}^*$ solves the maximization problem, then under the conditions of the Kuhn-Tucker
 7 theorem there exist two numbers γ^* , and η^* such that the following conditions are satisfied:

Eq.	(a)	(b)	(c)
(3)	$W_1^M(\mathbf{s}^*) + [W^{G'}(G(\mathbf{s}^*)) + g^*]G_1(\mathbf{s}^*) + [W^H(H(\mathbf{s}^*)) + h^*]H_1(\mathbf{s}^*) \leq 0$	$s_1^* \geq 0$	$[W_1^M(\mathbf{s}^*) + [W^{G'}(G(\mathbf{s}^*)) + g^*]G_1(\mathbf{s}^*) + [W^H(H(\mathbf{s}^*)) + h^*]H_1(\mathbf{s}^*)]s_1^* = 0$
(4)	$W_2^M(\mathbf{s}^*) + [W^{G'}(G(\mathbf{s}^*)) + g^*]G_2(\mathbf{s}^*) + [W^H(H(\mathbf{s}^*)) + h^*]H_2(\mathbf{s}^*) \leq 0$	$s_2^* \geq 0$	$[W_2^M(\mathbf{s}^*) + [W^{G'}(G(\mathbf{s}^*)) + g^*]G_2(\mathbf{s}^*) + [W^H(H(\mathbf{s}^*)) + h^*]H_2(\mathbf{s}^*)]s_2^* = 0$
(5)	$G(\mathbf{s}^*) - g \leq 0$	$\gamma^* \geq 0$	$[G(\mathbf{s}^*) - g]\gamma^* = 0$
(6)	$H(\mathbf{s}^*) - h \leq 0$	$\eta^* \geq 0$	$[H(\mathbf{s}^*) - h]\eta^* = 0$

8

9 In the table, $G_i = \partial G / \partial s_i$, and $H_i = \partial H / \partial s_i$, for $i = 1, 2$, and γ^* and η^* represent the marginal
 10 social benefits (costs) of loosening (tightening) the SMSs g and h . Since both G and H are
 11 public goods, they increase social welfare: $W^{G'} > 0$, $W^{H'} > 0$. Because by conditions (5b) and
 12 (6b) the Lagrangian multipliers must be nonnegative, we conclude that the terms

13 $[W^{G'}(G(\mathbf{s}^*)) + g^*]$ and $[W^{H'}(H(\mathbf{s}^*)) + h^*]$ are both positive. From (3c) and (4c), if $W_1^M <$

14 0 , $G_1 < 0$, and $H_1 < 0$ for all \mathbf{s} , then the solution to the maximization problem is to set the
 15 levels of both instruments at zero: $s_1^* = s_2^* = 0$. The intuition is that if raising the level of
 16 instrument s_1 always lowers market-based welfare and always lowers the levels of the public
 17 goods, then there is no reason to use the policy instruments—raising their values makes

1 everything worse. Similarly, if raising the instrument s_1 always raises market-based welfare
2 and always raises the levels to the public goods, then (3c) and (4c) imply that higher values of
3 the policy instrument are always better, and so there is no solution to the maximization
4 problem. For the problem at hand to be interesting, therefore, there must be values of the
5 policy instruments at which raising their levels leads to both benefits in some parts of the
6 economy and losses in other parts. Given that the conditions hold that result in an interior
7 solution to the maximization problem, conditions (3c) – (6c) imply a system of identities:

$$8 \quad (7) \quad \begin{cases} W_1^M(\mathbf{s}^*) + [W^{G'}(G(\mathbf{s}^*)) + g^*]G_1(\mathbf{s}^*) + [W^H(H(\mathbf{s}^*)) + h^*]H_1(\mathbf{s}^*) = 0 \\ W_2^M(\mathbf{s}^*) + [W^{G'}(G(\mathbf{s}^*)) + g^*]G_2(\mathbf{s}^*) + [W^H(H(\mathbf{s}^*)) + h^*]H_2(\mathbf{s}^*) = 0 \\ G(\mathbf{s}^*) - g \equiv 0 \\ H(\mathbf{s}^*) - h \equiv 0 \end{cases}$$

9 For notational brevity, let

$$10 \quad (8) \quad W_{ij} \equiv W_{ij}^M + W^{G'}G_iG_j + W^{H'}H_iH_j + [W^{G'} + g^*]G_{ij} + [W^{H'} + h^*]H_{ij}, \text{ for } i = 1, 2; j = 1, 2.$$

11 Differentiating (8) with respect to g and putting the results into matrix form, we get,

$$12 \quad (9) \quad \begin{pmatrix} W_{11} & W_{12} & -G_1 & -H_1 \\ W_{21} & W_{22} & -G_2 & -H_2 \\ G_1 & G_2 & 0 & 0 \\ H_1 & H_2 & 0 & 0 \end{pmatrix} \begin{pmatrix} \frac{\partial s_1^*}{\partial g} \\ \frac{\partial s_2^*}{\partial g} \\ \frac{\partial g^*}{\partial g} \\ \frac{\partial h^*}{\partial g} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 1 \\ 0 \end{pmatrix}$$

13 From (9) it can be shown that

$$14 \quad (10) \quad \frac{\partial h^*}{\partial g} = \frac{G_2H_1W_{12} + G_1H_2W_{12} - G_1H_1W_{22} - H_2G_2W_{11}}{(G_2H_1 - G_1H_2)^2}.$$

1 Equation (10) shows how the marginal benefit of loosening the SMS on H is affected by
2 marginally loosening the SMS on G , given that it is safe to do so. If loosening the SMS on G
3 raises the marginal social benefit of loosening the SMS on H , (that is, if $\partial\eta^*/\partial g > 0$), then we
4 say that the two SMSs are *complements*. If $\partial\eta^*/\partial g < 0$, then loosening the SMS on G lowers
5 the marginal social benefit of loosening the SMS on H , and we say that the two SMSs
6 *conflict*.

7 To better understand intuitively the forces that drive SMS conflict or complementarity,
8 consider the case in which increased use of either policy instrument increases the level of
9 each public good: $G_1, G_2, H_1, H_2 > 0$, but creates deadweight in markets: $W_1^M < 0, W_2^M < 0$.
10 Furthermore, assume that the marginal deadweight from using s_i increases as its level of use
11 increases: $W_{ii}^M < 0$ for $i = 1, 2$. (This might occur, for example, because the Harberger
12 triangles get bigger at a “faster” rate as use of the instrument rises). Also assume that
13 marginal production of public goods is falling in the use of the instruments, $G_{ii} < 0$ and $H_{ii} <$
14 0 for $i = 1, 2$. Under these conditions, the definition in (8) implies that $W_{ii} < 0$ for $i = 1, 2$.
15 Assume also that the cross derivatives are positive: $G_{ij} > 0, H_{ij} > 0$, and $W_{ij}^M > 0$ for $i \neq j$.
16 Then increased use of s_i increases the marginal return of s_j in the creation of public goods,
17 and lowers the market-derived deadweight loss from a marginal increase in s_j . Under these
18 conditions, we have $W_{ij} > 0$ for $i \neq j$, and so, from (11), we have $\partial\eta^*/\partial g > 0$: the SMSs are
19 complementary regulations.

20

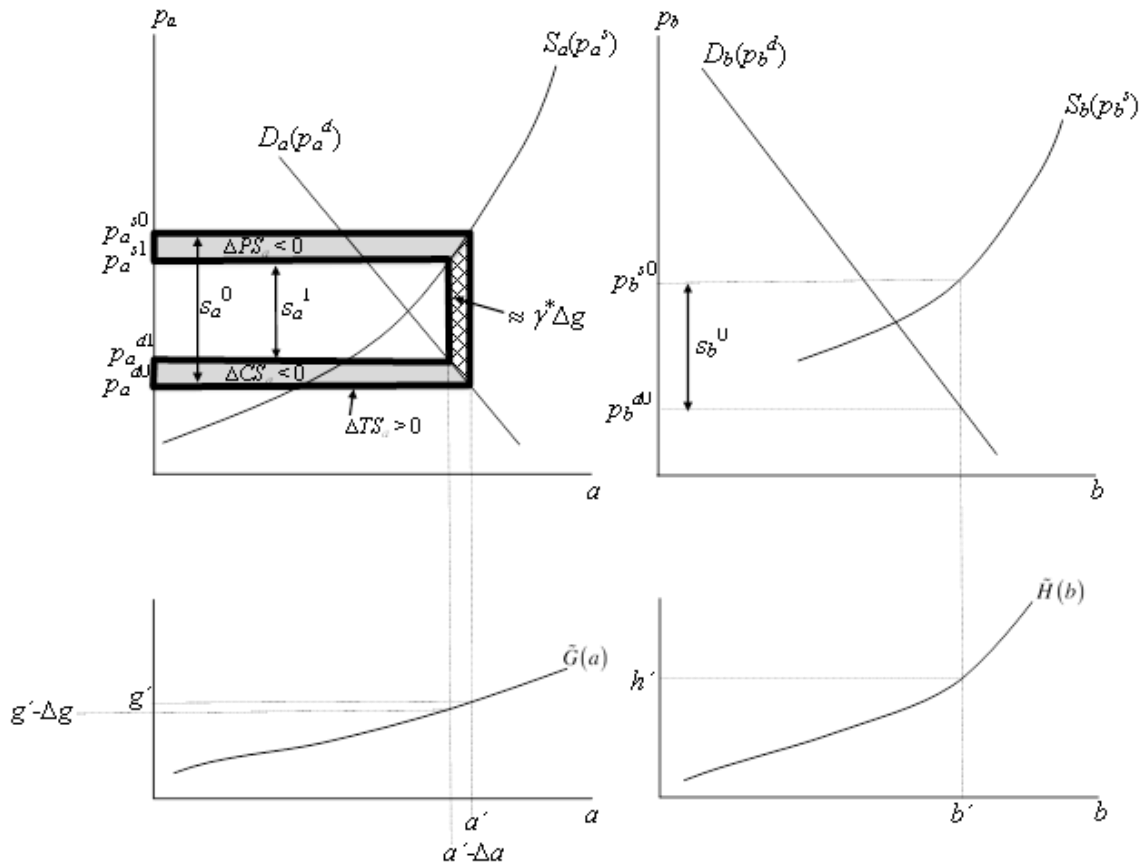
21 **3.2 Illustration: Effects of a marginal change of the SMS of public good G**

22 Equation (10) makes clear that even in this simple framework the specific parameterization of
23 the market characteristics and the functional forms of the relationships among social welfare
24 and public goods determine whether public goods are conflicting or complementary. Using a

1 welfare-theoretical model, we illustrate the intuition behind equation (10) by deriving
2 comparative static results of a marginal change of the SMS of public good G .

3 Consider an economy with two agricultural inputs, a and b . Say that there are two policy
4 instruments available to the government, per-unit subsidies s_a and s_b . When a is produced or
5 used, jointly some other public good G is produced according to the relationship $G = \tilde{G}(a)$.
6 In our example, this public good might be “food security”, which will be further discussed in
7 section 4.2. Similarly, when b is used in agricultural production, jointly some other public
8 good H is produced according to the relationship $H = \tilde{H}(b)$. Input b might be permanent
9 grassland for forage production. The public good that accompanies the use of b might be
10 “agrobiodiversity”, which will be further discussed in section 4.2. Initially, assume that the
11 public goods’ SMS levels are g' and h' . The relationship between the market equilibrium
12 quantities of the two goods and policy are described by functions $a(s_a, s_b)$ and $b(s_a, s_b)$. It
13 follows that $G(s_a, s_b) \equiv \tilde{G}(a(s_a, s_b))$ and similarly $H(s_a, s_b) \equiv \tilde{H}(b(s_a, s_b))$. As depicted, to
14 maintain g at g' , the equilibrium quantity of a must be maintained at a' , and to maintain H
15 and h' , the quantity of b must be maintained at b' . The policy (s_a^0, s_b^0) results in quantities
16 that satisfy these SMSs. We assume in figure 1 that in the production process that uses inputs
17 a and b , the inputs are neither substitutes nor complements. That is, a change in the price of
18 input a does not affect demand for input b , nor vice-versa. This assumption is relaxed below.
19 Still, the prices of a and b , P_a and P_b , may change endogenously due to changes in SMS
20 levels. Figure 1 illustrates the effects on η^* , the marginal social value of public good H , when
21 the government is able to safely relax the SMS on G by a marginal amount. To see this,
22 consider that it is safe for the SMS of G to be reduced by Δg . The looser constraint allows the
23 government to lower the subsidy rate on a from s_a^0 to s_a^1 . This raises the demand price for a
24 from p_a^{d0} to p_a^{d1} , and lowers the supply price from p_a^{s0} to p_a^{s1} . The resultant loss in profits of
25 the firms that use input a are illustrated by the shaded trapezoid ΔCS_a (Just, Hueth, and

1 Schmitz 2004, pp. 59-60). Similarly, the resultant loss in the profits of the suppliers of input a
 2 is the shaded trapezoid ΔPS_a (Just, Hueth, and Schmitz 2004, pp. 52-54). Taxes to finance the
 3 subsidy in the market for a can also be lowered, and so taxpayers save the thick-bordered
 4 region ΔTS_a .



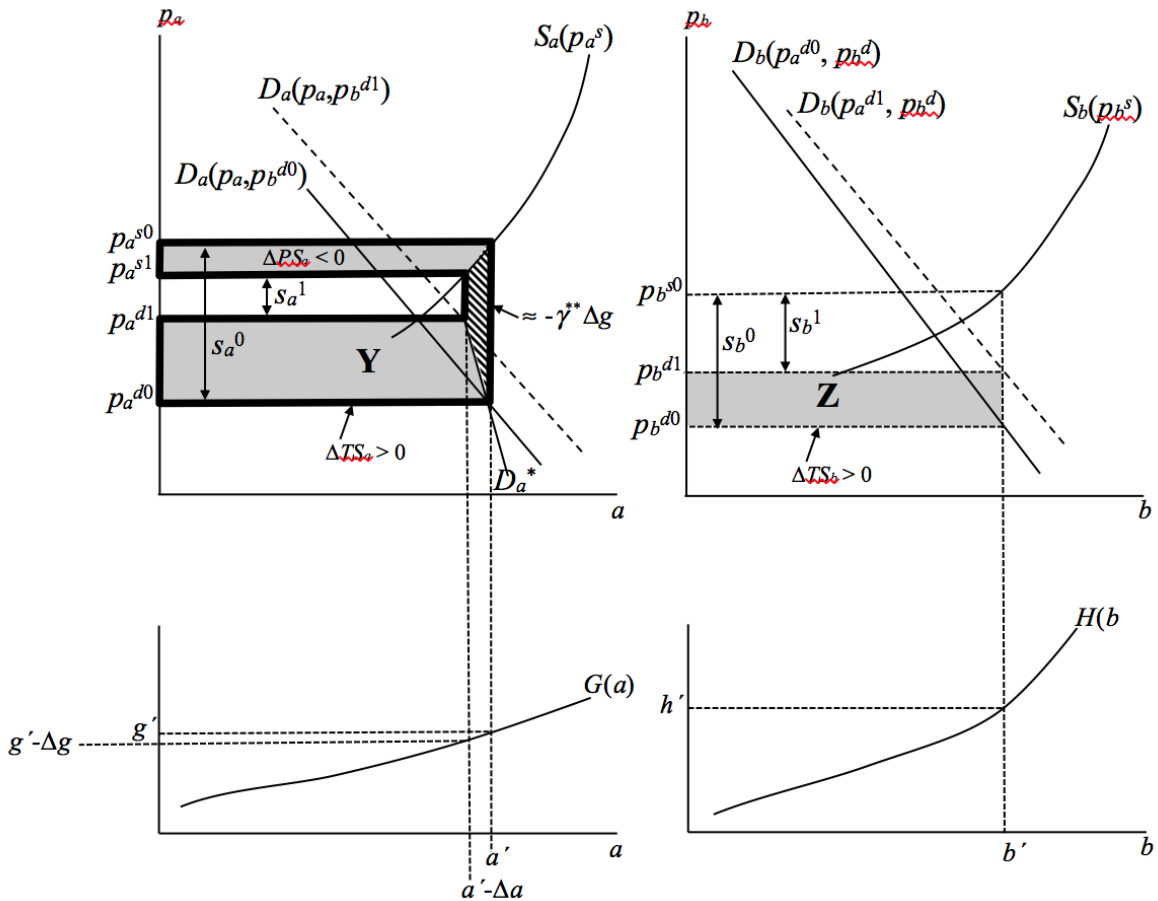
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 6 *Figure 1. The effect of a marginal change in SMS g on market welfare, given that the SMS*
 7 *level of h is maintained at h' , and assuming inputs a and b are neither substitutes nor*
 8 *complements in production of a final good*

9
 10 Summing the changes in welfare derived from the production, selling, buying and
 11 consumption of the private goods, the aggregate gain is the cross-hatched trapezoid. This is
 12 approximately equal to the marginal benefit of being able to safely relax g times the drop in
 13 g , labeled $\gamma^* \Delta g$. Intuitively, this is how much the original Harberger deadweight triangle

1 could be reduced because the subsidy s_a could be lowered from s_a^0 to s_a^1 when it became
 2 possible to safely lower the SMS from g' to $g' - \Delta g$.

3 In figure 1, using one policy instrument does not affect the marginal social return of using
 4 the other policy instrument. The cross-price derivatives of the input demand functions are
 5 assumed to be zero. Nor, since h remains unchanged, is there a change in the social welfare in
 6 this market associated with the ability to relax g . Hence, $\partial \eta^* / \partial g = 0$. The two public goods
 7 are neither complementary nor in conflict.

8 Figure 2 represents the case of a marginal change of the SMS g assuming that inputs a
 9 and b are substitutes. Therefore the cross-derivatives in equation (10) are not zero.



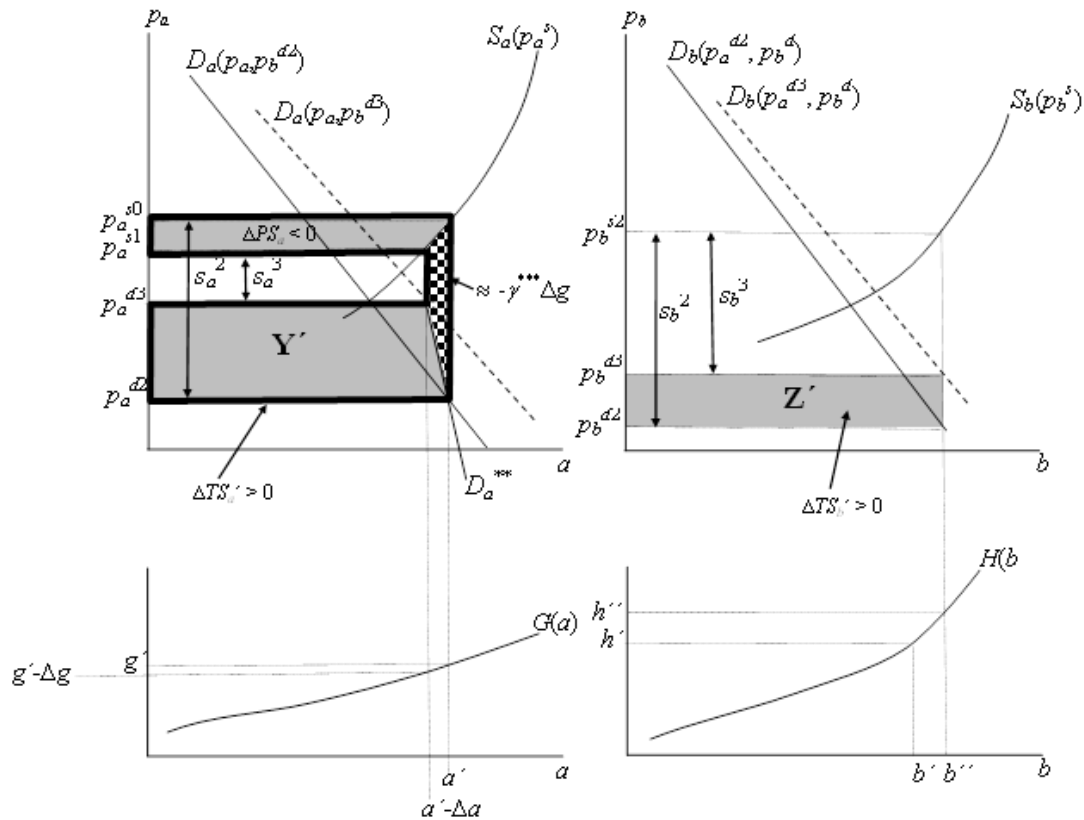
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11 *Figure 2. Effect on social welfare of a marginal change in g given h' and assuming*
 12 *substitution between a and b*

13

1 In this case, being able to safely lower g by Δg allows not only a reduction in the per-unit
 2 subsidy on a , but a reduction in the per-unit subsidy on b as well. The demand price for a
 3 rises and shifts out the demand curve for b . The outward shift increases the demand price for
 4 b , and so shifts out the demand for a . In the new equilibrium, the SMSs $g' - \Delta g$ and h' can be
 5 brought about with smaller-per unit subsidies: $s_a^1 < s_a^0$ and $s_b^1 < s_b^0$. The reduced subsidy on
 6 a raises the demand price from p_a^{d0} to p_a^{d1} , and lowers the supply price from p_a^{s0} to p_a^{s1} .
 7 Producer surplus in market a is lowered by the shaded area ΔPS_a . Taxpayers save the thick-
 8 bordered area ΔTS_a . We show in the appendix that the drop in the profits of the users of
 9 inputs a and b caused by the increase of the input demand prices can be measured by shaded
 10 area **Y** plus the shaded area **Z**. In market b , taxpayers save ΔTS_b , which is equal to area **Z**.
 11 The welfare of suppliers of input b does not change since the producer price stays constant at
 12 p_b^{s0} . In sum, the rise in aggregate welfare is the cross-hatched trapezoid, approximately equal
 13 to $-\gamma^{**} \Delta g$.

14 Finally, consider the change in aggregate welfare due to the loosening of the SMS on g if
 15 the initial SMS on h had been higher, namely at h'' instead of at h' (figure 3).



1

2 *Figure 3. Effect on social welfare of a marginal change in g given $h'' > h'$ and assuming*
 3 *substitution between a and b*

4

5 With the SMS in market b at the higher level, h'' , the relaxation of the other SMS by Δg
 6 increases social welfare by approximately $-\gamma^{***} \Delta g$, as represented by the cross-hatched
 7 trapezoid. Note that this trapezoid is larger than the corresponding one in figure 2, labeled $-\gamma^{**} \Delta g$. In this illustration, the more restrictive is one SMS, the more beneficial is loosening
 8 $\gamma^{**} \Delta g$. In this illustration, the more restrictive is one SMS, the more beneficial is loosening
 9 the other SMS. The reason is fundamentally tied to the substitutability between the two
 10 inputs. In either market, deadweight is incurred when a marginal unit of the input is produced
 11 at a marginal cost greater than the marginal benefit of its demand. The difference between the
 12 heights of the supply and demand curves in this market at that particular quantity of the good
 13 is the marginal social deadweight from the production and consumption of the inputs. For
 14 example, the more of good b is required by the SMS, the lower will be the marginal benefit of

1 consuming another unit of a , since a and b are substitutes. Thus, if the SMS of h , which is
2 brought about by b , is raised, more b must be consumed, and the lower is the marginal benefit
3 of consuming a . Therefore, when the restriction on a is loosened, the marginal gain to society
4 is larger than it would have been if the SMS in market b had not been forcing additional
5 consumption of b on consumers.

6

7 **4. Modelling public goods in Jordmod**

8 The analysis above shows that whether two or more public goods are complements or in
9 conflict depends on the specific values of the model's parameters. For that reason, we
10 illustrate these outcomes in Jordmod, a numerical model of the Norwegian agriculture sector
11 which allows the endogenous determination of the marginal costs of achieving SMSs.

12

13 **4.1 Model overview**

14 Jordmod is a price-endogenous, spatial, comparative-static, and partial equilibrium model for
15 the Norwegian agricultural sector in the tradition of Takayama and Judge (1971). It consists
16 of two modules: a supply module and a market module. The supply module comprises
17 optimization models for farms and for the food industry. The farm optimization models
18 generate input-output coefficients for eleven farm types in thirty-two regions by maximizing
19 farm income. The maximization procedure is subject to fixed input and output prices,
20 Leontief technology for intermediate inputs, non-linear cost functions for labour and capital,
21 and subsidies with partly non-linear payment rates. The responses of cereals and grass yields
22 to nitrogen inputs are modelled as non-linear, as is the relationship between milk yields and
23 feed mix. We examined the use of two types of policy instruments: payments which are
24 (partially) regionally differentiated to compensate for unfavourable natural conditions, and
25 sometimes have successively lower rates to counter economies of scale, and commodity

1 policies such as milk quotas. There are further constraints on agronomic practices (e.g., feed
2 requirements, crop rotation and nutrient needs). Data are taken from the economic accounts
3 (BFJ, div.) and farm account statistics (NILF, div.).

4 The food industry optimization models minimize total industry costs subject to volume
5 and regional distribution of raw commodities, transport costs between farms and plants, and
6 processing costs at the plants. Models are set up for the dairy industry and the meat industry.
7 Firms process raw commodities into 41 products for final demand. This setup reflects the
8 close connection between primary agriculture and the food industry. It also allows for a
9 detailed representation of trade and trade policies at the processing stage of the food value
10 chain. Except for the cases of dairy products and meat, fixed processing margins are applied
11 for final demand.

12 The market module consists of 41 final markets. The supply part of the final markets
13 consists of identical farms for each type and region, as well as food industry firms. The
14 number of farms and firms is determined in equilibrium. Final demand enters through linear
15 demand functions that are calibrated to base year levels for each of five market regions
16 aggregated from the production regions. Trade in raw commodities and in final goods occurs
17 between the market regions and the rest of the world at fixed world market prices. Net trade
18 between the world market and the market regions takes place in the presence of trade policies
19 such as import tariffs, import quotas and export subsidies.

20 As will be explained below, the SMSs are modelled as constraints to the model's
21 overall objective function. If binding, the marginal costs of tightening the SMSs (or marginal
22 benefits of loosening them) can be inferred directly from the respective shadow prices in the
23 model's dual solution. If not binding, an SMS imposes no constraint on the economy, and no
24 costs are borne to meet it. In the current approach, we impose the SMSs at the national level,
25 with the exception of one of the agrobiodiversity indicators, which we apply at the regional

1 level. Equilibrium in all markets is found by maximizing the sector's aggregate welfare. In
2 principle, the overall solution is found in an iterative process between the supply module and
3 the market module, by which information on output prices and quantities from the market
4 module are used to update the optimization models in the supply module. In the current
5 approach, only one iterative step was required. The model's base year is 2006.

6

7 **4.2 Defining safe minimum standards in Jordmod**

8 **4.2.1 SMS for food security**

9 According to the FAO, "food security exists when all people, at all times, have physical and
10 economic access to sufficient, safe and nutritious food that meets their dietary needs and food
11 preferences for an active and healthy life" (FAO, 1996). For a developed country like
12 Norway, monetary access to food as well as the food's quality is of minor concern. Defining
13 a safe minimum standard becomes merely a matter of calculating the level of natural and
14 human resources necessary to secure adequate food availability and composition in case of a
15 temporary disruption in foreign food supplies.

16 We calculate the SMS for national food security as depending on the quantities of energy,
17 protein, and fat that Norwegian agriculture would need to generate in the case of an
18 international crisis that cut off imported food supplies to the country (Brunstad *et al.*, 2005).
19 Based on the predicted composition of age and gender in the Norwegian population in 2020
20 (Statistics Norway, 2011), Following the Food and Nutrition Board (2002), we assign the
21 values 2360 kcal/day³, 38 g/day⁴, and 22 g/day⁵ as the minimum daily individual food
22 requirements for energy, protein and fat (table 1). Then we subtract from these estimates the
23 per-capita amounts of energy, protein, and fat that Norway could provide to its citizens from
24 domestic seafood production and domestic grain stocks. The latter two food sources are

³ Estimated Average Requirement (EAR)

⁴ Estimated Average Requirement (EAR)

⁵ Lower end of Adequate Macronutrient Distribution Range (AMDR)

1 exogenous to the model and account for twenty-three percent of the energy requirement,
 2 seventy-two percent of the fat requirement, and the entire protein requirement. The remaining
 3 difference is the required “crisis food production” in Norway.

4

5 **Table 1.** Safe minimum standard for national food security (“crisis menu”)

	Energy ^a	Protein ^a	Fat ^a
Requirement	2 360	38.00	22.00
Seafood	284	38.68	14.33
Grain stocks	267	8.12	1.43
Crisis food production	1 809	0.00	6.24

6 ^a kcal per capita and day for energy, g per capita and day for protein and fat

7 Source: Own calculations based on Food and Nutrition Board (2002), Norwegian Food
 8 Safety Authority (2011) and FAO (2011)

9

10 Our approach improves upon Brunstad *et al.* (2005) as we explicitly take into account that
 11 available resources can be turned into nutrient-providing activities in case of a crisis. We
 12 value the national resource base for its potential nutrient provision, not its observed
 13 provision. For example, arable land is associated with the same yield-based potential nutrient
 14 provision coefficient, independent of the crop currently observed planted. Current and
 15 potential nutrient provision from animal-based food is identical since we abstract from the
 16 possibility of building up animal herds.

17 The indicator for the food security SMS, FS , is defined as the smallest value of the three
 18 nutrient level sub-indicators:

19
$$FS = \min \left\{ \frac{e}{SMS_e}, \frac{p}{SMS_p}, \frac{f}{SMS_f} \right\},$$

20 where e , p and f stand for energy, protein and fat. Food security is obtained when $FS \geq 1$,
 21 that is, when the consumption of all three nutrients are at least as great as their SMSs, and

1 therefore all citizens are fully nourished. The indicator allows for full substitution at the
2 nutrient level (“one calorie is one calorie”), regardless of food source. However, no
3 substitution across nutrients (“one calorie is not one unit of fat”) can help achieve the SMS.⁶
4 The availability of each nutrient $m \in \{e, p, f\}$ for consumption in a crisis is,

$$m = \sum_{i=1}^I a_m^i LEVL^i + SF_m + GS_m$$

5
6 where a_m^i is the per-unit potential provision of nutrient m from activity $i = 1, \dots, I$, and
7 $LEVL^i$ is the current level of activity i . SF_m and GS_m is the provision of nutrient m from
8 seafood and grain stocks, respectively.

9

10 **4.2.2. SMS for agrobiodiversity**

11 Although there is a large literature on agrobiodiversity indicators (Feld *et al.* 2009, Büchs
12 2003), only a few examples exist in which such indicators have been implemented in large-
13 scale agricultural sector models. A main obstacle is that many models operate at most at the
14 regional level whereas the measurement of agrobiodiversity requires site-specificity (Britz
15 and Heckelei 2008). Notable exceptions include Verboom *et al.* (2007) and Britz *et al.*
16 (2011), which feature indicators calculated *ex post*. In our approach, we do not overcome the
17 problem of site-specificity, but the indicators are part of the model’s objective function and
18 affect the equilibrium solution.

19

⁶ This holds particularly for calories and protein. It seems that a fat consumption somewhat beneath the lower end of the AMDR can be compensated by a higher energy intake. However, if the compensation consists of carbohydrates, such a diet increases health risks (Food and Nutrition Board, 2002).

1 **Table 2.** Definition of indicators for agrobiodiversity

Indicator	Definition	Description
Semi-natural grassland (SG_r)	$SG_r = LEVL_r^{SG} / SMS_r^{SG}$	Semi-natural grassland in ha in region r relative to SMS in r
High Nature Value Farmland (HNVF)	$HNVF = \frac{(LD \times NS_c) \times share_c + (RD \times NS_f) \times share_f + NS_o \times share_o}{SMS_{HNVF}}$	Units of High Nature Value Farmland, <i>share i</i> : share of crop group $i = \{c, f, o\}^a$
Landscape diversity (LD) ^b	$LD = \sum_j share_j \log_{10}(share_j)$	<i>Share j</i> : share of crop j on all 12 potential crop activities on arable land
Ruminant density (RD) ^b	$RD = 1.6 - 1.2 \sqrt{LU/AREA}$	<i>LU</i> : unit of ruminants, <i>AREA</i> : total fodder area
Nitrogen surplus for crop group i (NS_i) ^b	$NS_i = 2.25 - 0.97 \log_{10} N_{surplus_i}$	$N_{surplus_i}$ in $kg\ ha^{-1}$, $i = \{c, f, o\}^a$

2 ^a*c*: cereals, *f*: fodder, *o*: other arable crops

3 ^b Sub-indicator for HNVF

4

5 Norwegian agrobiodiversity has weakened, both quantitatively in terms losses in

6 agrobiodiverse-rich land area, and qualitatively as the remaining areas are less rich in

7 agrobiodiversity. Flowery meadows are a particular type of agrobiodiversity rich-area, which

8 have been threatened by the overgrowth of forest caused by reduced or abandoned

9 agricultural activity. Another threat has been the intensification of chemical input use in

10 remaining agricultural areas (DirNat, 2010). Hietala-Koivu *et al.* (2004) underlined the

11 importance of semi-natural areas for the agrobiodiversity of agricultural landscapes. Their

12 agrobiodiversity depends on agricultural activities like mowing and grazing (Olsson and

13 Rønningen, 1999). Table 2 reports how we quantify the state of biodiversity using two

14 indicators. The first is the model's area in semi-natural grassland. This indicator is

15 regionalized. The level of the SMS in region r is set to region r 's base year level of semi-

1 natural grassland. The second indicator measures High Nature Value Farmland (*HNVF*)
2 assessing the relationship between certain types of farming and their environmental outcomes
3 in terms of biodiversity, habitats, and rural landscapes (Eurostat 2015). The formal
4 calculation of the indicator is based on Paracchini and Britz (2007). The *HNVF* indicator is
5 composed of sub-indicators for cereals, other arable crops and fodder. The sub-indicators are
6 calculated for each region and turned into a national value using the regions' shares. Building
7 on the idea that agrobiodiversity increases with a richer crop composition and lower nitrogen
8 surpluses, the contribution of cereals is defined as the product of landscape diversity (*LD*)
9 and nitrogen surplus on cereals (NS_c). The contribution of fodder takes into account ruminant
10 density (*RD*) and nitrogen surpluses in fodder (NS_f) production. It assumes that *HNVF* is
11 positively correlated with a decrease in *RD* and a reduction of NS_f . For other arable crops,
12 only nitrogen surpluses NS_o are considered. The overall *HNVF* indicator is defined as the sum
13 of the three indicators for cereals, other arable crops and fodder weighted with their
14 respective national shares. The SMS is set to the national level in the base year, and the
15 indicator is defined as the actual national level of *HNVF* divided by the national level
16 required by the SMS. This definition allows for some flexibility between regions and between
17 the three sub-indicators.

18

19 **4.2.3. SMS for GHG emissions**

20 The Norwegian agricultural sector is responsible for twelve percent of the national GHG
21 emissions, but only 0.3 percent of GDP. The main sources are methane from the metabolisms
22 of ruminant animals, nitrous oxide from fertilizer and animal manure, and the release of
23 carbon from the ground when fields and marshlands are ploughed (Trømborg *et al.*, 2007).

24 Total Norwegian GHG emissions account for less than 0.5 percent of global emissions
25 levels (UNFCCC, 2011), and reducing GHG emissions from Norwegian agriculture would

1 have an insignificant impact on the earth's climate. Implementing a safe minimum standard
2 to sustain global emissions levels would thus be meaningless. However, reducing GHG
3 emissions from Norwegian agriculture could be a by-product of making the economy more
4 efficient (Blandford *et al.*, 2010). If there were attributed no value to the public goods
5 generated in agriculture, then the value of the sector would, consist of of little else than the
6 market value of the food production. In this case, reducing national emissions from
7 agriculture could come at a negative social cost. The government could simply reduce its
8 subsidies, and the overall result would be lower national GHG emissions and a more efficient
9 economy.

10 In order to avoid emissions leakages and achieve complete internalization of a potential
11 carbon price for all Norwegian food consumption, we extend the reduction commitment to
12 food imports and feed imports. Emissions related to food imports are taken from Britz and
13 Witzke (2011), while emissions related to feed imports (soybean meal) are from Dalgaard *et*
14 *al.* (2008). Further, we implement two alternative GHG emissions reduction approaches:

- 15 - 'Emissions cap' assumes a twenty percent reduction of agricultural GHG emissions
16 from base year levels. The reduction rate is the same as for other sectors and based
17 on Norway's official commitment.
- 18 - 'Emissions tax' assumes a tax of 350 NOK per ton CO₂-equivalent, which roughly
19 corresponds to the upper limit of market analysts' (CCC, 2009) expected 2020 quota
20 price range for the EU CO₂-emissions permit scheme.

21 We define the indicator for GHG emissions as $GHG = LEV_E/SMS_E$, where LEV_E and
22 SMS_E are defined as the current GHG emissions level and GHG emissions level required by
23 the SMS. SMS_E is defined as eighty percent of base year GHG emissions levels from
24 domestic food production, food imports and feed imports. This means that total emissions
25 reductions will be the sum of emissions reductions from the Norwegian agricultural sector

1 and carbon leakage through imports. The indicator takes values between zero and infinity. It
2 will be unity if GHG emissions are reduced to the level of the SMS. Lower (higher) values
3 indicate that actual GHG emissions are lower (higher) than the level of the SMS.

4

5 **5. Scenarios examined in Jordmod**

6 The baseline is constructed as a continuation of current policies (i.e., subsidies, milk quotas
7 and tariffs) and other trends affecting the agricultural sector. The model's simulation year is
8 2020. Values of exogenous variables are projected based on historic trends and available
9 forecasts⁷.

10 The results of the theoretical model show that SMSs influence each other under certain
11 conditions. We elaborate this point by defining three scenarios for each of the emissions cap
12 and emissions tax approaches to GHG emissions: (1) food security (FS), (2) agrobiodiversity
13 (BD), and (3) food security and biodiversity combined (FSBD). This gives a total of six
14 scenarios in addition to the baseline. Contrary to the baseline, current import tariffs and
15 subsidies are set to zero in the six scenarios. The model then generates shadow prices of the
16 SMSs in the absence of support. These shadow prices will indicate the undisturbed least-cost
17 payment rates necessary to achieve the SMSs, illustrating what a least-cost support system in
18 the scenarios would look like.

19

20 **6. Selected results**

21 This section presents the simulation results of the modelling exercise. First, we report the
22 levels of the public goods and bads under the different policy scenarios, paying particular
23 attention to which SMSs bind and which do not. We then present the corresponding shadow

⁷ Trend growth per annum in important exogenous variables: Inflation: 2.5 % (Statistics Norway, 2010). Population growth: 1 % (Statistics Norway, 2010). Real interest rate: 1.9 % (Statistics Norway, 2010). Nominal world market prices: 1.0 – 5.0 % (OECD and FAO, 2011). Technical progress (input savings) at farm level (except labour, capital and N needs, which are endogenously determined): 0.5 % (own assumptions). Technical progress at food industry level: 1.0 % (own assumption).

1 prices and discuss these in the light of the results from the theoretical model. We discuss how
2 the simultaneous satisfaction of the SMSs of food security and agrobiodiversity affects GHG
3 emissions from domestic production and imports. Finally, we examine how the various parts
4 of the agricultural sector adapt to the imposition of SMSs, and the implications for production
5 and social welfare.

6 In table 3 we report the values of the indicators for food security, agrobiodiversity and
7 GHG emissions under the six scenarios. The baseline illustrates that a continuation of current
8 policies will lead to cases of undersupply and of oversupply of the various public goods,
9 relative to the SMS. The food security requirement is highly overshoot, ninety percent above
10 the SMS, indicating that the public good is supplied at excessive social cost. Regarding
11 agrobiodiversity, semi-natural grassland is slightly undersupplied (0.99 in table 3), while the
12 level of High Nature Value Farmland farmland is at 1.05, and thus above the SMS of unity.
13 Finally, GHG emissions increase to over thirty percent above the level of the SMS (1.31 in
14 table 3). These results imply that if satisfying the SMSs is a main purpose of the Norwegian
15 government's intervention in agriculture, policies are clearly misspecified.

16 In all six scenarios, GHG emissions fall from the baseline value of 1.31. Under the carbon
17 cap, the SMS is not binding, and the emissions tax proves to be higher than necessary to
18 achieve the reduction requirement. The required GHG emissions reductions are hence not in
19 conflict with maintaining food security and/or agrobiodiversity in the current state of the
20 Norwegian agricultural sector. This particular result is driven by the values set for the SMSs.
21 One can easily imagine that GHG emissions reductions would eventually conflict with the
22 two other public goods, if the reduction requirement were sufficiently strengthened. The
23 emissions in FSBD are significantly higher than in scenarios FS and BD. Moving from
24 scenario FS (BD) to FSBD is thus an example of tightening an SMS on biodiversity (food
25 security), as discussed in section 3. Since the tightening of the SMS in FSBD relative to FS or

1 BD leads to an increase in GHG emissions, there are conflicts between GHG emissions
 2 reductions and each of the public goods food security biodiversity.

3

4 **Table 3.** Policy indicators by scenario

	Baseline	Emissions cap			Emissions tax		
		FS ^a	BD ^a	FSBD ^a	FS ^a	BD ^a	FSBD ^a
Food security	1.90	1.00	0.64	1.00	1.00	0.63	1.00
GHG emissions	1.31	0.60	0.63	0.77	0.59	0.61	0.76
Agrobiodiversity							
- Semi-natural grassland	0.99	0.04	1.00	1.00	0.08	1.00	1.00
- HNMF	1.05	1.50	1.05	1.19	1.44	1.07	1.22

5 ^a FS: Food security, BD: Agrobiodiversity, FSBD: Food security and agrobiodiversity

6 Source: Own calculations.

7

8 The relationship between food security and agrobiodiversity is more complex and
 9 depends on whether the two public goods are addressed jointly. Sole focus on food security
 10 (FS), where the SMS is binding, results in a semi-natural grassland indicator value far below
 11 one, meaning that there is no strong relationship with semi-natural grassland. On the other
 12 hand, the actual level of High Nature Value Farmland is higher than its SMS, indicating a
 13 positive relationship. Sole focus on agrobiodiversity (BD), where the SMS is binding for
 14 semi-natural grassland, but not for HNMF, indicates some complementarity with food
 15 security, but not enough to achieve the SMS. Although the scenario solution implies that
 16 more than enough protein and fat can be produced during a crisis⁸, only about sixty percent of
 17 needed calories can be produced. We see the complementarity with respect to grassland,
 18 ruminants and other livestock. However, sole focus on agrobiodiversity implies relatively low
 19 levels of arable land, laying hens and poultry, which are relatively efficient for calorie

⁸ This holds for all SMS-scenarios, so our focus in the rest of the article will be on calorie production when we discuss food security

1 production. If food security and agrobiodiversity are addressed jointly (FSBD), both the
 2 SMSs for food security and semi-natural grassland are binding, whereas the SMSs for the
 3 HNVF index and GHG emissions are non-binding.

4 Looking at how the supply of public goods varies among scenarios, we see that the SMSs
 5 of food security or semi-natural grassland are binding restrictions that will generate shadow
 6 prices. However, when one of these SMSs is binding, the supply of HNVF will be above its
 7 SMS, indicating complementary public goods in this aspect. The conflict between the public
 8 goods lies in supplying semi-natural grassland and supplying food security, at least when
 9 maintaining SMS levels. This conflict has consequences for the shadow prices.

10 The shadow prices for the SMS illustrate in more detail the relationship between the
 11 public goods (table 4).

13 **Table 4.** Shadow prices for SMS and imputed support in baseline and scenarios

	Baseline	Emission cap			Emission tax		
		FS ^a	BD ^a	FSBD ^a	FS ^a	BD ^a	FSBD ^a
Food security ^b		1 545		2 132	1 807		2 101
Agrobiodiversity ^c			18 422	22 709		20 655	24 287
Net support ^d	17 002	4 551	4 143	11 322	4 449	3 676	10 511
- Food security ^d		4 551		6 215	5 314		6 192
- Agrobiodiversity ^d			4 143	5 107		4 645	5 462
- GHG emissions tax ^d					865	969	1 143

14 ^a FS: Food security, BD: Agrobiodiversity, FSBD: Food security and agrobiodiversity.

15 ^b NOK per million kcal

16 ^c NOK per ha

17 ^d million NOK

18 Source: Own calculations

19
 20 The top two lines of table 4 show the shadow prices for achieving the SMSs for food security
 21 and agrobiodiversity, separately and jointly. There is no shadow price for emissions

1 reductions, since the restriction requiring a minimum reduction of thirty percent is not
2 binding in any of the scenarios. We see that at their SMS levels, food security and
3 agrobiodiversity are conflicting public goods. Supplying an additional “unit of food security”
4 (a resource base for one million kcal) is more costly when both food security and
5 agrobiodiversity must be supplied than when food security is supplied alone. The shadow
6 price for food security is thirty-eight percent higher (emissions cap scenario) and sixteen
7 percent higher (carbon tax scenario) for joint production, compared to separate production.
8 We see the same pattern for agrobiodiversity.

9 Under joint production, the effects on the public goods’ shadow prices are consistent with
10 the theoretical model in section 3.2. Some of the inputs for producing the different public
11 goods are substitutes. When comparing scenarios FS and FSBD, we see that the SMS for
12 semi-natural grassland forces the substitution of more calorie-efficient agricultural inputs,
13 thus driving up the cost of providing food security. When comparing BD and FSBD, we see
14 that the SMS on food security drives up the opportunity cost of land, making it more costly to
15 maintain the SMS for agrobiodiversity.

16 Since supplying public goods jointly results in higher shadow prices on each public good
17 compared to when producing them separately, the support requirement for each public good
18 is higher under joint production. Net support with joint production is about thirty percent
19 higher than the sum of support from supplying the public goods separately.

20 The bottom four lines of table 4 show that the total costs of maintaining the SMS in all six
21 scenarios are lower than the costs in the baseline scenario. This is consistent with Brunstad *et*
22 *al.* (2005), though they found possibilities for greater reductions in agricultural support. They
23 estimated that one third of current support levels were sufficient to achieve food security and
24 landscape preservation. We estimate that about sixty-five percent of the baseline net support

1 level is necessary to achieve the SMSs. The main reason for these differences in total support
2 levels is that Brunstad *et al.* (2005) imposed a looser SMS for food security.

3 As discussed above, we see from the results that the public goods food security and
4 agrobiodiversity are conflicting, but we also see that their provision involves some GHG
5 emissions. In addition, we see that achieving the SMSs for both food security and
6 agrobiodiversity results in greater emissions than if only one of the SMSs had to be met. If
7 the emissions cap had been sufficiently more ambitious, emissions reductions would have
8 had a positive shadow price, and the shadow prices of the other public goods would have
9 increased.

10 The theoretical model in section 3 showed that balancing public goods in agriculture
11 involves complex trade-offs, and the simulations confirm this result.

12

13 Table 7 compares the changes in welfare under the SMS-scenarios to the baseline
14 scenario. All of the SMS scenarios entail higher consumer surplus, and lower (or unchanged)
15 producer surplus. In sum, social welfare is 13 per cent - 28 per cent higher in the SMS
16 scenarios than in the baseline. This is in addition to any social welfare attached to the public
17 goods and reduced tax burden.

1 **Table 7.** Key indicators

	Baseline	Emissions cap			Emissions tax		
		FS ^a	BD ^a	FSBD ^a	FS ^a	BD ^a	FSBD ^a
Production index ^b	100	62	35	71	63	35	72
Food price index ^b	100	57	69	55	58	70	56
Welfare ^c	88	113	101	113	113	100	112
Consumer surplus ^c	81	106	99	107	106	99	107
Producer surplus ^c	7	7	2	5	7	1	5

2 ^a FS: Food security, BD: Agrobiodiversity, FSBD: Food security and agrobiodiversity.

3 ^b Baseline = 100

4 ^c billion NOK

5 Source: Own calculations

6

7 Our calculations show that it is possible to simultaneously maintain the safe minimum
 8 standards for both food security and agrobiodiversity and achieve other socio-economic
 9 improvements. These other improvements lead to a forty-two percent decrease in GHG
 10 emissions from Norwegian agricultural production and imports, an increase in the sum of
 11 producer and consumer surplus by twenty-eight percent, and a reduction in the public tax
 12 burden of 6.5 billion NOK per year. These results show that Norwegian agricultural policy is
 13 highly misspecified if the policy goal is to achieve safe minimum standards for public goods
 14 at the lowest social cost. The results suggest major potential for increasing the socio-
 15 economic efficiency of Norwegian agricultural policy.

16

17 **7. Discussion and outlook**

18 The paper provides clear and intuitive definitions of when SMSs of public goods are
 19 complements or in conflict: if loosening an SMS on one public good *raises* the marginal
 20 social benefit of loosening the SMS of another public good, the public goods are

1 complements. In contrast, if loosening a SMS on one public good *lowers* the marginal social
2 benefit of loosening the SMS of another public good, the public goods are conflicting. The
3 theoretical framework suggests that public goods tend to be conflicting when the inputs for
4 producing them are substitutes. In such a case, lowering the SMS for one public good will not
5 only reduce the subsidy requirement for that public good, but also for the other public good,
6 thus reducing the public's support burden and the corresponding Harberger-triangles and so
7 increasing aggregate welfare. When the inputs for producing different public goods are
8 substitutes, a stricter SMS on one public good, will result in a greater welfare increase from
9 loosening the other public good's SMS.

10 Our application of the theoretical framework to the Norwegian agricultural sector using
11 the Jordmod model revealed that the relationships between public goods and the private
12 goods to which they are related can be complex. We therefore argue that general statements
13 on these relationships are not possible *a priori*, but require case studies and modelling
14 activities. Our empirical results largely support the findings of Brunstad *et al.* (2005): if
15 Norwegian agricultural policy is redesigned to pursue maintenance of public goods and
16 reductions of public bads, the need for support is reduced.

17

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24

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1 **Appendix**

2 Here we prove that the loss in the final-product producer's profits in figure 2 is area Y plus
 3 area Z . Assume that producers of the final good x use inputs a and b , and buy them for prices
 4 P_a^d , and P_b^d . They receive an exogenously given price P_x^0 for their output. The SMS level for
 5 the second public good is h' . The following six equations describe market equilibrium, and
 6 under the conditions of the Implicit Function Theorem implicitly define endogenous variables
 7 P_a^d , P_a^s , P_b^d , P_b^s , s_a , and s_b as functions of the parameter g :

8 (A.1) $S_a(P_a^s) = D_a(P_x^0, P_a^d, P_b^d)$

9 (A.2) $S_b(P_b^s) = D_b(P_x^0, P_a^d, P_b^d)$

10 (A.3) $\tilde{G}(S_a(P_a^s)) = g$

11 (A.4) $\tilde{H}(S_b(P_b^s)) = h'$

12 (A.5) $P_a^s + s_a = P_a^d$

13 (A.6) $P_b^s + s_b = P_b^d$.

14 Label the six functions thus defined by the parameter g with asterisks: $P_a^{s*}(g), \dots, s_b^*(g)$.

15 Profits of the producers of the final good are defined as

16 (A.7) $\Pi(P_x^0, P_a^d, P_b^d) = P_x^0 S_x(P_x^0, P_a^d, P_b^d) - P_a^d D_a(P_x^0, P_a^d, P_b^d) - P_b^d D_b(P_x^0, P_a^d, P_b^d)$.

17 Let parameter g change its value from g' to $g' - \Delta g$. Let a path of integration L be defined as
 18 the curve parameterically defined by g , $P_a^{d*}(g)$, $P_b^{d*}(g)$, as g changes from g' to $g' - \Delta g$.

19 Following Kaplan (1984, pp. 291-293), we can write:

20 (A.8) $DP = \int_L \left(\frac{\partial \Pi(P_x^0, P_a^d, P_b^d)}{\partial P_a^d} dP_a^d + \frac{\partial \Pi(P_x^0, P_a^d, P_b^d)}{\partial P_b^d} dP_b^d \right)$

1 The integral on the right-hand side of (A.8) is a line integral, with L being an *arbitrary*
 2 piecewise smooth path of integration in \mathbb{R}^2 , with endpoints (P_A^{d2}, P_B^{d2}) and (P_A^{d3}, P_B^{d3}) (Kaplan
 3 1984, pp. 292-293, especially equation (5.48)). By Hotelling's lemma, we know,

$$4 \quad (\text{A.9}) \quad \text{DP} = \int_L \left(-D_a(P_x^0, P_a^d, P_b^d) dP_a^d - D_b(P_x^0, P_a^d, P_b^d) dP_b^d \right).$$

5 Because path L is an arbitrary one between endpoints (P_A^{d2}, P_B^{d2}) and (P_A^{d3}, P_B^{d3}) , we may
 6 choose the equilibrium price path defined by equations (A.1) – (A.6) as parameter g changes
 7 from g' to $g' - \Delta g$. Call this path E . Because prices along path E are market equilibrium
 8 prices, then market clearing implies demand for input b equals the quantity supplied for all
 9 price couples (P_a^d, P_b^d) along E . Therefore we may write,

$$10 \quad (\text{A.10}) \quad \text{DP} = \int_E \left(-D_a(P_x^0, P_a^d, P_b^d) dP_a^d - S_b(P_b^s) dP_b^d \right).$$

11 Because h remains at h' , the quantity supplied of b is constant at b' in all the equilibria.
 12 Therefore we may write,

$$13 \quad (\text{A.11}) \quad \text{DP} = - \int_E D_a(P_x^0, P_a^d, P_b^d) dP_a^d - \int_E b' dP_b^d.$$

14

15 The first line integral on the right-hand side of (A.11) is the geometric area behind the
 16 equilibrium demand curve D_a^* in figure 2, which is area Y (Just et al. 2004: 316-318). The
 17 second integral is simply $b'(P_b^{d3} - P_b^{d2})$, which is area Z .