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SYNERGIES AND TRADE-OFFS BETWEEN ADAPTATION, MITIGATION AND AGRICULTURAL PRODUCTIVITY: QUANTITATIVE RESULTS OF THE MODEL APPLICATION WITH FINNISH DATA

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The objective of this paper is to present the latest development of the theoretical and empirical models initiated in COM/TAD/CA/ENV/EPOC(2015)43 and policy simulations on the basis of data from Finland. The paper has been written by Jussi Lankoski (OECD Secretariat), Heikki Lehtonen (Natural Resources Institute, Finland), Sami Myyrä (Natural Resources Institute, Finland) and Markku Ollikainen (University of Helsinki, Finland).

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EXECUTIVE SUMMARY

While most governments recognise the need to address the policy objectives of enhanced agricultural productivity, climate change adaptation and climate change mitigation, trade-offs are to be expected between these objectives but are often not identified. Additionally, policy instruments targeting these objectives can also impact other environmental dimensions, such as water quality. Addressing the three objectives requires an understanding of possible alignment or contradictions between policies and their combined effect on these objectives. The purpose of this theoretical and quantitative analysis is to identify, through an empirical application of a theoretical model, the potential alignment or contradictions between various policy instruments on these objectives, providing insight that may contribute to improved policy design.

The theoretical and empirical models used in this paper describe crop production choices made by farmers given different sets of government policies and whereby crop yields can be impacted by climate change (through increased yield variability, decreased yield growth and potentially decreased expected yields). To help assess whether government intervention to address any of the policy objectives − productivity, climate change adaptation and climate change mitigation, along with water quality improvement − induces synergies or trade-offs with the other policy objectives, the models include two important features: it accounts for risks and risk behaviour, and it considers dynamic decision making. To account for risk and risk behaviour, the models consider whether farmers are risk-neutral or risk-averse, whether the productive inputs (e.g. nitrogen fertiliser) are risk-increasing or risk-decreasing (variance of yields increased or decreased with more us of the input), and whether investment in productivity enhancement is input-increasing (increases optimal fertiliser application) or input-saving (decreases optimal fertiliser application). Since farmers' optimal decisions also depend on how they consider the long-term nature of crop yield risks associated with climate change, the model enables to represent inter-temporal choices of input use, land allocation and investment under a given set of policy instruments. This allows one to analyse climate change adaptation as a dynamic decision problem.

The following policy instruments are considered in the model: i) a decoupled crop area payment and a crop yield insurance subsidy to support or maintain farm income, ii) an agri-environmental payment, a nitrogen fertiliser tax, a soil GHG emissions tax (based on GHG emissions propensity of different soil types), and a subsidy for green set-aside to address both GHG mitigation and water quality objectives, and iii) an investment subsidy for adaptive capital to enhance adaptation to climate change.

To identify how these policies interact, the theoretical model is applied to empirical data from Finland. The model aims to analyse and provide insights to the following policy questions:

- How do the stylised individual policy instruments perform in terms of synergies and trade-offs created between productivity, climate change mitigation and adaptation, and water quality objectives?

- In the case of policy packages are there contradictions between signals sent by the different policy instruments in the package regarding productivity, climate change, and water quality objectives?

- Would a different policy mix advance productivity, climate change and water quality objectives with less contradictory signals?

Key results

The analysis in this paper aims to illustrate the potential impacts of stylised policy instruments and policy packages and shed light on incentives created by different types of policy interventions, farmers' responses to these incentives, and the resulting direction (rather than exact magnitude) of outcomes regarding the considered policy objectives. The resulting outcomes depend on the agricultural and environmental contexts as well as the agricultural policy mix in a given country.

In the case of **individual policy instruments** quantitative results suggest that all policy instruments create some trade-offs across policy objectives. In other words, while meeting the objective in one policy area, performance in another area may be worse than having no instrument in place. However, their potential performance can differ greatly in this respect as follows:

- A subsidy for green set-aside, a nitrogen fertiliser tax, and a carbon tax for soil emissions appears to perform well with respect to all other objectives except adaptation to climate change.
- A decoupled area payment appears to provide more trade-offs than other policy instruments as it is simulated to increase GHG emissions and nutrient runoff and decrease total factor productivity and social welfare relative to a situation without policy.
- A crop insurance subsidy and an investment subsidy for adaptive capital seem to be relatively neutral - they do not create strong synergies or trade-offs - although their productivity performance is simulated to be slightly weaker than the benchmark provided by the market solution without government policy intervention.
- A decoupled area payment, a crop insurance subsidy, and an investment subsidy for adaptive capital appear to perform well with respect to adaptation.

In the case of **policy packages** the results illustrate that relative to **market solution** (without policy intervention) the stylised policy package consisting of a decoupled crop area payment and an agri-environmental payment is expected to shift land from idle land to cultivated crop land. The increased acreage under crop production could increase aggregate nutrient runoff and GHG emissions even though per hectare GHG emissions and nutrient runoff decreases (this is due to the fertilizer application constraints of agri-environmental payment). Hence, the extensive margin effect (increased emissions due to area expansion) dominates intensive margin effect (reduced emissions per ha). In this scenario, the increased crop production is not expected to offset the increased environmental damage and thus social welfare would be lower than under market solution.

Results further illustrate that modifications to the aforementioned policy package (a decoupled crop area payment and an agri-environmental payment) could improve adaptation and productivity performance when part of the decoupled crop area payment is allocated to crop yield insurance. The environmental performance (the reduction of GHG emissions and of nutrient runoff) is expected to be greatly improved by replacing an agri-environmental payment with environmental taxes (i.e. a nitrogen fertiliser tax and a soil GHG emissions tax), although this policy instrument switch would have somewhat negative impacts on productivity and adaptation. However, overall, the switch would be expected to lead to the highest level of social welfare within the context of the analysed policy packages.

On the basis of model simulations, overall productivity growth from the reference scenario of 2020 to 2060 under climate change is calculated to be 42.4% in the case of total factor productivity, indicating relatively slow productivity growth on an annual basis (less than 1%).

1. Introduction

1. While most governments recognise the need to address the objectives of enhanced agricultural productivity, climate change adaptation and climate change mitigation in a consistent way, synergies and trade-offs are likely to exist and need to be identified to improve policy design and implementation. Addressing the three objectives requires an understanding of possible synergies and trade-offs between policies promoting these objectives. Given that policies targeting these objectives can also impact other environmental dimensions, such as water quality, the impact of policies on water quality will also be considered when assessing the consistency of signals across various objectives.

2. A theoretical model and quantitative applications were developed for identifying potential synergies and trade-offs across various policy instruments addressing climate change and productivity objectives in COM/TAD/CA/ENV/EPOC(2015)43 and COM/TAD/CA/ENV/EPOC(2016)16. The theoretical model describes crop production under crop yield risk (increased variability of yields, decreased yield growth, and potentially decreased expected yields in certain locations) impacted by climate change.[1] The theoretical framework is a combination of an agronomic model and the expected utility framework. The latter describes the risk-attitudes and risk-behaviour of farmers. The agronomic model is based on a heterogeneous land quality framework, in which allocation of land between alternative crops, tillage methods, and the entry and exit of arable land are endogenous. While farmers are assumed to be risk-averse, the risk-neutral government designs policy instruments to alleviate uncertainty (Arrow and Lind 1970).[2]

3. Farmers' choices under uncertainty are characterised in the absence and presence of policy instruments. The theoretical model allows a comparison of incentive effects of alternative policy instruments qualitatively. Two versions of the model have been developed: a static and a dynamic model. The latter allows one to analyse climate change adaptation as a dynamic decision problem. The theoretical model can be used to characterise qualitative impacts of policy instruments and to provide recommendations concerning consistent policy design regarding the different policy objectives. The model includes the following policy instruments: a decoupled crop area payment, an agri-environmental payment, a nitrogen fertiliser tax, a soil GHG emissions tax (based on GHG emissions propensity of different soil types), a subsidy for green set-aside, an investment subsidy for adaptive capital, and a crop yield and revenue insurance subsidies. It should be noted that the potential problem of "leakage" related to mitigation policy instruments is not considered in this paper. Leakage refers to a situation when mitigation policies in one region raise agricultural production costs which, through trade and price changes, could incentivises an increase in production and emissions elsewhere, partially offsetting the emission reductions in the regulated region.

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1. We focus on the impact of climate change on the production. Climate change may also affect input and output prices, especially over the longer term, and these changes in prices may affect farmers' production decisions. The theoretical model assumes exogenous input and output prices, but different future prices (impacted by climate change) are employed in empirical applications when such information is available. However, designing consistent set of both input and output prices under future climate and socio-economic conditions is challenging.

2. In most cases uncertainty that private agents face is idiosyncratic in the sense that they are independent across farmers implying that some do well and some do poorly in the face of uncertainty. Across the society and by the law of large numbers, these differences even out. Therefore, the government can operate as a risk-neutral and choose policies that can improve upon the distortionary impacts of risk-averse behavior.

4. Government intervention to address any of the policy objectives − productivity, climate change adaptation and climate change mitigation, and water quality improvement − may have synergies or trade-offs with the other policy objectives depending on whether farmers are risk-neutral or risk-averse, whether the productive input (e.g. nitrogen fertiliser) is risk-increasing or risk-decreasing (variance of yields are increased or decreased), and whether investment in productivity enhancement is input-increasing (increases optimal fertiliser application) or input-saving (decreases optimal fertiliser application). Since farmers' optimal decisions also depend on how they consider the long-term nature of crop yield risks associated with climate change, the model allows inter-temporal analysis regarding farmers' choices of input use, land allocation and investment under a given set of policy instruments.

5. The paper presents a quantitative application drawing on data from Finland. The paper is structured as follows. A brief description of the theoretical model is presented in Chapter 2. Key features of the empirical model and Finnish data are presented in Chapter 3. The policy assessment strategy and quantitative results are presented in Chapters 4 and 5, respectively.

2. Synergies and trade-offs between agricultural productivity, climate change adaptation and mitigation: A theoretical model

2.1. Input use and investment

Crop production under risk

6. Let us consider agricultural production under heterogeneous land quality. The land is divided into field parcels which are of the same size and homogeneous in land quality. Land quality differs over field parcels and it can be ranked by a scalar measure *q*, with the scale chosen so that minimal land quality is zero and maximal land quality is one, i.e., $0 \le q \le 1$. Let *G(q)* denote the cumulative distribution of *q* (acreage having productivity *q* at most), while *g(q)* is its density. It is further assumed that *g(q)* is continuous and differentiable. The total amount of land is thus $G = \int_0^1 g(q)dq$.

7. The production function is usually expressed using a productive input (such as fertiliser, pesticide or irrigation water) as an argument, so that production, *y*, is $y = f(x;q)$, where x is the productive input and *q* refers to land quality. Crop production functions indicate how crop yields increase with increasing use of productive inputs. While the above formulation of crop production function reflects certainty, every farmer faces yield uncertainty caused by weather conditions and other factors. These risks can be captured using a simple but helpful approach suggested by Just and Pope (1978), who present production function in the following additive form:

$$y = f(x;q) + h(x;q)\varepsilon , \tag{1}$$

where ε denotes the yield risk. For theoretical analysis, it is useful to assume that E[ε] = 0 and Var(ε) = 1. Hence, the first term of equation (1) gives the expected yield as a function of productive input. The latter term indicates how the use of productive input impacts risk. This formulation allows us to distinguish between *risk-increasing* and *risk-decreasing* inputs. If *x* refers to fertiliser input, it is regarded as a risk-increasing input in this analysis, so that $h'(x) > 0$ and its use increases the variance of the production.[3] If *x*

3. When variance is taken as the sole measure of risk, nitrogen application usually increases the variance of yields. However, empirical evidence is mixed regarding whether nitrogen fertiliser is risk-increasing or risk-reducing input. In the empirical application on the basis of Finnish data in this paper nitrogen is

refers to the use of herbicides and pesticides, since they are typically regarded as risk-reducing inputs, then $h'(x) < 0$ indicating that increasing the use of x decreases the variance and thus risk of production. The empirical model is flexible and allows selecting nitrogen fertilizer to be risk-increasing, risk- decreasing or risk-neutral input depending on the underlying empirical evidence for a given application.

Enhancing agricultural crop yields and input use efficiency[4]

8. The farmer can invest in new technology (for example, precision farming equipment) to improve crop yields or efficiency of input use (that is, technology investments may serve multiple objectives). We let the investment be continuous, k, but it can be treated as a discrete investment as well. We assume for simplicity that investment does not impact the variance of yields.[5] We allow for a choice between current conventional tillage and new more climate-resilient cultivation method (e.g. no-till) (denoted by i = 1,2). Hence, the expected crop yield function under these tillage methods can be expressed as a function of inputs x_i and k, $y^i = f^i(x_i, k; q)$.

9. By assumption, the investment improves crop yields under both cultivation methods (current and climate resilient), that is, the first partial derivative is $f_k^i > 0$. We further assume that the investment has diminishing marginal returns and, thus, the second partial derivative is $f_{kk}^i < 0$. The investment k relates to the use of productive input x_i in three possible ways defined as follows:

> **Input-increasing investment**: the investment increases crop yields and promotes higher use of input. Mathematically, $f_{x_i k}^i > 0$, indicating the investment increases the marginal product of input.
>
> **Input-saving investment**: the investment increases crop yields with a reduction in the use of input. Mathematically, $f_{x_i k}^i < 0$, and the investment decreases the marginal product of input.
>
> **Input-neutral investment**: the investment increases yields and does not change input use. Mathematically, $f_{x_i k}^i = 0$, and investment has no impact on the marginal product of input.

Government can promote productive investments, for example, by providing investment subsidies (e.g. cost-share investment subsidy) to farmers.

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considered as risk increasing input due to low nitrogen use efficiency (60% of nitrogen input on average is only utilised by crop yield) and high crop yield variance in Finland.

4. The agricultural productivity in the theoretical model mainly focuses on productivity changes related to crop yield enhancement and input use efficiency gains.

5. Productivity enhancing technology is assumed to improve expected mean crop yields but not to affect crop yield variability caused by climate change. However, productivity enhancing technology which is assumed to increase the efficiency of nitrogen use might as well decrease the variability of crop yields and not only improve mean crop yield.

2.2. Optimal choices of input use and investment

10. Recall, *i* denotes two alternative cultivation methods, the current method and a new climate-resilient cultivation method (e.g. no-till).[6] In each field parcel the farmer chooses the cultivation method that provides the highest profits, and optimises the use of inputs and investment within the cultivation method. Thus, farmer's decision choices entail both discrete technology choices and continuous production choices. The model is solved in a recursive manner: production is optimised under both cultivation methods and the one providing the highest profit is chosen. Since land quality is homogenous within each field parcel there is a corner solution and the whole field parcel is cultivated with the method providing highest profits. However, profitability of cultivation methods differs over heterogeneous land quality and thus there are two unique critical land productivities that define: i) land allocation between cultivated cropland and idled land and ii) cropland allocation between different cultivation methods. That is, a minimum productivity of land below which land is not allocated to crop production and a critical productivity of land denoted q^c at which the land allocation switches from one tillage method (or crop) to another (see, for example, Lichtenberg, 2002). Thus, there exists a land quality level for each cultivation method, denoted $\hat{q}_i$, for which the profit is zero. Without a loss of generality it can be assumed that this marginal land quality is lower for traditional cultivation method (1) than for new cultivation method (2). Second, we assume that output of cultivation method 2 per unit land area is more responsive to increases in land quality than output of cultivation method 1, that is $f_q^1(x_1;q) < f_q^2(x_2;q), \forall q$. Third, it is assumed that at land quality $q = 1$ cultivation method 2 has a higher profit than method 1.

11. Let the price of crop be *p,* unit cost of productive input be *c*, per hectare cultivation costs be M_i, unit price of investment be *w* and the decoupled crop area payment be *A*. Cultivation costs M_i include among other things labour (measured in working hours). We assume that capital investment reduces labour input, thus, $M_i'(k) < 0$. Let *E* denote the agri-environmental (A-E) payment that compensates income forgone and extra costs incurred due to participation in A-E scheme (including compliance requirements, such as fertiliser application constraints and buffer strip establishment and management). To make the exposition simpler the upper limit on fertiliser application is translated to an equivalent nitrogen tax, *t.* Furthermore, $\overline{m}$ denotes the mandatory buffer strip and let $h(\overline{m})$ denote the costs of establishing the mandatory buffer strip. Then the stochastic profits of the risk-averse farmer participating in an agri-environmental programme are,

$$\tilde{\pi}^i(\varepsilon) = (1-\overline{m})\left[p(f^i(x_i,k;q) + h(x_i)\varepsilon) - (c+t)x_i\right] - M_i(k) - wk + E - h(\overline{m}) + A. \quad (2)$$

12. The farmer can hedge against the risks by taking insurance, like crop insurance, where the farmer buys coverage for the yield risk. Typically, insurance companies supply a set of coverages for a given set of premiums. Hence, the choice of insurance is a discrete 0-1 choice and determined by the requirement that a farmer must be better off with the insurance contract than without it. Nevertheless, once insured, the farmer's choices may be impacted by the insurance contract and this requires a separate analysis. A typical crop insurance compensates based on the chosen coverage, δ, and yield loss, defined as the difference between agreed normal yield, $\bar{y}$, and actual yield, where yield is below normal. Thus, the compensation is $p\delta(\bar{y}_i - y_i)$, but it is zero if $\bar{y}_i < y_i$. Furthermore let *v* be indemnity and *n* the premium. To examine other potential policy instruments, suppose that the government subsidises crop insurance by a subsidy s_1

6. Powlson et al. (2014) argue that there is abundant evidence that no-till is beneficial for the functioning and quality of soil in many situations (though not all) and resulting soil conditions offer potential for increased resilience to weather variability and climate change.

and investment for adaptive capital (such as improved subsurface drainage) by a subsidy s_2 (see equation 3 below).

13. Another policy instrument to explore is a subsidy for green set-aside. It is assumed that due to the climate and water quality benefits associated with green set-aside, a government provides a subsidy for green set-aside establishment and management. When a given field parcel is allocated to long-term green set-aside, the depleted carbon content of soil starts gradually increasing via sequestration. This process is finite in terms of both quantity and time of soil carbon sequestration. Let *B* denote government subsidy for green set-aside reflecting the climate benefits from sequestered carbon when the costs of green set-aside maintenance and establishment is denoted by z_G. It is natural to assume that low productivity field parcels (that have low opportunity costs) are most likely to be allocated to green set-aside.

14. The stochastic profits under the agri-environmental programme subject to all policy instruments and over all land productivities can be expressed as

$$\tilde{\pi}^i(\varepsilon) = \int_0^1 ((1-\overline{m})\left[p(f^i(x_i,k;q) + h(x_i)\varepsilon) - (c+t)x_i + v(p\delta(\bar{y}-y))) - n(\delta)(1-s_1) - w(1-s_s)k\right] - M_i(k) + E - h(\overline{m}) + A)L_1 + (B - z_G)(1-L_1)g(q)dq \tag{3}$$

where L_1 denotes the share of land allocated to crop production and $L_2 = (1-L_1)$ denotes the share of land allocated to green se-aside.

15. A risk-averse farmer maximises the expected utility from stochastic profits,

$$EU(\pi^i) = E\left[U(\tilde{\pi}^i(\varepsilon)\right]. \tag{4}$$

16. The first-order conditions characterising the optimal choice of inputs and land allocation are[7]

$$x_i : E\left[U'(\pi^i)(pf_x^i + h'(x_i) - v'(p\delta(\bar{y}-y))\frac{\partial y_i}{\partial x_i} - c)\right] = 0 \tag{5a}$$

$$k : E\left[U'(\pi)(pf_k^i - w(1-s_2) - M_i'(k))\right] = 0 \tag{5b}$$

$$q^c : E\left[U'\hat{\pi}^i\right] - E\left[U'\pi^B\right] = 0 \tag{5c}$$

17. Starting with equation (5b), as marginal utility is always positive, it must hold that $pf_k^i - w - M_i' = 0$. Investment increases up to the point where the value of marginal product equals the unit price of investment plus the reduction in cultivation costs. The choice of productive input is more interesting. Assume first that no insurance is present. Then (5a) becomes a product of two uncertain variables and can be expressed as,

7. Optimal input use (x_i) and investment (k) are solved for each differential land quality (q).

$$pf_x^i - c + \frac{\mathrm{cov}(U'(\pi), h'(x_i)\varepsilon)}{E[U'(\pi)]} = 0 \qquad (6)$$

18. The first two terms indicate the choice of a risk-neutral farmer. Reflecting risk-aversion, the third term is the risk-adjustment term. The covariance is negative, as high ε is associated with high π and the marginal utility is decreasing. Therefore, derivative $h'(x_i)$ determines the sign of the risk term. If the input is risk-increasing, $h'(x_i) > 0$, the risk-adjustment term is negative indicating that the use of input is lowered relative to the case of risk-neutrality. If we instead have $h'(x_i) < 0$, so that the input reduces the risk, input intensity is increased above what it would under a risk-neutral situation. Adding insurance modifies the choice leading to an increase in use of risk-increasing input and decrease in use of risk-reducing input.

19. Green set-aside competes with crop production on lower productivity field parcels. By (5c), there is a critical land quality q^c that makes the expected utility from crop production ($\hat{\pi}^i$) and green set-aside (π^B) equal. Thus, field parcels with productivity equal or higher than the critical productivity q^c are allocated to crop production and below that to green set-aside. The mandatory buffer strip does not impact the choice of productive input but affects the size of profits or utility.

20. Comparative statics helps to trace out how policy instruments impact farmers' choices. A feature associated with risk-averse behaviour is that the size of profits (wealth) matters. An increase in an exogenous lump sum income (such as decoupled area payment) may impact optimal choices of inputs and investment as well as land allocation. When a farmer exhibits decreasing absolute risk-aversion, an increase in the lump sum income payment makes the farmer better-off and decreases risk aversion. Thus, the farmer increases input use and input-increasing agricultural investment but decreases input-decreasing investment. The impact of the wealth effect of, for example, the decoupled crop area payment and agri-environmental payment on land allocation is to shift more land to cultivation from green set-aside (if these payments are not paid for land under green set-aside) and the opposite way when payment to green set-aside is increased.[8] An increase in the size of the mandatory buffer strip causes a negative wealth effect and shifts land to green set-aside. Moreover, a risk-averse farmer shifts land from crop cultivation to green set-aside because there is greater risk associated with crop cultivation than with a non-stochastic payment for green set-aside.

2.3. Farmers' inter-temporal choices under climate change

21. There is a need to account for impact of climate change in the long-run, that is, climate change results in lower yields in the future in many areas, and through these changes the profitability of cultivation methods. The prior static model is expanded by introducing a second period. This second period allows incorporating a decreasing trend in yields to represent the effect of climate change.[9] It implies following

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8. We consider the decoupled crop area payment eligible only if a field parcel is kept in a state where farming would still be possible. A parcel going idle, i.e. not maintained in good agricultural condition, would gradually become naturally forested and therefore not suitable for farming.

9. The effect of climate change on crop yield is likely to vary across crops, locations and time. Moreover, the yield change may be absolute or relative to a baseline projection that reflects rising productivity gains. For each empirical case study this assumption can be changed based on available literature for a given crops, location and time.

technical condition $f_1^i(\bar{x}_1^i, \bar{k}) > f_2^i(\bar{x}_2^i, \bar{k})$. Thus, the use of a similar amount of inputs produces lower yields during the second period. Also, it is assumed that the current cultivation method (conventional tillage) performs worse in the second period than the new more climate-resilient cultivation method (e.g. no-till). In addition to the downward trend in yields, the choice of cultivation methods depends on farmers' learning process, which is reflected in the crop yield function during the second period as a multiplicative term, $\sigma_i n$, where *n* refers to the number of farms having adopted the new method; σ_i is a dummy variable, $\sigma_i = 1$ for new cultivation method and $\sigma_i = 0$ for current method. Furthermore, investment made during the first period is assumed to increase productivity during the second period relative to the case without investment.

22. The profit function of a risk-neutral farmer can be expressed as a present value of profits over the two periods, $\Pi^i = \pi_1^i + (1+r)^{-1}\pi_2^i$ where *r* refers to the discount rate. Hence, under the instruments we have

$$\begin{aligned}
\Pi^i = &\int_0^1 ((1-\overline{m})\left[p(f^{i1}(x_{i1}, k; q) + h(x_i)\varepsilon) - (c+t)x_{i1} + v(p\delta(\bar{y}-y))) - n(\delta)(1-s_1) - w(1-s_s)k\right] - M_{i1}(k) + E \\
&- h(\overline{m}) + A)L_1 + (B - z_G)(1-L_1)g(q)dq + \\
&(1+r)^{-1}[\int_0^1 ((1-\overline{m})\left[p(f^{i2}(x_{i2}, k; \sigma_i n, q) + h(x_i)\varepsilon) - (c+t)x_{i2} + v(p\delta(\bar{y}-y))) - n(\delta)(1-s_1)\right] - M_{i2}(k) + E \\
&- h(\overline{m}) + A)L_1 + (B - z_G)(1-L_1)g(q)dq]
\end{aligned} \tag{7}$$

23. Differentiating the profits with respect to input and investment yields,

$$x_{i1} : pf_x^{i1} - (c+t) = 0 \tag{8a}$$

$$k : pf_k^{i1} - w(1-s_2) - M'_{i1}(k) + (1+r)^{-1}(pf_k^{i2} - M'_{i\,2}(k)) = 0 \tag{8b}$$

$$x_{i2} : (pf_x^{i2} - (c+t)) = 0 \tag{8c}$$

The use of inputs is determined by the usual condition: the value of marginal product is equal to the effective input price. The first-order condition of investment is much different from the static case, because now the farmer accounts also for future returns to the investment. Simply, the sum of current and future value of marginal product of investment must be equal to the effective unit-cost of investment. Hence, relative to the static model, investment is increased.

Adoption of new technology and learning

24. Incorporating optimal input use and investment in the inter-temporal profit function allows one to compare the relative profits of current and new cultivation methods:

$$\pi_1^1(x_1^{1*}, k^*) + (1+r)^{-1}\pi_2^1(x_2^{1*}, k^*) > (<)\ \pi_1^2(x_1^{2*}, k^*) + (1+r)^{-1}\pi_2^2(x_2^{2*}, k^*) \tag{9}$$

Relative to comparisons in static analysis, we now have new factors impacting the choice between cultivation methods. Recall that due to climate change crop yields during the second period are lower than for the first period, and by assumption new climate-resilient cultivation methods (e.g. no-till) perform better in these circumstances. Hence, the case for the new cultivation method is strengthened. Also, there is a positive externality present via learning since the marginal impact of each new adopter on productivity increases.

Impact of monetary policy

25. An increase in the real interest rate decreases the use of first period input ($\partial x_1^i / \partial r < 0$) if investment is input-increasing but increases it for input-saving investment ($\partial x_1^i / \partial r > 0$). While this seems very surprising, it can be explained by what happens to investment. Investment is unambiguously decreased ($\partial k / \partial r < 0$) by higher interest rate, so that reduction in the use of input reflects reduction in input-increasing investment and in a similar vein, the increase in input use reflects a reduction in input-saving investment. As input choice is the only continuous decision variable during the second period, we have that $\partial x_2^i / \partial r = 0$.

Adaptation through research and development

26. Suppose that government invests in research and development to produce crop varieties that are better suited to the changing climate. These can include for instance crop varieties that are resistant to drought. Let *Q* denote research and development effort, which increases crop yield resilience and impacts the per hectare (or acre) costs during the second period. They are exogenous to the farmer who cannot affect research and development. To see how research and development impacts the farmer's profits, suppose that research and development enters the second period yield function as follows $p\alpha(Q) f^{i2}(x_{i2}, k, \sigma_i n; q)$. Then, by comparative statics we find that $\partial x_{i1} / \partial Q < 0$ if investment is input-saving and $\partial x_{i1} / \partial Q > 0$ if investment is input-increasing. For investment the effect is negative if investment is input-increasing but ambiguous if investment is input-saving.

3. Description of the key features of the empirical model

Key features of the empirical model

27. The empirical application is built on the key features of the theoretical model. It is calibrated to Finnish agricultural conditions. Two scenarios of crop yield risks are considered: the baseline (without climate change impact) and the climate change scenario, with uncertain yields in both cases. The utility function with a production function is given different parameterisations related to tillage options (conventional tillage or no-till), soil types (clay, mineral and organic soils) and productivity levels and crops (barley, wheat and rapeseed seed). Inter-temporal decisions may have input use decreasing or increasing properties.

28. Eighteen differential regional cases (or production units) are specified in the Finnish data. All cases are run in four different climate scenarios: in 2020 and 2060 for the reference climate and in 2020 and 2060 for the A2 climate change scenario. The model can be solved in cases of static profit or utility maximisation for each scenario, and in the case of dynamic utility maximisation with inter-temporal investment and productivity dynamics between 2020-2060, in a reference scenario and in a climate change scenario. However, in this report we focus mainly on dynamic utility maximising analysis.

29. In insurance systems a farmer has to pay some net costs (premium) for the reduced income variability avoided by a given insurance system. The utility function in the empirical model explicitly works in this way – there is a trade-off between reduced risk and increased cost due to insurance adoption, and a farmer has the option of non-adoption of yield or revenue insurance. Yield and revenue insurance affect the utility function directly by increasing the value of the utility associated with reduced revenue

volatility and increasing the average revenue net of the annual premium (net of government premium subsidy) for the insurance. The model solves the optimal insurance coverage level (between 0 and 1) endogenously and simultaneously with other variables including nitrogen use, capital investment and land allocation.

30. The effect of crop yield and revenue insurance are modelled through four parameters: i) increased expected revenue of each crop in % revenue, **REVENUE**; ii) increased expected yield of each crop in %, **YLD**; iii) net payment for the insurance per area unit of each crop, **NETPAY**; and iv) reduced volatility of revenues due to the insurance in %, **REDREVVOL**.

31. The parameter for REVENUE is very close to zero. This is because insurance loading was expected to be 1.5, which indicates that the insurance company would be including its administrative and operating cost as part of the premiums by multiplying the actuarially fair premium by the factor 1.5. Simultaneously, the government is offering 65% premium subsidy for insurance. Thus loading and premium subsidy will override each other. NETPAY is the fair price for the insurance which will be effective for farmer. Parameters YLD and REDREVVOL are subject to fairly priced yield insurance.

32. Values for YLD and REDREVVOL are estimated using a Monte Carlo simulation with 10 000 draws. Yields are normally distributed. Yield insurance cuts the distribution and cover the average loss below coverage cut point with 100% scale. We simulate a 90% coverage level which describes shallow loss insurance. For the simulation we used yield distribution fitted to simulated water limited barley yield series for the cultivar Kustaa (medium maturity class) for baseline climate (1981-2010) and one future time slices (2071-2100) as projected by IPSL CM4 A2 for location Utti (60.90 °N, 26.90 °E) (Rötter *et al*., 2013). Mean yields of barley decrease by 7.5% and yield variance increase by a factor 2.017 (> 100%) 2020-2060, according to the crop modelling results due to climate change in the A2 climate scenario. These changes are imposed as exogenous changes in the model.

33. The dynamic model is based on a summation of the period-specific utility function optimisation problems, and dynamic capital change equations coupling the time periods. There are two kinds of capital. The first is the capital affecting efficient use of nutrients (e.g. precision farming equipment, drainage investments, or irrigation investments) and the second one is other capital (such as cultivation machinery). The capital affecting efficient use of nutrients depreciates at a slower rate than “normal” capital (machinery). Here we consider drainage investments as representative of the former type of capital, and these have long duration (up to 30-50 years). In contrast machinery investments have shorter productive durations (e.g. due to technological change).

34. The dynamic model also allows the use of a “tillage bonus”, that is, exogenous adaptation benefit (reduced negative impact of climate change on crop yields) for those tillage practices that are presumed to be more climate change resilient. For example, due to less soil erosion, no-till and reduced tillage may better sustain soil productivity under climate change.[10]

10. Tillage bonus is not applied in this application, since there was no crop modelling data available that would have enabled us to quantitatively differentiate the impact of different tillage practices on crop yields under climate change.

The crop production and environmental process functions and data

Crop production

35. Per hectare crop yield is modelled as a function of nitrogen fertiliser application. Mitscherlich yield function is applied for spring barley and wheat to define the optimal fertiliser application and yield level.

$$f(l_i;q_i) = \varphi_i(1-\sigma \exp(-\rho l_i)) \qquad (10)$$

Where l_i is nitrogen application rate in a given field parcel i (i=1…18) and φ_i, σ and ρ are parameters. These parameters have been estimated by Bäckman *et al*. (1997) on the basis of Finnish field experiments. The yield function for rapeseed seed is assumed to have the quadratic form

$$f(l_i;q_i) = a + b_i l_i + c l_i^2 \qquad (11)$$

where a, b_i and c are parameters. These parameters are based on Lehtonen (2001).

36. The three most common soil types in Finland are considered: clay, mineral and organic soil. Clay soils cover over half of the cropland area in Finland, organic soils about 14% and mineral soils 35% (Puustinen *et al.*, 2010). The crop yields depend on soil productivity and soil type and are highest on clay soils and lowest on mineral soils. Soil productivity differences are incorporated through maximum yield parameter, φ_i and slope parameter b_i. Production cost data are based on Tuottopehtori e-service (ProAgria Association of Rural Advisory Centres).

Environmental effects

37. GHG emissions include soil emissions and emissions from cultivation practices including nitrous oxide, carbon dioxide and methane fluxes from the life cycle of crop production (Ervola *et al*., 2012, Annex 1 Table A1 and A2). All soil types are sources of nitrous oxide emissions, and organic soils are also a substantial source of carbon dioxide. Methane fluxes are either very small or even negative (Regina and Alakukku, 2010; Lohila *et al*., 2004). According to Finnish empirical studies, carbon dioxide emission fluxes from agricultural soils are either similar or even greater under no-till compared to conventional tillage. No-till and conventional tillage may not differ in their impact on soil net carbon content, but the carbon is accumulated in different parts of the soil layer keeping the net carbon balance more or less equal (Baker *et al*., 2007; Luo *et al*., 2010). Green set-aside is a carbon sink in mineral soils but a source in organic soils. In order to derive carbon tax for GHG emissions, a constant marginal social damage estimate of €32/ton of CO2-eq is employed (Tol, 2005).[11]

38. The following nitrogen runoff function based on Simmelsgaard (1991) and Simmelsgaard and Djurhuus (1998) is employed,

$$Z_l^i = (1-m^\eta)\phi_i \exp(\gamma_0 + \gamma l_i(1-m)), \qquad (12)$$

where Z_l^i = nitrogen runoff at fertiliser intensity level l_i, kg/ha, ϕ_i = nitrogen runoff at average nitrogen use under tillage methods, $\gamma_0 < 0$ and $\gamma > 0$ are constants and l_i = nitrogen fertilisation in relation to the normal fertiliser intensity for the crop, $0.5 \le l \le 1.5$. The first term in (12) describes nitrogen uptake by the buffer

11. Estimating the climate cost of CO_2 emissions is difficult given the uncertainties over climatic and economic processes in the long term. OECD (2016) uses EUR 30/ton of CO_2-eq as a lower-end estimate of climate cost, which is in line with the values derived from reviews of recent evidence (Alberici et al. 2014).

strips. It is calibrated to reflect Finnish experimental studies on grass buffer strips (Uusi-Kämppä and Yläranta, 1992, 1996, Uusi-Kämppä and Kilpinen 2000).

39. In the case of phosphorus both dissolved reactive phosphorus (*DRP*) and particulate phosphorus (*PP*) are accounted. In compound fertiliser (*NPK*) the three main nutrients are in fixed proportions, which means that nitrogen fertiliser intensity also determines the amount of phosphorus used. Part of this phosphorus is taken up by the crop, while the rest accumulates and builds up in soil *P*. The concentration of dissolved phosphorus in surface runoff depends linearly on the easily soluble soil *P*, and the runoff of particulate phosphorus depends on soil erosion and the P content of eroded soil material.

40. Drawing on Finnish field experiment studies it is assumed that a 1 kg increase in soil phosphorus reserve increases the soil *P* status (i.e., ammonium acetate-extractable P) by 0.01 mg/l soil. Uusitalo and Jansson (2002) estimated the following linear equation between soil P and the concentration of dissolved phosphorus (*DRP*) in runoff: *water soluble P in runoff (mg/l) = 0.021*soil_P (mg/l soil) – 0.015 (mg/l)*. The surface runoff of potentially bioavailable particulate phosphorus is approximated from the rate of soil loss and the concentration of potentially bioavailable phosphorus in eroded soil material as follows: potentially bioavailable particulate phosphorus *PP* (mg/kg eroded soil) = 250 * ln [*soil_P* (mg/l soil)]-150 (Uusitalo 2004). Thus, the parametric description of surface phosphorus runoff is given by

$$Z_{DRP}^{i} = (1-m^{\beta})\varpi_i[\psi_i(0.021(\Phi + 0.01*(1-m)P_i) - 0.015]/100 \quad (13a)$$

$$Z_{PP}^{i} = (1-m^{\kappa})\Delta_i[\zeta_i\{250\ln(\Phi + 0.01*(1-m)P_i) - 150\}]*10^{-6}, \quad (13b)$$

where β and κ denote the reductive effect of the buffer strips as regards dissolved and particulate phosphorus runoff, respectively, ψ_i is runoff volume (mm), Φ is soil_*P* (common to all crops) and ζ_i is erosion kg/ha, and P_i is the phosphorus application rate. As in the case of nitrogen, tillage method differences in the runoff of dissolved and the potentially bioavailable particulate phosphorus are captured by parameters ϖ_i and Δ_i, respectively. Soil_ *P* is fixed at 10.6 mg/l on the basis of the average for Finnish soil test samples (MMM, 2004 and Myyrä *et al*., 2005).

Risk preferences

41. Regarding farmers' risk preferences, the flexible utility function developed by Saha (1997) is employed:

$$U(\pi,\sigma) = \pi^{\theta} - \sigma^{\gamma} \quad (14)$$

where θ > 0 and γ are parameters. The risk attitude measure is given by the marginal utility ratio of the utility function, $U(\pi,\sigma) = (\frac{\gamma}{\theta})\pi^{1-\theta} - \sigma^{\gamma-1}$. Risk aversion corresponds to θ > 0 and risk-neutrality to θ =0. Decreasing absolute risk aversion is presented by θ > 0.

4. Description of the policy assessment strategy

42. This paper explores the impact of government policies on the three objectives of enhanced agricultural productivity, climate change adaptation and climate change mitigation by investigating the impact of individual stylised policies as well as stylised policy packages.

43. For the individual policy instruments analysis, a benchmark scenario without any policy called "Market solution" is used to compare the performance of each policy instrument independently. The

individual policy scenarios considered for the analysis include: a decoupled crop area payment; a subsidy for green set-aside; a high coverage crop insurance subsidy; a nitrogen fertiliser tax; a tax for soil GHG emissions; and an investment subsidy for adaptive capital (which in this case is improved subsurface drainage). The stylised policy instruments are defined as follows:

- **Market solution** without government policy intervention
- **Decoupled area payment** (decoupled crop area-based payment, €190/ha)
- **Subsidy for green set-aside** (€ 120/ha for the establishment and management of green set-aside)
- **Crop insurance subsidy** (shallow loss crop yield insurance for barley and wheat; total insurance premium €38-59 /ha; €38/ha in a reference scenario and €59/ha in the climate change scenario). Decoupled crop area payment is reduced by €21.4/ha in a reference scenario and €38.8/ha in the climate change scenario to reflect the government subsidy share of total insurance premium.
- **Nitrogen fertiliser tax** (11% climate damage tax on CO_2-eq emissions from N fertiliser application and calculated as a basis of social damage estimate of €32/ton of CO_2-eq)
- **Carbon tax for soil emissions (**taxing the net GHG emissions linked to nitrogen use and soil carbon dioxide emissions or sequestration (€15/ton CO_2-eq climate damage tax to reflect CO_2-eq emissions from different soil types)[12]
- **Investment subsidy for adaptive capital** (40% cost-share subsidy for improved subsurface drainage)

44. For the assessment of policy packages, **policy package 1**, is used as the benchmark case. It includes the traditional farm income support and agri-environmental policy instruments. This benchmark is then compared to three other policy packages each representing a possible modification of the policy package 1.

45. More precisely the four stylised policy packages considered are defined as follows:

- **Policy package 1** includes: i) the decoupled crop area payment (€190/ha); and ii) agri-environmental payment (A-E scheme) which consist of a farm specific payment associated with nitrogen application constraints (€54/ha) and field-parcel specific payments for the establishment of green set-aside (€100-120/ha).
- **Policy package 2** includes: i) the decoupled crop area payment (€190/ha) and thus, it represents a traditional income support policy and decoupled area payment policy without an agri-environmental scheme.
- **Policy package 3** includes: i) the decoupled crop area payment (€190/ha); ii) agri-environmental payment (A-E scheme); and iii) crop insurance. The decoupled crop area payment is reduced by €21.4/ha in a reference scenario and €38.8/ha in the climate change scenario to cover for the crop insurance scheme and this budget saving is shifted to cover the cost of a public subsidy for crop insurance (this is a budget neutral policy shift). The crop insurance scheme is so called "high

12. This estimate is only half of the CO_2-eq social damage estimate used in other parts of the empirical analysis. Reason for using this lower estimate is that the social damage estimate of €32/ton of CO_2-eq leads to radical reallocation of land from crop cultivation to idled land and afforestation.

coverage or shallow loss" crop insurance scheme (cover 90%, scale 150%, loading 1.5 and premium subsidy 65% of fair price).

- **Policy package 4 (policy package 2 with environmental taxes)** includes: i) the decoupled crop area payment (€190/ha); a nitrogen tax for fertiliser (11%); and a tax for soil GHG emissions (€15/tCO_2). Revenues from these taxes are used to finance a subsidy for green set-asides (€120/ha).

46. The A-E scheme plays a significant role in determining fertiliser application levels and crop yields in the case of different soil types. There are specific upper bounds for nitrogen fertilisation for all crops and they vary between 80-120 kg N/ha on clay soils and mineral soils. The upper bounds are lower in the case of organic soils, 60-80 kg N/ha depending on the crop. Overall, the presence or absence of an A-E scheme in the policy packages makes a significant difference regarding fertiliser use, land use, commodity production and environmental effects.

47. With this selection of policy packages and individual policy instruments, the empirical analysis aims to provide responses to the following policy questions:

- How does the stylised policy mix consisting of decoupled crop area payment and agri-environmental payment compare with alternative policy mixes in terms of impact on productivity, climate change mitigation and adaptation?

- Are there contradictions between the signals sent by the different policy instruments in this stylised policy mix of decoupled crop area payment and agri-environmental payment regarding productivity, climate change adaptation and mitigation?

- Would a different policy mix advance productivity, climate change and water quality objectives with least contradictory signals?

48. Results regarding the impact of policies on water quality are also considered when assessing the consistency of signals across various objectives.

49. To do so the following indicators are used to assess and compare the impact of policy mixes on the policy objectives (productivity, climate change adaptation and mitigation, and water quality):

- For **productivity**, the indicator used is the total factor productivity (TFP). A divisia index is used to calculate outputs and inputs in each policy scenario relative to the reference scenario and the outputs are divided by inputs to get relative productivity levels for policy measures (see Annex 2 for a more detailed description of how TFP is defined and calculated);
- For **climate change mitigation**, the indicator is direct net GHG emissions from agriculture;
- For **adaptation to climate change**, the indicator used is an adaptation index.[13]
- A compound indicator is calculated to estimate **total social welfare** (SW) as the sum of farmers' net return from crop production (total revenue minus costs of production and excluding

13. Adaptation index is a multiplicative power function with constant returns to scale. It has equal elasticity for the investment in adaptive capital, crop yields under climate change and net-revenue from production under climate change. A situation without policy (Market solution) is a benchmark solution and corresponding results from policy instruments are represented as relative to Market solution.

government payment transfers), GHG emission damage, and water quality damage from nitrogen and phosphorus runoff.[14]

5. Results

50. This chapter provides the results of the empirical application of the model to data from Finland. The results for individual policy instruments are presented in section 5.1. The results for the policy packages are reported in section 5.2. These results demonstrate how individual policy instruments as well as packages of policy instruments have an impact on the three policy objectives of enhanced agricultural productivity, climate change adaptation and climate change mitigation.

5.1. Performance of individual stylised policy instruments on the policy objectives

Impact of stylised policy instruments on input use and investment

51. **Table 1** shows that a risk-averse farmer applies less nitrogen than a risk-neutral farmer (assuming nitrogen fertiliser is a risk-increasing input) and invests less for productive capital. Compared to the **Market solution**, which represents a benchmark solution, **Nitrogen fertiliser tax** has a strong negative impact on nitrogen application and investment for both risk-neutral and risk-averse farmers. **Investment subsidy for adaptive capital** increases both optimal nitrogen application and investment as improved subsurface drainage increases crop yields up to 9.5% relative to situation without drainage investment. Other policy instruments have smaller impact on nitrogen application. As economic theory indicates, due to the so-called wealth effect, **Decoupled area payment** has a small increasing impact on nitrogen application in the case of the risk-averse farmer as shown by the difference in nitrogen application intensity results for Market solution and Decoupled area payment. The same small wealth effect also affects the optimal investment under Decoupled area payment because when a farmer exhibits decreasing absolute risk-aversion, an increase in the lump sum income payment makes the farmer better-off and decreases risk aversion and thus input-increasing agricultural investment is increased. In the case of risk-neutral farmer, decoupled area payment slightly increases nitrogen application and investment. The reason for this is that in a dynamic model with endogenous capital a decoupled area payment increases profitability of production and boosts capital investments that increase productivity and thus also optimal fertiliser application increases. **Crop insurance subsidy** slightly increases both optimal nitrogen application and productive investment in the case of the risk-averse farmer. **Subsidy for green set-aside** reduces productive investments for both risk-neutral and risk-averse farmers.

14. Marginal water quality damage from nitrogen and phosphorus runoff is set at €6.8/kg of N-equivalent runoff (Gren 2001). Phosphorus runoff is converted to nitrogen runoff by employing Redfield ratio 7.2. For GHG emissions, a constant marginal social damage estimate of €32/tonne of CO_2-eq is employed (Tol, 2005). Social welfare performance of the given policy instruments are naturally sensitive for these social valuation estimates.

Table 1. Climate Change 2020-60: Nitrogen application for barley (kg N/ha) and investment cost (€/ha)

Stylised policy scenario	Nitrogen application (kg/ha)	Investment cost (€/ha)	Nitrogen application (kg/ha)	Investment cost (€/ha)
	Risk-neutral farmer		Risk-averse farmer	
Market solution	88.4	44.8	88.3	44.5
Decoupled area payment	89.1	48.2	88.7	47.7
Subsidy for green set-aside	88.4	44.1	88.0	43.9
Crop insurance subsidy	-	-	88.4	45.4
Nitrogen fertiliser tax	82.5	42.4	82.1	42.2
Carbon tax for soil emissions	87.2	37.1	87.3	36.8
Investment subsidy for adaptive capital	94.4	49.1	91.7	54.3

Performance of stylised policy instruments regarding policy objectives

52. In this section dynamic solution results are reported for a risk-averse farmer under Climate Change 2020-2060.[15]

53. **Table 2** provides aggregated results for all 18 cases including total crop production; farmers' profits; net-GHG emissions (emissions – soil carbon sequestration) from agriculture sector; nitrogen equivalent runoff; adaptation index value; total factor productivity (TFP); and social welfare (SW).

54. The results in Table 2 show that all policy instruments create some trade-offs across policy objectives, but their performance differs greatly in this respect. A subsidy for green set-aside, a nitrogen fertiliser tax, and a carbon tax for soil emissions provide the fewest trade-offs (they only fail in terms of adaptation) while a decoupled area payment appears to provide more trade-offs than other instruments. A crop insurance subsidy and an investment subsidy for adaptive capital are relatively neutral although their productivity performance is slightly weaker than the reference provided by market solution. A decoupled area payment, a crop insurance subsidy, and an investment subsidy for adaptive capital perform well with respect to adaptation.

55. Relative to a market solution, a decoupled area payment increases crop production but also GHG emissions and nutrient runoff. It therefore does not contribute to GHG mitigation and water quality objectives. Idled land is shifted to crop cultivation and thus a decoupled area payment increases GHG emissions and nutrient runoff mainly through its impact on the entry-exit margin between agricultural use and idled land[16]. Due to shifting crop cultivation towards low productivity and relatively high emission

15. A full set of simulation results (including results for risk-neutral farmer under both reference case and climate change) are available upon request. Assumption of risk-averse farmer and Climate Change 2020-2060 scenario were selected as a benchmark for comparison of alternative policy packages in order to reduce the amount of results to be reported.

16. In many countries eligibility for decoupled payments is determined by a fixed, historical base, so that cropland expansion does not necessarily take place, at least in the short-run. However, in the long run there may be expectations regarding the future update of historical base area, which may create incentives for cropland expansion.

intensive field parcels, a decoupled area payment performs poorly with respect to total factor productivity (TFP). As a result, overall social welfare (SW) is lower than under a market solution without government intervention. On the other hand it performs well with respect to adaptation objectives as both adaptation indicators are below the reference levels provide by market solution.

56. When compared with a market solution, a subsidy for green set-aside shifts land from idled land and barley cultivation to green set-aside. Farm profits are increased slightly and GHG emissions decreased. However, nutrient runoff increases slightly due to a land use change from idled land to green set-aside. Relative to market solution and decoupled area payment, a subsidy for green set-aside performs better with respect to total factor productivity. In this scenario, adaptation performance is weaker, but its overall SW performance is better, albeit still negative.

57. A crop insurance subsidy does not have a major impact on crop production or environmental effects. Moreover, crop insurance subsidy does not have impact on the entry-exit margin between cultivated cropland and idled land as was the case with a decoupled area payment. Wheat cultivation increases slightly and rapeseed cultivation decreases; due to this, nitrogen runoff increases little since wheat is more nitrogen fertiliser intensive crop than rape. Relative to decoupled area payment, farm profits are lower while environmental performance is better, which is reflected in its better performance with regards to SW. Meanwhile, a crop insurance subsidy performs well with respect to adaptation indicators.

Table 2. Climate Change 2020-60, risk-averse farmers (total land area 18ha): total production (tons/year; w=wheat, b=barley, r=rape); land use shares (wheat-barley-rape-green set-aside-idled land; w-b-r-s-i); farm profit, net-GHG emissions (CO2-eq); nitrogen equivalent nutrient runoff, adaptation index value; total factor productivity (TFP); and social welfare (SW)

Stylised policy scenario	Total production, t Land use shares (%)(w:b:r:s:i)	Farm profit, (€/ha)	Net-GHG emissions, t/ha (average)	Nitrogen-eq runoff, kg/ha (average)	Adaptation index (value)	TFP (value)	SW, €/ha
Market solution	w=20.4,b=33.7, r=1.4 27-57-7-0-10	129.5	6.4	15.9	1.000	1.004	-6
Decoupled area payment (€190/ha)	w=17.5,b=41.2, r=1.6 22-70-8-0-0	322.5	7.3	17.8	1.033	0.891	-27
Subsidy for green set-aside (€120/ha)	w=20.4,b=31.2, r=1.4 27-51-7-11-4	134.7	5.8	16.5	0.988	1.131	-4
Crop insurance subsidy (coverage 90%)	w=21.5,b=33.8, r=1.1 28-57-6-0-10	110.8	6.4	16.0	1.048	0.998	-7
Nitrogen fertiliser tax (11%)	w=13.0,b=34.3, r=1.7 17-58-9-0-17	103.9	5.7	13.5	0.923	1.035	14
Carbon tax for soil emissions (€ 15/t CO_2 eq)	w=17.5,b=18.4, r=0.9 22-30-4-0-43	68.4	3.1	11.6	0.819	1.127	41
Investment subsidy for adaptive capital (40%)	w=25.0,b=30.1, r=1.5 32-50-8-0-10	133.6	6.4	16.6	1.221	0.975	-15

58. A nitrogen tax decreases crop production and farm profits but also GHG emissions and nutrient runoff. Due to the negative effects of the tax on profitability of cultivation 17% of farmland becomes idled (share of idled land is 10% in market solution)[17]. Significantly reduced GHG emissions and nutrient runoff more than offset the reduced crop production. Consequently SW is positive and the second highest among the policy instruments analysed. However, a nitrogen tax performs poorly with regards to adaptation.

59. A tax on soil GHG emissions is effective at reducing GHG emissions - as net carbon sequestration takes place - and nutrient runoff. Crop production is reduced, though, and only higher

17. Tax revenue from nitrogen fertiliser tax could be recycled back to farmers, for example, as a cost-share subsidy for adopting GHG mitigation practices.

productivity field parcels are cultivated. Organic soils become idled (or even afforested) due to their high CO_2 equivalent emissions. In fact, 17% of field parcels become forest while 27% are idled under a soil GHG emissions tax. The lowest productivity organic soils are afforested and their GHG emissions are reduced significantly. A further reduction in GHG emissions takes place, as some lower productivity field parcels of mineral and clay soils are idled. Consequently, crop production is allocated to high productivity and low GHG emission intensity mineral and clay soils and as a result this policy leads to high SW performance. A tax on soil GHG emissions is the best performing policy among the policy instruments analysed, although it performs poorly with respect to adaptation.

60. An investment subsidy for adaptive capital (improved subsurface drainage) does not impact on the entry-exit margin between cropland and idled land. Crop production is shifted from barley to wheat and rapeseed cultivation. Relative to a market solution, it does not have major effects on crop production or environment. Nitrogen equivalent runoff is increased slightly due to land allocation shift from barley to wheat. Its productivity (TFP) and SW performance is relatively poor although better than corresponding performance of decoupled area payment. On the other hand it performs well with respect to adaptation.

61. Overall productivity growth from the reference scenario of 2020 (market solution) to 2060 under climate change is 42.4% for total factor productivity, indicating relatively slow productivity growth on annual basis (less than 1%).

62. Table 3 provides the summary of the synergies and trade-offs induced by different stylised policy instruments on the three objectives of productivity enhancement and climate change mitigation and adaptation.

Table 3. The synergies and trade-offs induced by policy instruments regarding the three policy objectives

Stylised policy instrument	Productivity	Mitigation	Adaptation
Decoupled crop area payment	-	-	+
Crop insurance subsidy	-	0	+
Nitrogen fertilizer tax	+	+	-
Investment subsidy for adaptive capital	-	0	+
Payment for green set-aside	+	+	-
Carbon tax for soil emissions	+	+	-

Legend: the table presents changes relative to situation without a policy (so called Market solution): + (improves achievement of policy objective), - (weakens achievement of policy objective), and 0 (no change).

5.2. Performance of alternative policy packages on the policy objectives

63. Table 4 provides aggregate results for risk-averse farmers and for all 18 farm cases including total production; land allocation; farmers' profits; net-GHG emissions (emissions – soil carbon sequestration) from agriculture sector; nitrogen equivalent nutrient runoff; adaptation index value; total factor productivity (TFP); and social welfare (SW). Table 3 presents the core results from different policy packages.

Table 4. Climate Change 2020-60, risk-averse farmers (total land area 18ha): total production (tons/year; w=wheat, b=barley, r=rape); land use shares (wheat-barley-rape-green set-aside-idled land; w-b-r-s-i); farm profit, net-GHG emissions (CO2-eq); nitrogen equivalent nutrient runoff; adaptation index value; total factor productivity (TFP); and social welfare (SW)

Stylised policy scenario	Total production, t Land use shares (%)(w:b:r:s:i)	Farm profit, (€/ha)	Net-GHG emissions, t/ha (average)	Nitrogen-eq runoff, kg/ha (average)	Adaptation index (value)	TFP (value)	SW, €/ha
Policy package 1 (decoupled area payment + A-E payment)	w=20.5,b=31.7,r=3.1 27-58-16-0-0	416	7.1	17.3	0.967	0.879	-40
Policy package 2 (decoupled area payment)	w=20.9,b=37.8,r=1.7 27-64-9-0-0	324	7.3	18.1	1.044	0.872	-37
Policy package 3 (decoupled area payment, A-E payment, and crop insurance subsidy)	w=20.7,b=32.5,r=2.8 27-59-14-0-0	358	7.1	17.4	1.018	0.880	-27
Policy package 4 (decoupled area payment with environmental taxes)	w=12.4,b=32.5,r=3.1 16-54-17-14-0	195	5.7	16.2	0.917	0.841	-15

64. Results in Table 4 show that modifications to the stylised policy package 1 (consisting of a decoupled crop area payment and an A-E payment) in policy package 2 (a decoupled area payment without A-E) improves adaptation performance while its performance is weaker with respect to GHG emissions and nutrient runoff. Policy package 3 improves productivity and adaptation performance while its environmental performance is similar to Policy package 1. Policy package 4 improves environmental and social welfare performance while it has somewhat negative impact on productivity and adaptation.

65. Relative to **market solution** (reported in Table 2), **policy package 1** shifts land from idled land to crop production. The increased acreage under crop production increases nutrient runoff and GHG emissions. In this scenario, the increased crop production does not offset the increased environmental damage and thus social welfare is lower than under market solution. Low environmental and social performance of this policy package is driven by its impact on entry-exit margin between idled land and cropland.

66. In **policy package 2**, the A-E payment is removed from the policy package 1. Farm profits are reduced and land allocation shifts from rapeseed to barley. GHG emissions and nutrient runoff increases

mainly due to the removal of nitrogen fertiliser application limits. Increased crop production (barley) offset increased GHG emissions and nutrient runoff, and thus social welfare is slightly higher than under **policy package 1** although negative. Adaptation performance is improved in **policy package 2**.

67. Replacing a portion of the decoupled area payment with a subsidy for "high coverage (or shallow loss)" crop insurance (i.e. comparing **policy package 1 and 3**) decreases farm profits and increases slightly nutrient runoff. However, it performs better than the current policy package with respect to adaptation and total factor productivity. Social welfare performance is also improved.

68. Replacement of the agri-environmental payment with a nitrogen tax and a soil GHG emissions tax (i.e. comparing **policy packages 1 and 4**) and using revenue raised with these taxes to finance a subsidy for green set-aside shifts land allocation from crop production to green set-aside. Crop production, profits, adaptation and productivity performance are somewhat decreased. Overall social welfare performance is increased relative to policy package 1 due to significantly decreased GHG emissions and nutrient runoff.

69. Overall, the changes considered to the stylised policy mix of decoupled crop area payment and A-E payment all induce some trade-offs, although these trade-offs are relatively minor in Policy package 3.

70. As caveats, the theoretical model and its quantitative application focus on crop production and related environmental effects, but do not consider the livestock sector that plays an important role regarding climate change mitigation in agriculture sector. Also the climate change adaptation options considered in the current modelling framework are quite limited. Considering limitations of available data and uncertainty related to climate change impacts on crop yields (both average yields and variance of yields) and environmental parameters, the quantitative application of the model aims to illustrate the dynamics at play and shed light on the incentives created by different types of stylised policy interventions, farmers' responses to these incentives, and the resulting direction rather than exact magnitude of outcomes regarding the considered policy objectives.

ANNEX 1. GHG EMISSIONS FROM CULTIVATION PRACTICES

Table A.1. GHG emissions of crop cultivation (excluding autonomous soil emissions)*

	Conv. till.	No-till	Note
Mouldboard plough tillage	90		
Harrowing	54		
Grain seeds	151	161	
Nitrogen manufacturing	432[2]	432[2]	4.32 kg CO_2-eq./kg N (1.81 kg CO_2/kg N)
Indirect and direct CO_2-eq. emissions due to N fertilizer application	760[2]	760[2]	0.0255 kg N_2O/kg N
Liming (production, transportation, application)	111[1]	111[1]	139 kg CO_2-eq./ton of lime
Liming (soil emissions)	345[1]	345[1]	431 kg CO_2/ton of lime
Planting	13	27	
Herbicide (manufacture, transportation)	44	70	
Herbicide (application)	13	19	
Harvesting	54	54	
Transportation of harvest to grain dryer	1	1	325 g CO_2-eq./ton, km
Grain drying	119	113	
Transportation of output to processing industry	29	28	
Total kg CO_2eq./ha	**2216**	**2121**	

[1] Lime application is done once in five years with an application rate of 4000 kg/ha.

[2] Emission rate is dependent on amount of nitrogen; rate is calculated for applied nitrogen of 100 kg/ha and converted to CO_2-eq. with GWP 298. As nitrogen is always applied as NPK-fertilizer, emission factors comprise also emissions from phosphorus and potassium.

* (Ervola *et al*. 2012).

Table A.2. Net emission fluxes from barley cultivation in experimental fields with different soil types under conventional tillage, no-till, and green fallow and afforestation*

GHG gas	Clay Soil	Loam soil	Organic
Conventional tillage			
av. CO_2-eq.	1855	2609	12477
CO_2	1468[a]	367[a]	7710
N_2O	1,29[c]	7,54[c]	16,04[c]
CH_4	0,09[c]	-0,18[c]	-0,53[c]
No-till			
av. CO_2-eq.	2094	5619	12322
CO_2	1497[d]	535[d]	6245[e]
N_2O	1,99[c]	17,09[c]	20,43[c]
CH_4	0,15[c]	-0,35[c]	-0,44[c]
Green fallow			
av. CO_2-eq.	-258	-3936	5647
CO_2	-1189[j]	-4695[j]	3240[b]
N_2O	3,15[j]	2,49[j]	8.22[b]
CH_4	-0,32[j]	0,69[j]	-1.65[b]
Afforested field			
av. CO_2-eq.	>-5085	>-5085	3304
CO_2	-5085[f]	-5085[f]	500[g]
N_2O	3,15[j]	2,49[j]	9,5[h]
CH_4	-0,21[j]	0,46[j]	-1,1[h]

* (Ervola *et al*. 2012).

Average CO_2-eq. accounted using GWPs of 298 (N_2O) and 25 (CH_4) (IPCC 2007).

ANNEX 2. DEFINITION AND CALCULATION OF TFP

Total factor productivity is estimated by using Törnqvist approximations for Divisia indices. Divisia index of total factor productivity (TFP) growth can be defined as the growth in scalar output (y = f(x,t; α)), which cannot be explained by the growth in the input quantity index (vector X) over time (t). A simple index method is used because it is otherwise difficult to provide meaningful definitions of real input or real output due to the heterogeneity of outputs produced and inputs used in different time periods or under different policy scenarios. However, it is possible to provide meaningful definitions of input growth and output growth between any two periods of time or between policy scenarios using index number theory. A separate quantity index is calculated for inputs and outputs, and TFP is measured by calculating the ratio between produced output quantity and input quantity.

A Törnqvist index is a discrete approximation to a continuous Divisia index. A Divisia index is a weighted sum of the growth rates of the various components, where the weights are the component's shares in total value. For a Törnqvist index, the growth rates are defined to be the difference in natural logarithms of successive observations of the input (output) components (i.e. their log-change) and the weights are equal to the mean of the factor shares of the components in the corresponding pair of periods (years, if productivity changes are measured over time) or policy scenarios (if productivity changes are measured between policy scenarios).

The estimated input (output) index over time:

$$\ln(Q_t / Q_{t-1'}) = \frac{1}{2}\sum_{j=1}^{k}(S_{jt} + S_{jt-1'})(\ln q_{jt} - \ln q_{jt-1'})$$

where Q_t= Divisia quantity index at time t

S_{jt}= output share of input j at time t

q_{jt}= quantity of the input j at scenario t

j= 1,2,…,k

k= the number of outputs

We used constant prices for all inputs and outputs over time and policy scenarios.

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