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Abstract

We develop a real options model to assess the impact of decoupled payments on agricultural investments. The context that we are addressing is the one set by the Common Agricultural Policy where farmers are eligible for decoupled payments as long as their land is properly maintained. We show that decoupled payments are non-neutral with respect to choices concerning timing and capacity. We find that they; i) induce earlier investment with lower productive capacity; ii) increase the value of the investment option associated with land and iii) reduce the volatility of farm income. A numerical exercise complements our theoretical analysis.

KEYWORDS: Decoupling; Real Options; Land Development; Capital Intensity; Passive Farming.

JEL CLASSIFICATION: C61, Q15, R14.

1 Introduction

The agricultural sector has traditionally been exposed to changes in the natural and economic environment. These changes have called for the employment of resilient policy schemes that can routinely be updated in order to address new challenges. In the European Union (EU) the Common Agricultural Policy (CAP) has been subject to several reforms over the years aiming at the improvement of its efficacy and the rationalization of the incentives provided to farmers and landholders. In this respect, the 2003 CAP reform constitutes a pivotal change since it fully decoupled transfers supporting farmers from the production of agricultural commodities. As of today, EU farmers are eligible for support as long as the *compulsory cross compliance* requirements are satisfied. These requirements are set in order to guide towards an environmentally responsible management of farmland and discourage practices with adverse economic and environmental effects such as the overproduction of unwanted commodities or the abandonment of marginal land.

As the extant literature has shown, decoupled payments affect farming activities in various ways. Among them, the impact on farm investments is perceived as a particularly important one (Sckokai and Moro, 2009). The reason is that investment response will have long-lasting impacts on production and will subsequently be reflected in forecasts and policy recommendations (Serra et al., 2009; Maart-Noelck and Musshoff, 2013).

In this paper, we employ a real options model to study how decoupled payments affect farmers' investment behavior. We consider a landholder contemplating the opportunity to invest in order to convert a piece of idle land into farmland. Upon investment the farmer can switch between two operating states: i) they can employ the installed capital making farming profits when stochastic commodity prices are high enough or, if otherwise, ii) they can suspend farming operations keeping however the land in stand-by mode thanks to the cross-compliance requirements. Notably the farmer qualifies for the CAP support irrespective of the actual state. The investment problem that the landholder faces is twofold since they need to choose the level of productive capacity characterizing the land development project and the timing of the investment at the same time. These two choices are distinct but not independent since investing in order to have a higher productive capacity is also more costly and hence the market conditions that favour it are more demanding.

Within this framework we find that an increase in decoupled payments accelerates farm investments and reduces the chosen productive capacity. The intuition is as follows. When the market conditions are favorable and the farmer is actively farming the developed land they have two sources of income, the profits from producing and selling agricultural commodities and the CAP support. When instead the conditions are unfavorable, the farmer is passively farming having access only to the latter. The decoupled payments are then influencing the farmers' income composition which does not depend exclusively on volatile farming profits but is implicitly receiving downside protection through the CAP. At the same time, eligibility for CAP support is conditional on land maintenance which guarantees that passively farmed land is readily available to become actively farmed as soon as the market conditions allow for it. The landholder responds to this policy by updating both their investment timing and capacity choice. In particular, they opt for earlier investment in order to get access to the decoupled support as early as possible and choose a lower capacity both in order to save in terms of investment cost and consequently in terms of waiting time, but also because profits coming from farming activities are not the only source of income for them. Apart from the impact on farmers livelihood, this response has broader implications since it is addressing the land abandonment issue as well by fostering the transition towards a productive state of land.

The paper proceeds as follows. In Section 2 we discuss the policy background and the extant literature. Section 3 presents the basic set-up, in Section 4 we derive the farm's operating value, and in Section 5 we determine its optimal productive capacity. In Section 6 we examine the value and the timing of the investment and in Section 7 we discuss the effects of the policy both analytically and numerically. Section 8 concludes.

2 Policy background and literature overview

2.1 The CAP

The CAP was firstly launched in 1962 with main objectives the provision of affordable and safe food for EU citizens and a fair standard of living for EU farmers (EC, 2012). To this end, it has provided financial support based on a two-pillar structure. Pillar I support includes direct payments to farmers and market intervention measures. Pillar II support focuses instead on promoting rural development. Over the last three decades, Pillar I has undergone a gradual change and support decoupled from production has replaced the instruments that were initially used. This change was motivated by the intention of the EU member states to increase the competitiveness of the farming sector and to preserve natural resources. The reason is that historically coupled subsidies exerted a strong influence on production as they were directly linked to activity levels through, for example, livestock numbers and crop area (EC, 2021b).

After the initial partial decoupling of agricultural support through the 1992 MacSharry and Agenda 2000 reforms, the 2003-CAP reform introduced full decoupling, a measure that the 2013-CAP reform has further cemented. Since then farmers must comply with legislation within the areas of the environment, public and animal health and welfare as stated in the Statutory Management Requirements (EC, 2021a) in order to be eligible for support. At the same time, farmland must be kept in Good Agricultural and Environmental Condition (GAEC) which refers to a set of standards related to soil and habitat protection as well as water management (Ciaian et al., 2010; Brady et al., 2017a,b). GAEC is also linked to the prevention of land from being abandoned since abandonment of marginal land would have serious implications for conservation of biodiversity, cultural landscapes and future production potential. For this reason farmland that cannot be readily used in production is not eligible for direct payments. Accordingly, most EU member states have introduced minimum agricultural activity requirements which guarantee the maintenance of land in a state which makes it suitable for grazing or cultivation. For instance, pastures must be grazed by animals each year while arable land can be managed mechanically with mowers to keep the vegetation down (Hristov et al. 2017). As noted by Brady et al. (2009); Renwick et al. (2013) and Söderberg (2016) had it not been for agricultural activity as an eligibility condition, marginal land would be abandoned.

2.2 Decoupling and passive farming

The main argument against the use of coupled payments is that they perversely influence production decisions at the farm level. Nevertheless, it is widely accepted that decoupled payments also exert influence on farming activities. The OECD (2001) conceptual paper analyzes some of the possible mechanisms through which decoupled payments may affect output and trade. It distinguishes broadly between static and dynamic effects of decoupling. The former arise whenever policies affect farmers' income by influencing input and output prices. The latter instead affect farm-level investment decisions. Hennessy (1998) analyzes the impact of decoupled payments on risk preference of farmers which can be altered by decoupled payments due to wealth and insurance effects. Additionally, by increasing the total cash flow, decoupling relaxes a farmer's credit constraints (Goodwin and Mishra, 2006; Bhaskar and Beghin, 2009) and alters the allocation of the factors of production (Ahearn et al., 2006). Decoupled payments may also affect labor/leisure choices, land values, land-use transitions, entry-exit decisions and the technical efficiency of the farm (Guyomard et al., 2004; Moro and Sckokai, 2013; Varacca et al., 2021). The impact of decoupled payments on farm investments has also attracted significant attention since investments critically affect farm operations in the long run. According to O' Toole and Hennessy (2015) decoupling affects investments mainly through financial channels since it facilitates the quick recovery of investment costs, it protects the farmer's income and it makes them more credit worthy.

Another notable effect of decoupling, provided that it is conditioned on cross compliance, is that it contributes to the preservation of marginal land (Van der Zanden et al., 2017). While the profitability of high-yielding land is not dependent on CAP support, marginal land may not be profitable and hence in the verge of abandonment. In this respect, Chau and De Gorter (2005) and De Gorter et al. (2008) find evidence that decoupled payments provide incentives to low productive farms to remain in the market. In fact in some regions of the EU as much as 10% of the agricultural area is not used for production, but it is maintained to meet the cross compliance land management obligations (Trubins, 2013; SCB, 2016). Landholders who manage most of their farmland in this way are referred to as passive farmers, while those producing commodities are called active farmers (Ander, 2012a,b). Active and expansion-oriented farmers have expressed for long their skepticism when it comes to the support of passive farmers arguing that passively farmed land is underutilized (Ciaian et al., 2010; Trubins, 2013), and that it constitutes a potential threat to food security (Renwick et al., 2013). It should be noted though that such characterizations are empirically unfounded. Instead passive farming has been shown to occur exclusively on land of low productivity that is not consistently profitable for commodity production. Passive farming has been instead associated with the provision of valuable public goods such as the preservation of marginal farmland and, by deterring land abandonment, future food security (Brady et al., 2017b).

2.3 The real options approach

A variety of theoretical and empirical methods has been employed for the analysis of the effects of decoupling on farmers' behavior. Among them, multi-period dynamic models have the capability of analyzing farmers' decisions with long-term effects such as investments (Moro and Sckokai, 2013).[1] To this end, the real options approach (ROA) has been established as a comprehensive explanation concept for farmers' investment behavior (Abel and Eberly, 1994; Dixit and Pindyck, 1994; Purvis et al., 1995; Wossink and Gardebroek, 2006; Pieralli et al., 2017). By the analogy between an American call option and a real investment, the ROA asserts that an investor can benefit from deferring an investment instead of undertaking it immediately if investment costs are at least partially irreversible and future investment returns are uncertain. The reasoning is that the value of an investment option has two components: the intrinsic value, which is equal to the classical NPV, and the value of waiting (Lambarraa et al., 2015). By investing, the investment option holder gives up the opportunity of waiting for new information with a potential positive effect on the profitability of the investment. This lost continuation value is an opportunity cost that should be added

[1] Continuous time is the standard assumption since it allows full differentiability when deriving the dynamic programming equation. However simpler models may be adopted in a discrete time framework, see e.g. Feinerman and Peerlings (2005).

to the investment costs (Feil et al., 2013). Notably, the ROA accounts for irreversibility, uncertainty and managerial flexibility and consequently generates results that are different from those generated by the standard NPV rule, which takes a "now-or-never" perspective when evaluating the investment decision (Musshoff et al., 2013). There have already been many empirical applications of the ROA to agricultural investment decisions (e.g. Purvis et al., 1995; Richards and Patterson, 1998; Pietola and Wang, 2000; Carey and Zilberman, 2002; Odening, Musshoff and Balmann, 2005; Hill, 2010). The ROA has been also applied more broadly to the study of land use transitions driven by a policy instrument such as a subsidy. Thorsen (1999) for instance presents the case where the afforestation of degraded land is subsidized; Song et al. (2011), Musshoff (2012) and Di Corato et al. (2013) analyze the use of subsidies to incentivize the cultivation of energy crops; and Schatzki (2003) considers decisions to set aside agricultural land for conservation purposes.

The model most similar to ours is the one presented by Di Corato and Brady (2019). That paper studies the effect of decoupled payments on i) the timing and the value of the option to invest in land development and ii) the bargaining between a potential farmer and a landowner for the definition of the rental payment. A main finding is that decoupled payments cause earlier investment compared to a no-policy scenario and later investment compared to a coupled-payments scenario. Secondly, the authors show that decoupled payments do not deter the potential farmer and the landowner from reaching a deal for the lease of land but, due to their capitalization, merely increase the rental payment. The key difference between our analysis and that presented in Di Corato and Brady (2019) lies in the consideration of the effect of decoupled payments on the managerial flexibility of a farm. In fact, while in that paper the switch from passive to active farming is irreversible, here we allow for a farmer who may switch back and forth over time. This operational flexibility provides downside protection against fluctuating farming profits. A second important difference is that in our model we acknowledge that potential farmers choose both the investment timing as well as the productive capacity that they are investing in. The balance between these two choices proves to be sensitive to changes in the magnitude of the decoupled payment providing a novel perspective to the effect of decoupling on investment decisions and farming operations.

Last, abstracting from its contextualization, our work contributes to the literature stream studying how the interaction between temporal and operational flexibility affects the value and timing of investments under uncertainty and irreversibility.[2] Our work is for instance close to papers such as Dangl (1999); Di Corato and Moretto (2011); Moretto and Rossini (2012); Di Corato and Montinari (2014); Huisman and Kort (2015); Hagspiel et al. (2016) and De Giovanni and Massabò (2018). What distinguishes our work from previous contributions is that while in these papers the available operational flexibility comes at a cost, both explicit, when investing, and implicit, later, due to potential excess capacity, in our paper flexibility comes at no cost as the alternative use of the asset (land) is possible due to the presence of a specific public policy (CAP support). Further, in our paper the operational flexibility is beneficial for the investor, not only because it allows rearranging operations, but also because it secures a risk-free return on the investment undertaken. Our results may then provide useful insight to policy makers intervening, using subsidies, in industries characterized by irreversible investments with uncertain future returns.

3 The basic set-up

Consider a landholder contemplating the development of idle land for crop production. As in Capozza and Li (1994) the underlying investment problem involves decisions about both the timing of development and the capital intensity, i.e. the level of capital investment per unit of land. We denote the capital intensity by $\alpha > 0$ and assume that the sunk investment cost the landholder incurs to develop the land is

$$I(\alpha) = k_1 + k_2\alpha, \tag{1}$$

[2] See, e.g., Kulatilaka (1988, 1993); Triantis and Hodder (1990); He and Pindyck (1992); Bengtsson (2001); Bengtsson and Olhager (2002); Fontes (2008); Li and Wang (2010); Benaroch et al. (2012) and Yang et al. (2014).

where $k_1 \geq 0$ includes any fixed cost associated with the mere conversion of land, e.g. deep cultivation, stone picking, removing brush, and herbicide treatments (see e.g. Miao et al., 2014), while $k_2\alpha$ with $k_2 > 0$ represents the cost associated with a level α of capital investment, e.g. tractors, vehicles, agricultural machinery, implements and equipment.[3]

Further assumptions are as follows:

Project timeline - The landholder contemplates the development of land over an infinite time horizon starting at the current time point $t = 0$. Further we assume that once the investment takes place at a time point $\tau \geq 0$: i) the project runs forever; ii) any generic time point $t \geq \tau$ is the starting date of a growing season with duration dt that we refer to as "growing season t"; iii) the crop completes its lifecycle within one growing season; and iv) at the end of each growing season t, the crop is entirely harvested and sold on the market. Assumption i) is standard and covers projects with finite duration that is long enough to be reasonably approximated, when discounting future payoffs, by an infinite time horizon.

Cross-compliance and decoupled payments - At each growing season $t \geq \tau$, a constant payment s is made to the landholder on the condition that the land satisfies the cross-compliance requirements set by the CAP. The periodic cost of compliance is equal to $m > 0$. We assume that the periodic payment is greater than or at most equal to the compliance cost. Hence, the net periodic payment accruing to the landholder is $p = s - m \geq 0$. This assumption is consistent with the aim of the CAP to support farmers.[4] Further, the CAP also recognizes that countryside services are produced jointly with commodities. This follows from the argument that an important feature

[3] The use of a more general cost function of the form $I(\alpha) = k_1 + k_2 \frac{\alpha^\omega}{\omega}$, with $\omega \geq 1$, would have no qualitative impact on our results.

[4] Notably decoupled payments differ from crop insurance schemes since, provided that the cross compliance requirements are satisfied, they are not contingent on any specific state of nature. Also, $s \geq m$ is a sufficient but not necessary condition for cross compliance requirements to be met. Even if $s < m$ some farmers might still find it optimal to conserve their land in order to preserve its long-term productivity. We thank an anonymous referee for bringing these to our attention.

of the agricultural landscape is that much of its inherent value is dependent on the maintenance of the built environment and cultural features that have evolved jointly with commodity production (Marshall and Moonen, 2002; Benton et al., 2003; Brady et al., 2009). In its simplest form, the cross compliance requirements imply mowing of grass fields on an annual basis (Brady et al., 2009).

Production - Once invested in a land development project characterized by a generic capital intensity level α, the following two post-investment scenarios may occur:

i) active farming: land is cultivated and the crop yield is increasing and concave in α. The crop yield is given by the following function:[5]

$$q(\alpha) = \alpha^{\gamma}/\gamma \text{ with } \gamma \in (0, 1) \tag{2}$$

The concavity of $q(\alpha)$ allows capturing diminishing returns on capital investment. This means that an increase in the capital applied to the cultivation of land produces a less than proportionate increase in the yield;

ii) passive farming: land is not cultivated and $q(\alpha) = 0$.

The unit production cost is constant and equal to $c > 0$. Note that c may include costs occurring at different times during the growing season. For instance, seeds and fertilizers are usually purchased at the beginning of the growing season, while harvest costs are usually paid at its end. Therefore, c should be seen as the sum of all the production costs discounted back to the beginning of the growing season. c can be, because of substitutability between capital and other inputs (e.g. labour) a function decreasing in α. Such a characterization will leave our analysis intact as long as the investment problem (Problem (6) below) remains well posed. Last, we assume that the capital installed does not depreciate. Allowing for capital depreciation would leave

[5]Eq. (2) follows from the assumption of a standard Cobb-Douglas production function. See Section A.1 in Appendix A for its derivation. The Cobb-Douglas functional form is widely used in Agricultural Economics and has solid empirical support (see e.g. Griliches, 1964; Hayami, 1970; Dawson and Lingard, 1982).

our findings qualitatively unchanged (Dixit and Pindyck, 1994, Ch. 7). In this case, the farmer would just wait longer before investing in the land development project.

Costless switching - The farmer can costlessly switch back and forth between active and passive farming. The rationale is that, by design, decoupled CAP support is a policy instrument addressing both the issue of land abandonment and future food security (see e.g. Miao et al. 2014; Schuh et al. 2020). Hence, the cross compliance requirements are presumably guaranteeing that switching between the two farming regimes is smooth. Nevertheless, it is true that cross compliance requirements are specified not at EU but at country level which means that EU member states have the flexibility to tailor the policy to their needs. Therefore, contradictions and inconsistencies between the application and the design of the policy cannot be ruled out but should be treated as exceptions. Allowing for switching costs,[6] would leave our findings qualitatively unchanged. We would only have a larger hysteresis, that is, the farmer would wait longer before switching from active to passive farming, and vice versa.

Commodity price - The commodity price x_t evolves according to the following geometric Brownian motion:

$$dx_t/x_t = \mu dt + \sigma dL_t \text{ with } x_0 = x \tag{3}$$

where μ is the drift parameter, $\sigma > 0$ is the instantaneous volatility and dL_t is the standard increment of a Wiener process.

The commodity price x_t corresponds to the expected present value taken at the time t of the commodity spot price at the end of the growing season, i.e. at $t + dt$, when the crop will be harvested and sold on the market. Alternatively, x_t can be viewed as the present value of the forward price set in a forward contract with delivery at the end of the growing season.[7]

[6]A complete analysis of the impact of switching costs when suspending and restarting a project is presented in Dixit and Pindyck (1994, Ch. 7).

[7]In a risk-neutral evaluation framework like ours, equilibrium forward prices are equal to the expected

Discounting and risk attitude - The farmer is risk-neutral and discounts future payoffs using the interest rate $r > \mu$.[8] Assuming risk-neutrality is standard in the real options literature. There are papers that relax this assumption incorporating risk aversion into dynamic investment models (e.g. Sckokai and Moro, 2009; Serra et al., 2009). However, in such models it is difficult to disentangle the impact of risk aversion on investment behaviour from investment reluctance due to irreversibility and uncertainty (Huettel et al., 2010). As noted by Moro and Sckokai (2013) and Ihli et al. (2014), risk aversion conceals the property of real options models to treat postponed investments as the outcome of optimal dynamic decision-making under uncertainty since risk averse farmers are intrinsically reluctant to invest. Therefore, in an attempt to keep the focus on the effect of irreversibility and uncertainty, we develop our model assuming risk-neutrality.

Last, our investment problem is, technically speaking, a standard optimal stopping problem. The underlying idea is that at each generic time period t the value of immediate investment (stopping) is compared with the expected value of waiting over the next dt (continuation), given the information available at that point in time and the knowledge of the process $\{dx_t, t \geq 0\}$. Therefore, the optimal investment timing results from an optimization of the value at stake given the dynamic of the state variable x_t and having a control variable, u_t, taking two possible values: $u_t = 0$ (stop), and $u_t = 1$ (continue).

Once introduced our model set-up, two final remarks are in order.

First, regarding the source of uncertainty, as already noted above we consider only the

future spot prices. This implies that the two characterizations provided here for x_t are equivalent (see e.g. Luenberger, 1998, Ch. 10).

[8]The condition $r > \mu$ is necessary in order to ensure that the value of the farm converges to a finite value. Note that this assumption is standard in that it makes the problem economically meaningful. In fact, otherwise, i.e. if $r \leq \mu$, the potential investor will never invest since they will always prefer to keep the investment option alive but never exercise it (see Dixit and Pindyck, 1994, p. 138). Last, in order to use an interest rate incorporating a proper risk adjustment, expectations should be taken with respect to a distribution of x_t adjusted for risk neutrality (see e.g. Cox and Ross, 1976).

commodity price. Price volatility has been treated as a main source of uncertainty in several studies on investment in the farming sector (Sckokai and Moro, 2009; Feil et al., 2013). However, it is certainly not the only one. In fact, the dynamic of agricultural incomes over time may very well be affected by the random evolution of yields and production costs (Hennessy, 1998; Kim et al., 2020). Adding these two sources of uncertainty can be done as follows:

i) assume that the crop yield is stochastic and that it is given by the following function:

$$\widetilde{q}_t(\alpha) = \theta_t q(\alpha)$$

where $\theta_t > 0$ is a stochastic term capturing shocks affecting the yield (weather, pests, etc.) and $q(\alpha)$ is the deterministic yield associated with capacity α (as in Eq. (2)). Further, assume that also the commodity price x_t and the production cost c_t are stochastic. The periodic farming profit is then equal to:

$$\pi_t = \widetilde{q}_t(\alpha)(x_t - c_t) = M_t q(\alpha)$$

where $M_t = \theta_t(x_t - c_t)$;

ii) assume that M_t evolves according to the following arithmetic Brownian motion:

$$dM_t = \mu dt + \sigma dL_t \text{ with } M_0 = M \tag{3.1}$$

which allows for both positive and negative realizations;

iii) it then suffices replacing Eq. (3) with Eq. (3.1) and solving the investment problem accordingly.

Second, uncertainty about future policy scenarios may be an issue as well considering that policies like the CAP are routinely updated (see Breen et al., 2005 and references therein). Policy uncertainty concerning for instance the duration of the policy itself and/or changes in the magnitude of the payments granted may be incorporated in our model in the following way. We can characterize any sudden shift through a Poisson process. The flow of payments should then be discounted using a rate adjusted to account for i) the likelihood of a jump in the process, i.e. the intensity of the Poisson process, and ii) the impact of the shift on the payment level (see Dixit and Pindyck, 1994, Ch. 5, pp. 167-173, and Ch. 9, pp. 303-309).

4 The operating value of the farm

At the beginning of each growing season, i.e. at each t, the farmer decides whether land should be actively or passively farmed in that season. Profit maximization requires that the decision taken returns, in expected present terms, the highest possible payoff. Concerning the definition of the payoffs we must take into account that apart from the income associated with farming the farmer receives the CAP net payment p. Hence, the periodic total profit flow is:

$$\pi_t = \begin{cases} q(\alpha)(x_t - c) + p & \text{when actively farming} \\ p & \text{when passively farming} \end{cases}$$

Active farming is the most profitable opportunity when $x_t > c$. Otherwise, i.e. when $x_t \leq c$, the farmer should opt for passive farming. Hence, depending on the price level at each time point, the profit flow associated with the farm is as follows:

$$\pi_t = \begin{cases} q(\alpha)(x_t - c) + p & \text{for } x_t > c \\ p & \text{for } x_t \leq c \end{cases} \tag{4}$$

Further, the farmer can be viewed; when active, as holding the option to suspend farming operations whenever active farming becomes unprofitable , i.e. as soon as $x_t \leq c$ and; when passive, as holding the option to restart farming operations as soon as active farming becomes profitable, i.e. as soon as $x_t > c$.

Let $V(x_t, \alpha)$ represent the operating value of the farm upon investment. Solving the underlying dynamic programming problem, we obtain:[9]

$$V(x_t, \alpha) = \begin{cases} \widetilde{A} x_t^{\beta_2} + E_t \left\{ \int_t^\infty [q(\alpha)(x_z - c)] e^{-r(z-t)} dz \right\} + \int_t^\infty p e^{-r(z-t)} dz & \text{for } x_t > c \\ \widetilde{B} x_t^{\beta_1} + \int_t^\infty p e^{-r(z-t)} dz & \text{for } x_t \leq c \end{cases} \tag{5}$$

where $\beta_2 < 0$ and $\beta_1 > 1$ are the roots of the characteristic equation $\Lambda(\beta) = (1/2)\sigma^2\beta(\beta -$

[9]See Section A.2 in Appendix A.

$1) + \mu\beta - r$,

$$\widetilde{A} = Aq(\alpha) = \frac{r - \mu\beta_1}{(\beta_1 - \beta_2)r(r - \mu)} c^{1-\beta_2} q(\alpha) > 0, \tag{5.1}$$

$$\widetilde{B} = Bq(\alpha) = \frac{r - \mu\beta_2}{(\beta_1 - \beta_2)r(r - \mu)} c^{1-\beta_1} q(\alpha) > 0, \tag{5.2}$$

and $E_t\{.\}$ is the expectation taken at time point t.

In Eq. (5) the terms $\widetilde{A}x_t^{\beta_2}$ and $\widetilde{B}x_t^{\beta_1}$ represent the values associated with the option to suspend and restart farming respectively, and the option constants $\widetilde{A}$ and $\widetilde{B}$ are both positive and linearly increasing in the crop yield $q(\alpha)$. The value of the option to suspend farming by switching from active to passive farming decreases in the price level x_t and increases in the production cost c. This is because the option to suspend becomes more valuable when profits from active farming fall. In contrast, the value of the option to restart farming by switching from passive to active farming increases in the price level x_t and decreases in the production cost c. This is because the option to restart becomes more valuable when profits associated with active farming rise. Last, the term $E_t\left\{\int_t^\infty [q(\alpha)(x_z - c)]e^{-r(z-t)}dz\right\}$ represents the expected present value at the generic time point t of the flow of income if land is actively farmed, while the term $\int_t^\infty pe^{-r(z-t)}dz$ is the present value of net payments accruing to the farmer.

5 The optimal productive capacity

In this section we determine the productive capacity that the landholder should adopt when setting up the farm. By Eq. (2) this is equivalent to choosing the capital intensity that should characterize the investment project.

The landholder chooses the capital intensity taking into account the potential future evolution of farming profits and the operational flexibility associated with the options to switch between passive and active farming. These two aspects are clearly interrelated since the available operational flexibility allows hedging against the volatility that, via the market price, affects farming profits. Of course productive capacity does not come for free. The corresponding benefits must be traded off with an investment cost that increases with the level of capital intensity. Operational flexibility instead comes at no cost since land is always in a good state and readily available for agricultural production thanks to cross compliance.

In the following we determine the optimal capital intensity for the scenario where investment in land development occurs at a time point t where active farming is profitable, i.e. for $x_t > c$.[10] As land can be immediately farmed the optimal level of capital intensity $\overline{\alpha}$ must be such that the expected net present value associated with the current and future farm operations is maximized, that is:

$$\overline{\alpha} = \arg\max NPV(x_t, \alpha) \tag{6}$$

where,

$$\begin{aligned} NPV(x_t, \alpha) &= V(x_t, \alpha) - I(\alpha) \qquad (6.1) \\ &= \widetilde{A} x_t^{\beta_2} + E_t \left\{ \int_t^{\infty} [q(\alpha)(x_z - c)] e^{-r(z-t)} dz \right\} + \int_t^{\infty} p e^{-r(z-t)} dz - (k_1 + k_2 \alpha) \, . \end{aligned}$$

The capital intensity $\overline{\alpha}$ is set on the basis of the expected net present value taken at a specific time point t. In fact, $NPV(x_t, \alpha)$ is obtained by subtracting the investment cost $I(\alpha)$ from the expected present value of the flow of income accruing to the farmer from that time t onward, a flow whose evolution over time depends on the fluctuations of x_t and the switching policy in Eq. (4).

Now, by using Eq. (5.1) and knowing that[11]

$$E_t \left\{ \int_t^{\infty} [q(\alpha)(x_z - c)] e^{-r(z-t)} dz \right\} = q(\alpha) \left(\frac{x_t}{r - \mu} - \frac{c}{r} \right),$$

and

$$\int_t^{\infty} p e^{-r(z-t)} dz = \frac{p}{r},$$

Eq. (6.1) can be rearranged as follows:

$$NPV(x_t, \alpha) = q(\alpha) O(x_t) + \frac{p}{r} - I(\alpha) \tag{6.2}$$

[10] A scenario where the landholder opts for investment in land development when active farming is not profitable, i.e. $x_t \leq c$, seems to us less realistic. We provide, however, the relative analysis in Appendix B.

[11] See pp. 79-82 in Dixit and Pindyck (1994) for the calculation of expected present values.

where $O(x_t) = Ax_t^{\beta_2} + \frac{x_t}{r-\mu} - \frac{c}{r}$ represents the expected present value of the flow of farming profits per unit of productive capacity. This term measures the actual contribution of active farming operations to the total value $V(x_t, \alpha)$.

Solving problem (6) we find that:

Proposition 1 *The optimal capital intensity level when investing at $x_t > c$ is:*

$$\overline{\alpha}(x_t) = \left(\frac{O(x_t)}{k_2} \right)^{\frac{1}{1-\gamma}} \tag{7}$$

Proof. See Section A.3 in Appendix A. ■

The optimal capital intensity $\overline{\alpha}(x_t)$ is increasing in $O(x_t)$ and, as shown in Section A.3 in Appendix A, increasing in x_t. This property results from the sum of two opposing forces within the term $O(x_t)$. First, in $O(x_t)$ the term $\frac{x_t}{r-\mu} - \frac{c}{r}$ is increasing in x_t. This term represents the expected present value of the flow of profits generated by a farm that is always actively farmed. Consistently, the higher the $\frac{x_t}{r-\mu} - \frac{c}{r}$ the higher the capital intensity and, consequently, the productive capacity in which the farmer would consider optimal investing in. In contrast, the term $Ax_t^{\beta_2}$, that is, the value of the option to switch to passive farming, decreases in x_t. This is because the higher the x_t, the less likely is the farmer's switching to passive farming in the future and, consequently, the lower the value of the hedge against the volatility of farming profits. As shown in the Appendix, the first force prevails. Last, plugging Eq. (7) into the expected net present value function we obtain:

$$NPV(x_t) = \overline{\alpha}(x_t) \left(\frac{1}{\gamma} - 1 \right) k_2 + \frac{p}{r} - k_1 \tag{8}$$

which is increasing in x_t.

6 Value and timing of the investment

Let us now determine the value of the option to invest in the land development project and the optimal investment timing. We do so assuming that the current time point is $t = 0$ where $x_0 = x$.

Denoting by $\widehat{x}$ an arbitrary price threshold triggering investment and assuming that the current market price x is below this threshold, i.e. $x < \widehat{x}$,[12] the value of the option to invest is equal to

$$F(x, \widehat{x}) = \max_{\tau > 0}[E_0 \left\{e^{-r\tau}\right\} NPV(\widehat{x})], \tag{9}$$

where $E_0 \{e^{-r\tau}\}$ is the expected value of the stochastic discount factor $e^{-r\tau}$ associated with the random investment time $\tau = \inf\{t > 0 \mid x_t = \widehat{x}\}$. In the Appendix we show that $E_0 \{e^{-r\tau}\} = (x/\widehat{x})^{\beta_1}$. Hence, Eq. (9) can be rearranged as follows:

$$F(x, \widehat{x}) = \max_{\widehat{x} > x}[(x/\widehat{x})^{\beta_1} NPV(\widehat{x})] \tag{9.1}$$

The option to invest must be optimally exercised. The first-order condition requires that:

$$\left(\frac{x}{x^*}\right)^{\beta_1} \frac{dNPV(x^*)}{dx^*} = \frac{\beta_1}{x^*} \left(\frac{x}{x^*}\right)^{\beta_1} NPV(x^*) \tag{9.2}$$

where the term on the left of the equality sign is the expected marginal benefit of investment delay while the term on the right is the expected marginal cost of investment delay. Rearranging Eq. (9.2), the optimal investment threshold x^* for a project with capital intensity $\overline{\alpha}(x^*)$ is the solution of the following equation:

$$\frac{x^*}{NPV(x^*)} \frac{dNPV(x^*)}{dx^*} = \beta_1 \tag{10}$$

The insight behind Eq. (10) is straightforward. The term $\frac{x^*}{NPV(x^*)} \frac{dNPV(x^*)}{dx^*}$ is the elasticity of the expected net present value, $NPV(x^*)$, with respect to x^* while β_1 is the elasticity of the discount factor $(x/x^*)^{\beta_1}$ with respect to x^*. Hence, optimality requires that at a threshold x^* the positive impact that delaying the investment has on the $NPV(x^*)$ must equal the negative impact that delaying has on the discounting of future payoffs.[13]

Last, we complete our analysis with two limit cases. First, if

$$\frac{\widehat{x}}{NPV(\widehat{x})} \frac{dNPV(\widehat{x})}{d\widehat{x}} < \beta_1, \text{ for any } \widehat{x} \geq x \tag{10.1}$$

[12]If $x \geq \widehat{x}$ the problem reduces to the mere maximization of the net present value in Eq. (8).

[13]See Section A.4 in Appendix A for the derivation of Eq. (10). An exhaustive discussion of the underlying solution concept is provided by Dixit et al. (1999).

the expected marginal net benefit of investment delay is negative at any $\tau \geq 0$. This implies that postponing investment is not optimal and that the landholder should invest immediately in a land development project with capital intensity $\overline{\alpha}(x)$ provided that $NPV(x) > 0$.

Second, if

$$\frac{\widehat{x}}{NPV(\widehat{x})}\frac{dNPV(\widehat{x})}{d\widehat{x}} > \beta_1, \text{ for any } \widehat{x} \geq x \tag{10.2}$$

the landholder should never undertake the land development project. This is because the expected marginal net benefit from further investment delay is positive at any $\tau \geq 0$.

7 The effect of the policy

In the following, we first discuss the comparative statics concerning the impact of the net payment p on productive capacity choices, investment timing, farm income volatility and the value of idle land. We then complement this analysis with a numerical exercise calibrated using figures from a case study.

7.1 Comparative statics

The optimal timing of a farmland investment represents a fundamental decision for agricultural entrepreneurs (Maart-Noelck and Musshoff, 2013). Further, the ability to invest at variable productive capacity interacts with the investment timing and this interaction has important implications for the investment strategy (Capozza and Li, 1994; Dangl, 1999). We accordingly start our analysis by studying the effect of a net payment p on productive capacity and investment timing and we find the following:

Proposition 2 *The optimal productive capacity and the investment threshold are decreasing in the net payment.*

Proof. See subsection A.4.1 of Appendix A. ■

In the real options literature, the option to invest is viewed as a call option with the investment cost as its strike price. In our problem, as a net payment p accrues over time irrespective of whether the land is actively or passively farmed, the landholder can count on a flow of net payments having a present value equal to p/r. The actual strike price is then $I(\overline{\alpha}(x^*)) - (p/r)$ since the investment cost is implicitly lowered by cashing p/r upon investment. As is well known in option theory, to a lower strike price corresponds an earlier option exercise which in our frame implies an earlier investment. Hence, the higher the net payment, the lower the strike price and the lower the threshold x^* that the commodity price x_t must reach to trigger investment. Notably, the impact of the net payment on the investment timing goes beyond the mere reduction of the strike price of the investment option. As mentioned above, capacity and investment timing choices interact. As a result, when it comes to our problem, the impact of the net payment passes through two channels. This can be shown by differentiating the strike price $I(\overline{\alpha}(x^*)) - (p/r)$ with respect to p, which yields:

$$\frac{d(I(\overline{\alpha}(x^*)) - p/r)}{dp} = k_2 \frac{d\overline{\alpha}(x^*)}{dp} - \frac{1}{r} < 0 \tag{11}$$

The second term in Eq. (11) corresponds to the reduction of the investment cost which, ceteris paribus, is merely associated to a higher p. This is reminiscent of the wealth effect of decoupling described in the extant literature (Hennessy, 1998) and can be viewed as the effect of the implicit subsidy (p/r) on the investment cost $(I(\overline{\alpha}(x^*)))$. The first term instead, which is also negative, stands for the reduction of the investment cost due to the adoption of a lower capacity in response to a higher net payment p and is an additional effect fostering investment with respect to the case where the capacity choice is omitted (see e.g. Pennings, 2000). It is worth highlighting that this result shows from a novel perspective that CAP payments are non-neutral since they do affect the capacity choices taken at farm level.

Apart from the timing and capacity choices of the landholder, the net payment p affects the farm periodic income as well. As noted by Hennessy (1998), policies that support farm income often have a second purpose in addition to income support which is income stabilization. In fact, differentiating farm periodic income with respect to p we find that:

$$\frac{d(q(\overline{\alpha}(x^*))(x_t - c))}{dp} = \frac{dq(\overline{\alpha}(x^*))}{dp}(x_t - c) < 0 \tag{12}$$

As we have seen in Eq. (11), the investor opts for a farm with a lower productive capacity in order to foster the exercise of the investment option. However, this choice has important implications for the composition of the farm income since, by Eq. (12), an increase in the net payment p, that is, the risk-free component of the farm income, reduces the risky component represented by the volatile farming profit. Hence, thanks to CAP payments the potential investor chooses a farm of smaller capacity (Proposition 2) which implies a more stable income flow.

Another issue that has attracted attention in the literature concerns the capitalization of CAP payments into land values (see e.g. Weber and Key, 2012; Gocht et al., 2013; Ciaian et al., 2014, 2017). Proposition 3 touches upon this point:

Proposition 3 *The value of the option to invest is increasing in the net payment p.*

Proof. See Section A.4.1 of Appendix A. ∎

As discussed above, a lower productive capacity in response to a higher p implies i) a reduction in the investment cost (Eq. (11)) and ii) an income flow less exposed to the volatility of the farming profits (Eq. (12)). When studying the effect of an increase in the net payment p on the value of the option to invest, these two effects offset each other and eventually the residual effect is:[14]

$$\frac{dF(x, x^*)}{dp} = \frac{1}{r}\left(\frac{x}{x^*}\right)^{\beta_1} > 0 \tag{13}$$

By Eq. (13), the increase in the value of the option to invest is equal to the marginal increase in the present value of the flow of net payments, i.e. p/r, discounted using the stochastic discount factor $(x/x^*)^{\beta_1}$ in order to take into account the time that the farmer should wait before, once invested, start cashing the net payments. It is worth highlighting that by increasing the value of the option to invest, CAP payments increase the value of idle land. This result is in line with findings concerning the capitalization of CAP payments into land and has clear implications for land markets.

[14] In the Appendix we show that Eq. (13) is derived by plugging Eq. (8) in Eq. (9.1) and then applying the envelope theorem.

Finally, some remarks concerning the case of immediate investment are in order. One of the goals set by the CAP is avoiding land abandonment. In this respect, by Proposition 2, the policy maker may speed up the transition of abandoned land toward well maintained land by fostering investments through an increase in the level of p. If socially relevant, the policy maker may even induce an immediate transition. This could be done by setting p at a level such that, by inequality (10.1), the landholder would immediately exercise their option to invest.

7.2 Numerical exercise

For our numerical exercise we use data from a region in southern Sweden known as Götalands Mellan Bygder (GMB) where passive farming practices have been observed. GMB is a mixed farming region characterized by specialized crop, livestock, and mixed farms. Cereals, especially winter wheat and spring barley, are the most important annual crops, comprising 41% of the arable area. Since passive farming is associated with land of low productivity, we choose for our exercise the GMB subregion associated with lower-value fodder production. Details about the farm activities in GMB are provided in Brady et al. (2017b) and Hristov et al. (2020). The calibration that we adopt is based on data from the technical report by Hristov et al. (2017) whose source is the Swedish Board of Agriculture. They define passive farms as farms with no livestock and land that can be managed only as fallow. Land maintenance through passive farming is a costly practice as, in its simplest form, passive farming implies mowing grass fields on an annual basis (Brady et al., 2009).

The annual cost of keeping land in fallow state (m) is SEK/ha 950.4 whereas the cost of actively farming the land producing lower-value fodder (e.g., barley, oats, triticale, maize) is SEK/ha 1876.72. Hence the cost of active farming net of land maintenance expenses (c) is SEK/ha 926.32. The price of output (x) is SEK/tonne 1250. Hristov et al. (2017) make no reference to land conversion costs so we assume $k_1 = 0$. As for k_2, the cost of investing in one unit of machinery, the only source of capital for which data is available, is SEK/ha 19811.7. Regarding the parameters associated with the commodity price fluctuations we adopt the values in Feil et al. (2013) who assume $\mu = 0$ and $\sigma = 0.2$. For robustness we also discuss the cases with higher ($\sigma = 0.3$) and lower ($\sigma = 0.1$) volatility. As for the discount rate, our benchmark is 3% (Hristov et al., 2017) but for robustness we also discuss the cases with $r = 2\%$ and $r = 4\%$. The level of decoupled payment s in the region of interest was equal to SEK/ha 1827 when the measure was first introduced (2008-2013). Sweden has since chosen to equalize farm subsidies within the country and as of 2019 all farms receive SEK/ha 1527. Here we discuss a broader range of decoupled payments allowing for $s \in [m, 1827]$. Notably, p ranges from zero when $s = m$ up to SEK/ha 876.6 when $s = 1827$ and is equal to SEK/ha 576.6 when $s = 1527$. Last, accounting for the standard yield of the typical farm in the region of interest the parameter capturing the concavity of the productive capacity γ is set equal to 0.217.

Figure 1 plots investment thresholds, that is, the levels that the commodity price must exceed to justify land development. Figure 2 plots the productive capacity level that corresponds to each threshold value. In line with our theoretical findings the optimal investment threshold and capacity level are decreasing in p for all combinations of r and σ.

Figure 1 about here

Figure 2 about here

When commodity prices are very volatile, and unless the landholder is relatively more impatient (high r), threshold and capacity curves are strictly decreasing and continuous. This is the case for the volatility-discount rate combinations $(0.3; 0.02)$ and $(0.3; 0.03)$. In these two occasions the landholder chooses to defer investment irrespective of the level of p which means that there is no p that can induce immediate exercise of the investment option. This of course does not mean that the landholder is not responsive to changes in p. On the contrary a higher net payment is, as expected, favoring earlier investment and the choice of a lower capacity level. For any other combination of σ and r beyond $(0.3; 0.02)$ and $(0.3; 0.03)$ there is a critical level of p in the range of interest beyond which the landholder opts for immediate investment. For p above this critical level, the timing and capacity choices of the landholder are unaffected by changes in p. Notably, the position of the point of discontinuity and the magnitude of the jump depend on the parameter combination. The jumps are naturally taking place for lower p when r is higher capturing the impatience of the landholder to invest. Discontinuities in the optimal investment threshold curves (Figure 1) translate in discontinuities in the corresponding optimal productive capacity curves (Figure 2). It is worth noting that immediate investment should not necessarily be attributed to a policy scheme that overpays farmers. As deterring land abandonment is one of the goals of the CAP, immediate investment might be intentionally induced by a policy maker who is considering the immediate transition from idle/abandoned land to minimally maintained land optimal from a welfare perspective. In this case, p is not only supporting farmers' income but is also compensating them for investing suboptimally early with respect to when it would have been privately optimal to invest if no policy were in place.

In the following we focus on the range of p for which immediate investment is not preferable. First, we notice that higher volatility implies higher investment threshold and a higher capacity choice. The landholder chooses to exercise later an investment option associated with a more volatile commodity price and, since the chosen capacity level is increasing in the price level, chooses also a farm of larger capacity. This is why in all six panels the curve that corresponds to high (low) volatility is above (below) the other two and the curve that corresponds to moderate volatility is in the middle. A second observation has to do with the curves corresponding to the same volatility level but different discount rates. A lower discount rate corresponds to a, all other things being equal, higher investment threshold and capacity choice. For instance, the investment threshold curve that corresponds to the combination $(0.3; 0.02)$ (Fig. 1a, squared marker) obtains values two (three) times larger than the values of the same curve in the Fig. 1b (Fig. 1c). This is of course to be expected since a more impatient potential investor chooses a lower investment threshold. The same pattern is naturally appearing in the panels in Figure 2. It is also worth noting that very high (low) investment threshold levels are associated with very high (low) productive capacity choices and, even if these levels seem extreme when studied separately, they make sense when seen as a timing-capacity combination. For example, a landholder who discounts future payoffs with $r = 0.02$ and faces a very volatile commodity market ($\sigma = 0.3$) chooses investment thresholds above 12000 SEK/tonne, a number that seems unreasonable at first sight. This threshold choice is however associated with the fact that, for this parameter combination, the optimal productive capacity is very large (more than 40% larger than the capacity choice for higher r) dictating a more expensive investment option that is naturally exercised for a significantly larger investment threshold.

By studying Figures 1 and 2 one reaches the following conclusions regarding decoupling and landholders' investment decisions. The potential investors' response to this policy instrument is not uniform but instead depends on the characteristics of the investment option at hand. For instance, some landholders who would opt for high investment thresholds for $p = 0$, update their investment strategy choosing significantly lower investment thresholds for $p = 576.6$ even if they do not find this level of support high enough to choose the combination $[x; q(\bar{a}(x))]$. See e.g. the curves corresponding to $\sigma = 0.3$. Nevertheless, others are responding differently to this p and are willing to invest immediately, see for instance the curves corresponding to $\sigma = 0.1$. We also observe that, provided that the difference between s and m does not force immediate investment, decoupling has important implications when it comes to the choice of timing and capacity. For four combinations of σ and r, $(0.2; 0.02)$ and all three combinations when $\sigma = 0.3$, the payment $p = 576.6$ makes the landholder hasten their investment considerably but without making immediate investment optimal. For instance, for $(0.3; 0.04)$, a payment of $p = 576.6$ implies a 36% decrease in the optimal investment threshold and a 15% decrease in the chosen productive capacity with respect to the $p = 0$ scenario. Similarly, for $(0.2; 0.02)$, the decrease is around 30% for the optimal level threshold and 12% for the chosen productive capacity level.

The numerical exercise corroborates our analytical findings suggesting that decoupled payments conditional on land maintenance favor earlier investments in farms with smaller capital intensity. However, the responsiveness of a given potential investor to this policy instrument depends largely on the economic fundamentals of the project that they are contemplating investing in.

8 Conclusions

According to Article 33 of the Treaty establishing the European Community (EU, 2002) the objectives of the CAP are: i) to increase agricultural productivity by promoting technical progress and by ensuring the rational development of agricultural production and the optimum utilization of the factors of production, ii) to guarantee a fair standard of living for the agricultural community, iii) to stabilize markets, and iv) to guarantee availability of supplies that reach consumers at reasonable prices.

In accordance with these objectives, and thanks to the introduction of decoupled payments, the beneficiaries of the CAP currently enjoy some financial security while they are also encouraged to respond to market signals. The current version of the policy takes great account of the reality of an open world and, according to the World Trade Organization, 90% of the payments are regarded as non-trade-distorting (EU, 2013). Nevertheless, the introduction of decoupled payments and the gradual phasing out of the traditional forms of farming subsidies that were conditional on the production of agricultural commodities was, and still is, heavily disputed in European circles. In this paper, we study how timing and capacity decisions concerning investment in land development projects are affected by decoupling. We analyze the case of a potential farmer who is contemplating investing in a piece of idle land in order to convert it into farmland. They must choose both the productive capacity and the timing of the investment given that, once they enter the farming business, they will have the opportunity to actively farm the land when the profit margin is positive, and when otherwise, farm passively.

We present four original findings. We show that decoupled payments encourage the acceleration of the investment in question. This is due to the hedge against volatile farming profits that decoupling implicitly provides. This in turn implies a faster transition of land previously idle/abandoned towards land maintained in good agricultural and environmental condition so that it may provide valuable ecosystem services and serve as potential buffer for securing additional supply of food. We also show that decoupled payments affect the level of productive capacity chosen by the investor favoring the adoption of farms with smaller productive capacity. Last, we find that decoupled payments increase the value of the option to invest since they provide a valuable hedge against farming profit fluctuations. A numerical exercise calibrated to data from a region in southern Sweden completes the analysis.

There is a plethora of ways to advance the present work. First, it would be interesting to see how decoupling affects a farmer's decision to leave the farming industry. The analysis related to the option to exit would complement our present analysis, giving a clearer picture of how decoupling affects structural change in the farming sector. Second, it would be informative to approach the same topic allowing for both coupled and decoupled payments. In this way, one could isolate the effects of each of these two policies while discussing any composite effects. Last, a welfare analysis that analytically considers the total costs and benefits of decoupling, including its impact on environment and rural landscape conservation, would allow policymakers to determine the socially optimal payment in the light of a given set of cross-compliance rules.

A Appendix

A.1 The production function

Assume that the crop yield Q results from the following production function:

$$Q = F(L, K) \tag{A.1.1}$$

where L and K represent the amounts of land and capital.

Assume that the crop yield:

i) increases in both input factors, i.e.

$$\frac{dF(L, K)}{dL} > 0, \frac{dF(L, K)}{dK} > 0, \tag{A.1.2}$$

ii) exhibits diminishing marginal returns to each input factor, i.e.

$$\frac{d^2F(L, K)}{dL^2} < 0, \frac{d^2F(L, K)}{dK^2} < 0, \tag{A.1.3}$$

iii) exhibits constant returns to scale, i.e.

$$F(\theta L, \theta K) = \theta F(L, K) \text{ with } \theta > 0, \tag{A.1.4}$$

iv) and satisfies the Inada conditions

$$\lim_{L \to 0} \frac{dF(L, K)}{dL} = \lim_{K \to 0} \frac{dF(L, K)}{dK} = +\infty. \tag{A.1.5}$$

Note that since, by Eq. (A.1.4), the crop yield function $F(L, K)$ is linearly homogeneous, it can be written as crop yield per unit of land, i.e.

$$q(\alpha) = Q/L = F(1, \alpha)$$

where $\alpha = K/L$ is the capital intensity.

A production function that satisfies the properties (A.1.2-A.1.5) is, for instance, the following Cobb-Douglas production function

$$Q = L^{1-\gamma}K^{\gamma} \text{ with } 0 < \gamma < 1$$

where $1-\gamma$ and γ represent the elasticities of output with respect to L and K, respectively (see e.g. Dawson and Lingard, 1982).

The crop yield $Q(L, K)$ can then be rewritten in terms of crop yield per unit of land:

$$q(\alpha) = \alpha^{\gamma} \tag{A.1.6}$$

Last, in order to obtain Eq. (2) it suffices to normalize Eq. (A.1.6) dividing on both sides by γ.

A.2 The operating value of the farm

The value of the farm $V(x_t, \alpha)$ at time t can be expressed as the sum of the income accruing over the current growing season and a continuation value. Denoting by $V^H(x_t, \alpha)$ the value of the farm when $x_t > c$ and by $V^L(x_t, \alpha)$ the value of the farm when $x_t \leq c$, $V(x_t, \alpha)$, can be determined by solving the following system of Bellman equations:

$$\begin{aligned} V^H(x_t,\alpha) &= q(\alpha)(x_t - c) + p + e^{-rdt}E_t\left\{V^H(x_t + dx_t, \alpha)\right\} \quad && \text{for } x_t > c \\ V^L(x_t,\alpha) &= p + e^{-rdt}E_t\left\{V^L(x_t + dx_t, \alpha)\right\} && \text{for } x_t \leq c \end{aligned} \tag{A.2.1-A.2.2}$$

Expanding the right-hand side of Eqs. (A.2.1-A.2.2) using Ito's lemma and rearranging yields the following differential equations:[15]

$$\begin{aligned} &\tfrac{1}{2}\sigma^2 x_t^2 \tfrac{d^2V^H(x_t,\alpha)}{dx_t^2} + \mu x_t \tfrac{dV^H(x_t,\alpha)}{dx_t} - rV^H(x_t,\alpha) = -\left[q(\alpha)(x_t - c) + p\right] \quad && \text{for } x_t > c \\ &\tfrac{1}{2}\sigma^2 x_t^2 \tfrac{d^2V^L(x_t,\alpha)}{dx_t^2} + \mu x_t \tfrac{dV^L(x_t,\alpha)}{dx_t} - rV^L(x_t,\alpha) = -p && \text{for } x_t \leq c \end{aligned} \tag{A.2.3-A.2.4}$$

Eqs. (A.2.3-A.2.4) must be solved subject to the following boundary conditions:

$$\begin{aligned} &\lim_{x_t\to\infty} V^H(x_t,\alpha) = E_t\left\{\textstyle\int_t^\infty [q(\alpha)(x_z - c)]e^{-r(z-t)}dz\right\} + \textstyle\int_t^\infty pe^{-r(z-t)}dz \quad && \text{for } x_t > c \\ &\lim_{x_t\to 0} V^L(x_t,\alpha) = \textstyle\int_t^\infty pe^{-r(z-t)}dz && \text{for } x_t \leq c \end{aligned} \tag{A.2.5-A.2.6}$$

where

$$E_t\left\{\int_t^\infty [q(\alpha)(x_z - c)]e^{-r(z-t)}dz\right\} = q(\alpha)\left(\frac{x_t}{r-\mu} - \frac{c}{r}\right)$$

[15] On Ito's lemma, see pp. 79-82 in Dixit and Pindyck (1994).

and

$$\int_t^{\infty} pe^{-r(z-t)}dz = \frac{p}{r}$$

Note that by introducing conditions (A.2.5-A.2.6) we require that the value of the farm converges towards the expected present value of the flow of operating profits under each of the two considered scenarios, that is, active farming forever (since the likelihood of switching to passive farming goes to 0 for $x_t \to \infty$) and passive farming forever (since the likelihood of switching to active farming goes to 0 for $x_t \to 0$).

Hence, the general solution to the differential Eqs. (A.2.3-A.2.4) takes the form:

$$\begin{aligned} V^H(x_t,\alpha) &= \widetilde{A}x_t^{\beta_2} + q(\alpha)(\tfrac{x_t}{r-\mu} - \tfrac{c}{r}) + \tfrac{p}{r} && \text{for } x_t > c \\ V^L(x_t,\alpha) &= \widetilde{B}x_t^{\beta_1} + \tfrac{p}{r} && \text{for } x_t \leq c \end{aligned}$$

At $x_t = c$, standard optimality conditions, i.e. the value matching and smooth pasting conditions, require that

$$\begin{aligned} &\widetilde{A}c^{\beta_2} + \tfrac{\alpha^\gamma}{\gamma}(\tfrac{c}{r-\mu} - \tfrac{c}{r}) + \tfrac{p}{r} = \widetilde{B}c^{\beta_1} + \tfrac{p}{r}, \\ &\widetilde{A}\beta_2 c^{\beta_2 - 1} + \tfrac{\alpha^\gamma}{\gamma}\tfrac{1}{r-\mu} = \widetilde{B}\beta_1 c^{\beta_1 - 1}, \end{aligned} \tag{A.2.7}$$

where $\beta_2 < 0$ and $\beta_1 > 1$ are the roots of the quadratic equation $\Lambda(\beta) = \frac{1}{2}\sigma^2\beta(\beta-1)+\mu\beta-r$. Solving the system (A.2.7) we obtain:

$$\widetilde{A} = Aq(\alpha) = \frac{r-\mu\beta_1}{(\beta_1-\beta_2)\,r(r-\mu)}c^{1-\beta_2}q(\alpha) > 0 \tag{A.2.8}$$

$$\widetilde{B} = Bq(\alpha) = \frac{r-\mu\beta_2}{(\beta_1-\beta_2)\,r(r-\mu)}c^{1-\beta_1}q(\alpha) > 0 \tag{A.2.9}$$

A.3 Optimal capital intensity (Proof of Proposition 1)

Suppose that $x_t > c$. The optimal capital intensity is

$$\begin{aligned} \overline{\alpha} &= \arg\max \left\{ \widetilde{A}x_t^{\beta_2} + q(\alpha)\left(\frac{x_t}{r-\mu} - \frac{c}{r}\right) + \frac{p}{r} - I(\alpha) \right\} \\ &= \arg\max \left\{ q(\alpha)O(x_t) + \frac{p}{r} - (k_1 + k_2\alpha) \right\} \end{aligned} \tag{A.3.1}$$

where $O(x_t) = Ax_t^{\beta_2} + \frac{x_t}{r-\mu} - \frac{c}{r}$.

The first-order condition for Problem (A.3.1) yields,

$$\overline{\alpha} = (O(x_t)/k_2)^{\frac{1}{1-\gamma}}. \tag{A.3.2}$$

The second-order condition is always satisfied.

Note that, to be feasible, $\overline{\alpha}$ must be higher than 0 which in turn implies that the following condition must hold:

$$O(x_t) > 0$$

We note that

$$O(c) = \frac{r - \mu\beta_2}{(\beta_1 - \beta_2)r(r-\mu)}c = Bc^{\beta_1} > 0,\ O'(c) = \frac{r - \mu\beta_2}{(\beta_1 - \beta_2)r(r-\mu)}\beta_1 > 0,$$
$$\lim_{x_t \to 0} O(x_t) = \infty.$$

Hence, by the convexity of $O(x_t)$, it follows that $O(x_t) > 0$ and $O'(x_t) > 0$ for any $x_t > c$.

A.4 Value and timing of the investment

Once the optimal intensity level is set, we can determine the net present value corresponding to the land development project by substituting $\overline{\alpha}(x_t)$ into the function $NPV(x_t, \alpha) = V(x_t, \alpha) - I(\alpha)$. This yields:

$$\begin{aligned} NPV(x_t) &= q(\overline{\alpha}(x_t))O(x_t) + \frac{p}{r} - I\left(\overline{\alpha}(x_t)\right) \\ &= \overline{\alpha}(x_t)\left(\frac{1}{\gamma} - 1\right)k_2 + \frac{p}{r} - k_1 \end{aligned} \tag{A.4.1}$$

Denote by $\widehat{x}$ an arbitrary investment threshold. Hence, using standard arguments, in the continuation region $x < \widehat{x}$ the value of the option to invest in the land development project is:

$$F(x, \widehat{x}) = \max_{\tau > 0}[E_0\left\{e^{-r\tau}\right\} NPV(\widehat{x})] \tag{A.4.2}$$

where $\tau = \inf\{t > 0 \mid x_t = \widehat{x}\}$ is the first time point at which x_t hits the barrier $\widehat{x}$ from below and E_0 is the expectation taken at the initial time point $t = 0$.

Let us define

$$D(x; \widehat{x}) = E_0\left\{e^{-r\tau}\right\}.$$

In the continuation region $x < \widehat{x}$, $D(x;\widehat{x})$ is the solution of the following Bellman equation (see pp. 315-316 in Dixit and Pindyck, 1994):

$$D(x;\widehat{x}) = e^{-rdt}E_0\left\{D(x+dx;\widehat{x})\right\}$$

Expanding the right-hand side of this equation using Ito's lemma and noting that $e^{-rdt} = 1 - rdt$ for sufficiently small dt yields the following differential equation

$$\frac{1}{2}\sigma^2 x^2 \frac{d^2 D(x;\widehat{x})}{dx^2} + \mu x \frac{dD(x;\widehat{x})}{dx} - rD(x;\widehat{x}) = 0. \tag{A.4.3}$$

The general solution of Eq. (A.4.3) is

$$D(x;\widehat{x}) = H_1 x^{\beta_1} + H_2 x^{\beta_2}$$

where $\beta_1 > 1$ and $\beta_2 < 0$ are the roots of the quadratic equation $\Lambda(\beta) = (1/2)\sigma^2\beta(\beta-1) + \mu\beta - r$.

Eq. (A.4.3) must be solved subject to the following boundary conditions:

$$\lim_{x\to 0} D(x;\widehat{x}) = 0$$

$$\lim_{x\to \widehat{x}} D(x;\widehat{x}) = 1$$

Using these conditions, we get $H_2 = 0$ and $H_1 = \widehat{x}^{-\beta_1}$. Hence, the solution to Eq. (A.4.3) is

$$D(x;\widehat{x}) = (x/\widehat{x})^{\beta_1}. \tag{A.4.4}$$

Substituting Eq. (A.4.4) into Eq. (A.4.3) yields:

$$F(x,\widehat{x}) = \max_{\widehat{x}>x}[(x/\widehat{x})^{\beta_1} NPV(\widehat{x})] \tag{A.4.5}$$

Following Dixit et al. (1999), the following first-order condition holds at the optimal threshold x^*:

$$\frac{d[(x/x^*)^{\beta_1} NPV(x^*)]}{dx^*} = (x/x^*)^{\beta_1}\frac{dNPV(x^*)}{dx^*} - \frac{\beta_1}{x^*}(x/x^*)^{\beta_1} NPV(x^*) = 0 \tag{A.4.6}$$

Rearranging Eq. (A.4.6), we obtain:

$$\frac{x^*}{NPV(x^*)}\frac{dNPV(x^*)}{dx^*} = \beta_1 \tag{A.4.7}$$

Last, for Problem (A.4.5) to be well-posed, the following condition must hold at x^*:

$$\left.\frac{d^2[(x/x^*)^{\beta_1}NPV(x^*)]}{dx^2}\right|_{x=x^*} > \left.\frac{d^2NPV(x)}{dx^2}\right|_{x=x^*}$$

$$\rightarrow$$

$$\frac{dNPV(x^*)}{dx^*} > \frac{x^*}{\beta_1 - 1}\left.\frac{d^2NPV(x)}{dx^2}\right|_{x=x^*}$$

$$\rightarrow$$

$$x^*\frac{d^2\overline{\alpha}(x^*)}{dx^{*2}} - (\beta_1 - 1)\frac{d\overline{\alpha}(x^*)}{dx^*} < 0 \tag{A.4.8}$$

Finally, note that

i) if

$$\frac{d[(x/\widehat{x})^{\beta_1}NPV(\widehat{x})]}{d\widehat{x}} > 0 \text{ for any } \widehat{x} > x,$$

then the expected marginal net benefit from investment delay is positive at any $\tau \geq 0$ and therefore the landholder should never undertake the land development project.

ii) if instead

$$\frac{d[(x/\widehat{x})^{\beta_1}NPV(\widehat{x})]}{d\widehat{x}} < 0 \text{ for any } \widehat{x} > x,$$

then the expected marginal net benefit from investment delay is negative at any $\tau \geq 0$ and therefore the landholder should invest immediately in a land development project with capital intensity $\overline{\alpha}(x)$ provided that $NPV(x) > 0$.

A.4.1 Policy impact (Proof of Propositions 2 and 3)

Substituting Eq. (A.4.1) into Eq. (A.4.7) and rearranging yields:

$$x^*\frac{d\overline{\alpha}(x^*)}{dx^*} = \beta_1\left(\overline{\alpha}(x^*) + \frac{\gamma}{1-\gamma}\frac{\frac{p}{r} - k_1}{k_2}\right) \tag{A.4.9}$$

From this we obtain

$$\frac{dx^*}{dp} = \frac{\frac{\gamma}{1-\gamma}\frac{1}{k_2}\frac{\beta_1}{r}}{x^*\frac{d^2\overline{\alpha}(x^*)}{dx^{*2}} - (\beta_1 - 1)\frac{d\overline{\alpha}(x^*)}{dx^*}}. \tag{A.4.10}$$

We can conclude that $dx^*/dp < 0$ since by condition (A.4.8) the denominator is strictly negative.

Since $\overline{\alpha}(x_t)$ and $q(\overline{\alpha}(x_t))$ are both increasing in x_t, it follows that:

$$\frac{d\overline{\alpha}(x^*)}{dp} = \frac{d\overline{\alpha}(x^*)}{dx^*}\frac{dx^*}{dp} < 0 \tag{A.4.11}$$

and

$$\frac{dq(\overline{\alpha}(x^*))}{dp} = \frac{dq(\overline{\alpha}(x^*))}{dx^*}\frac{dx^*}{dp} < 0 \tag{A.4.12}$$

A straightforward application of the envelope theorem yields:

$$\frac{dF(x, x^*)}{dp} = \frac{1}{r}\left(\frac{x}{x^*}\right)^{\beta_1} > 0 \tag{A.4.13}$$

From this we also obtain:

$$\frac{d^2F(x, x^*)}{dp^2} = -\frac{1}{r}\frac{\beta_1}{x^*}\left(\frac{x}{x^*}\right)^{\beta_1}\frac{dx^*}{dp} > 0 \tag{A.4.14}$$

B Appendix

For the readers' convenience we also provide the analysis corresponding to the case where $x_t \leq c$, that is, the region where the commodity price is lower than the unit cost of production. Recall that in this region a landholder, once invested in order to develop their land, would manage it passively and cash periodically the net payment p while holding the option to switch to active farming which is worth $\widetilde{B}x_t^{\beta_1}$.

B.1 Optimal capital intensity

Suppose that $x_t \leq c$. The optimal capital intensity $\underline{\alpha}$ is given by:

$$\begin{aligned}\underline{\alpha} &= \arg\max\{\widetilde{B}x_t^{\beta_1} + \frac{p}{r} - (k_1 + k_2\alpha)\}\\ &= \arg\max\left\{\frac{\alpha^\gamma}{\gamma}Bx_t^{\beta_1} + \frac{p}{r} - (k_1 + k_2\alpha)\right\}\end{aligned} \tag{B.1.1}$$

The first-order condition for Problem (B.1.1) yields,[16]

$$\underline{\alpha}(x_t) = (Bx_t^{\beta_1}/k_2)^{\frac{1}{1-\gamma}}. \tag{B.1.2}$$

By Eq. (3), $x_t > 0$ at each t, hence $\underline{\alpha} > 0$ for any $x_t \leq c$.

[16] The second-order condition is always satisfied.

B.2 Investing in land development

Once the optimal intensity level is set, we can determine the net present value corresponding to the land development project by substituting $\underline{\alpha}(x_t)$ into the function $NPV(x_t, \alpha) = V(x_t, \alpha) - I(\alpha)$. This yields:

$$\begin{aligned} NPV(x_t) &= q(\underline{\alpha}(x_t))Bx_t^{\beta_1} + \frac{p}{r} - I\left(\underline{\alpha}(x_t)\right) \\ &= \underline{\alpha}(x_t)\left(\frac{1}{\gamma} - 1\right)k_2 + \frac{p}{r} - k_1 \end{aligned} \tag{B.2.1}$$

Denote by $\check{x}$ the optimal development threshold. In the continuation region, $x < \check{x}$, the value of the option to invest in the land development project is given by the following function:

$$F(x, \check{x}) = \max_{\check{x} > x}[(x/\check{x})^{\beta_1} NPV(\check{x})] \tag{B.2.2}$$

Taking the first derivative of the objective with respect to $\check{x}$ we obtain:

$$\frac{d[(x/\check{x})^{\beta_1} NPV(\check{x})]}{d\check{x}} = -\frac{\beta_1}{\check{x}}\left(\frac{x}{\check{x}}\right)^{\beta_1}\left(\frac{p}{r} - I(\underline{\alpha}(\check{x}))\right) \tag{B.2.3}$$

The sign of the first derivative depends on the term $\frac{p}{r} - I(\underline{\alpha}(\check{x}))$. Three potential scenarios may arise:

(i) if $\frac{p}{r} \leq k_1 \rightarrow \frac{d[(x/\check{x})^{\beta_1} NPV(\check{x})]}{d\check{x}} > 0$ for any $x \leq \check{x} \leq c$: the landholder should postpone investing up to $x_t = c$ and undertake the investment only if $NPV(c) \geq 0$, that is, if:

$$\underline{\alpha}(c) \geq \frac{\gamma}{1-\gamma}\frac{k_1 - \frac{p}{r}}{k_2}$$

(ii) if $k_1 < \frac{p}{r} < I(\underline{\alpha}(c))$: Problem (B.2.2) has the following interior solution:

$$x^{**} = \left[\left(\frac{k_2}{B}\right)\left(\frac{\frac{p}{r} - k_1}{k_2}\right)^{1-\gamma}\right]^{1/\beta_1}$$

To be feasible, x^{**} must be lower or, at most, equal to c. As $\underline{\alpha}(x_t)$ is increasing in x_t, this leads to the following condition:

$$\underline{\alpha}(x^{**}) = \frac{\frac{p}{r} - k_1}{k_2} \leq \underline{\alpha}(c)$$

(iii) if $\frac{p}{r} \geq I(\underline{\alpha}(c)) \rightarrow \frac{d[(x/\check{x})^{\beta_1} NPV(\check{x})]}{d\check{x}} < 0$ for any $x \leq \check{x} \leq c$: the landholder should invest immediately as the sunk investment cost $I(\underline{\alpha}(x))$ is lower than the present value of the flow of net payments $\frac{p}{r}$.

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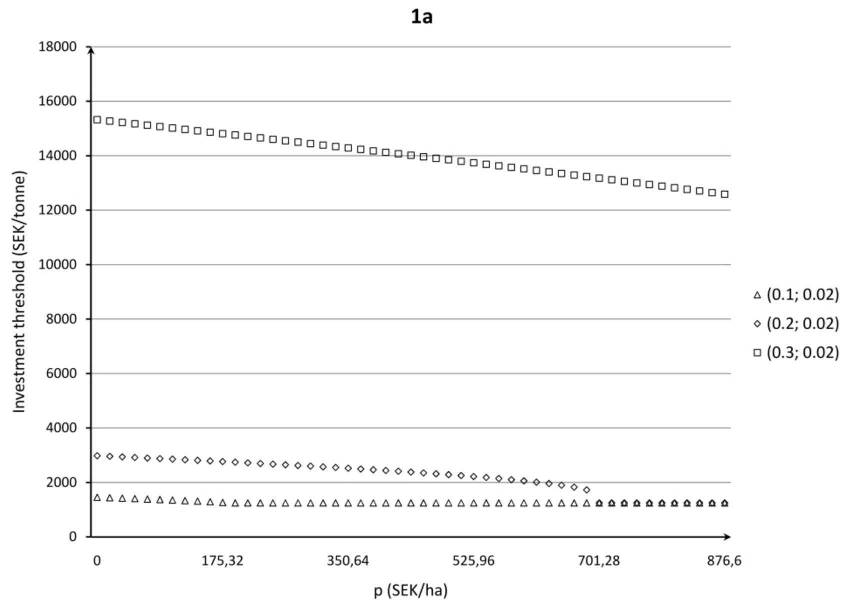

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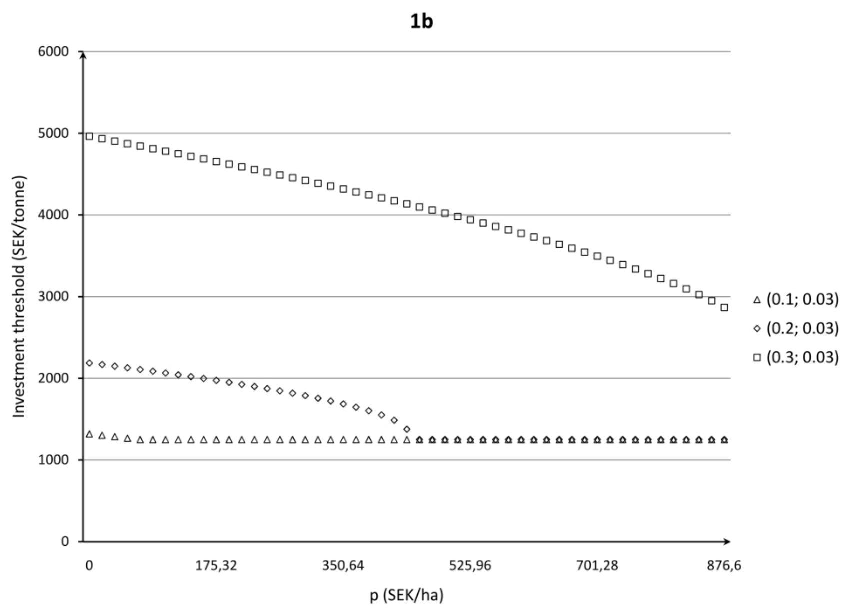

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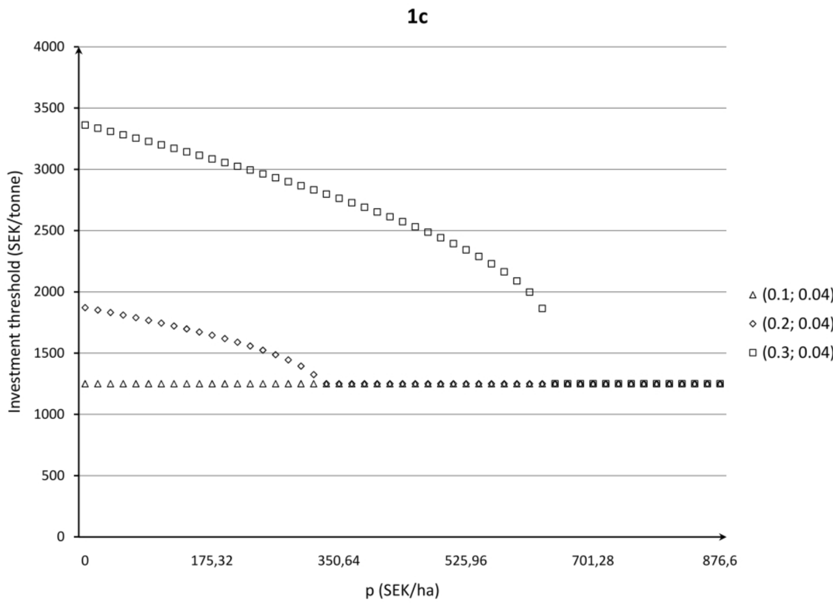

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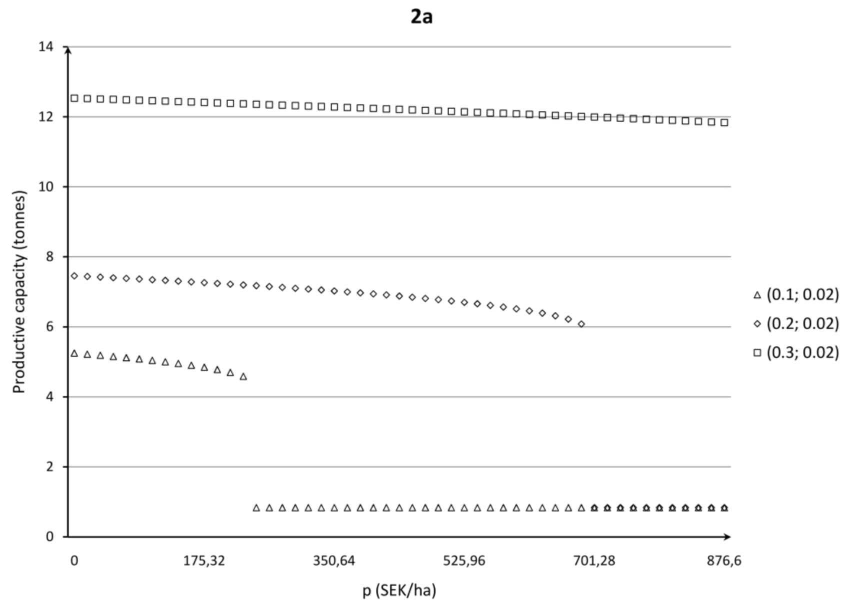

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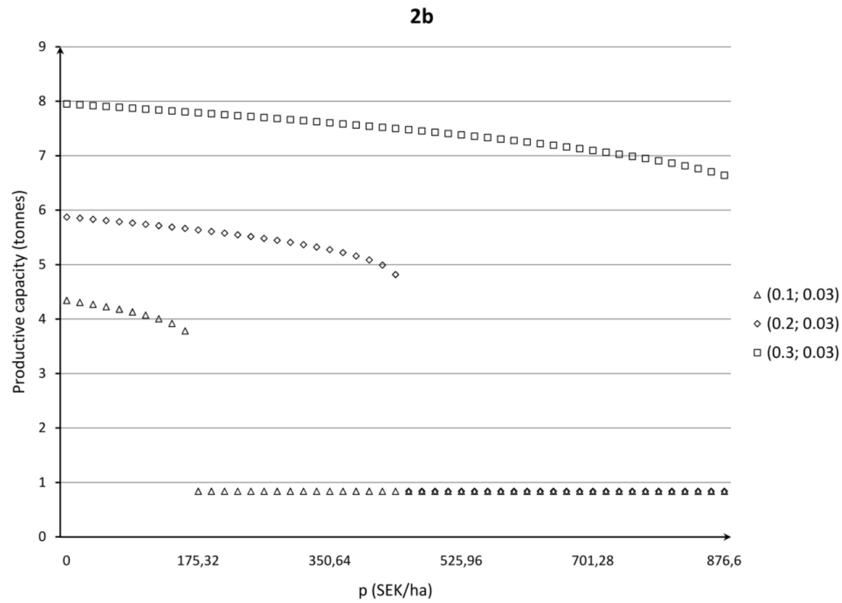

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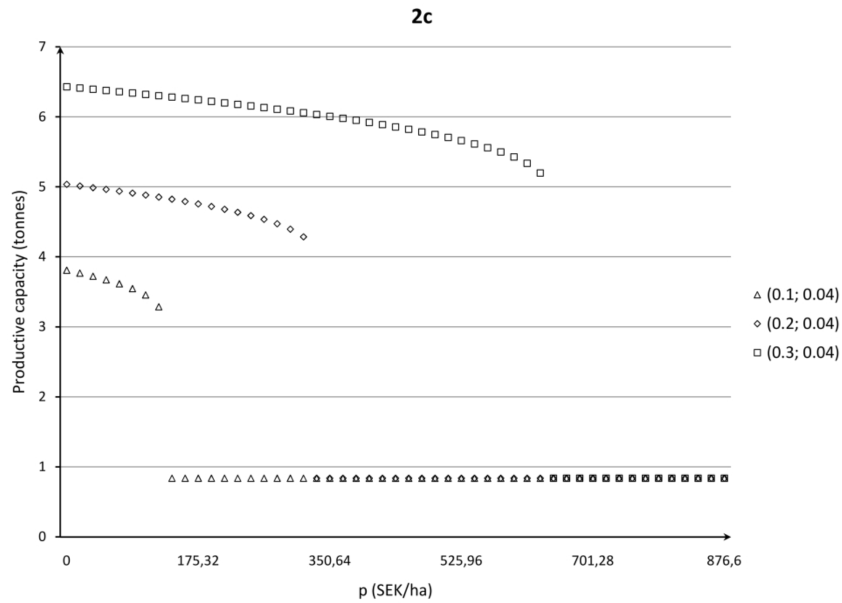

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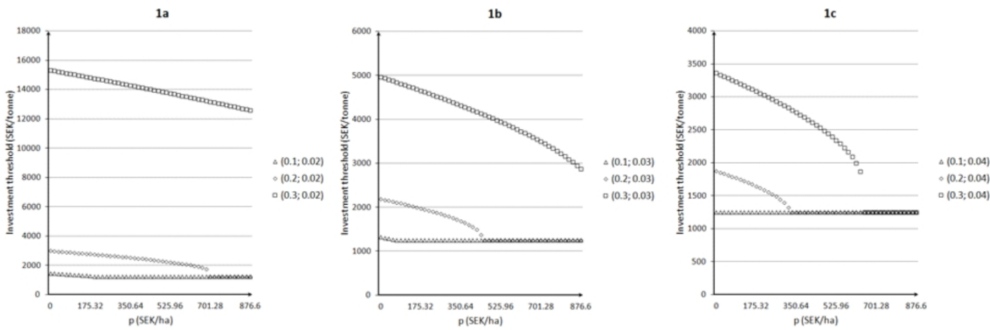

Fig 1. Investment thresholds. The figure contains three panels referring to the optimal investment threshold for net payment in the range [0, 876,6]. Each panel corresponds to a discount rate in the range [0.02; 0.03; 0.04]. Each curve corresponds to a volatility level in the range [0.1; 0.2; 0.3] for a given discount rate. We use triangular, rhombic and squared markers when volatility is low, moderate and high respectively.

431x143mm (118 x 118 DPI)

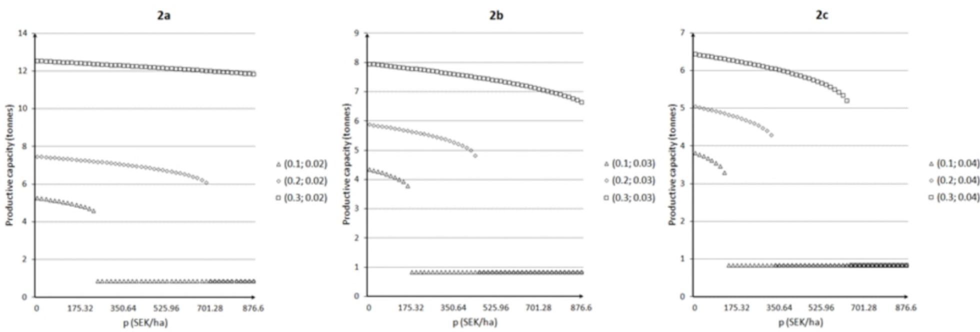

Fig 2. Productive capacities. The figure contains three panels referring to the optimal productive capacity for net payment in the range [0, 876,6]. Each panel corresponds to a discount rate in the range [0.02; 0.03; 0.04]. Each curve corresponds to a volatility level in the range [0.1; 0.2; 0.3] for a given discount rate. We use triangular, rhombic and squared markers when volatility is low, moderate and high respectively.

431x143mm (118 x 118 DPI)